UNDERSTANDING POWER CONCEPTS BASIC COURSE PARTS 1, 2, & 3

PART 4 WILL BE ADDED IN REV 1.

Continuing Education Course

Revision 0 (April 2013)

References

- IEEE, NFPA,
- Schneider Electric
- General Electric
- Chevron
- DuPont
- Phillips
- Allen Bradley
- Siemens
- Powell Electric
- Fluke
- SEL
- ABB
- Readily available power points on the internet.
- ExxonMobil
- ECM
- Baldor
- Toshiba
- Post Glover

Understanding Power Concepts

- This course was put together using readily available material from the internet, and from older IEEE presentations. It is for educational purposes only. The user of this material should consult a licensed professional engineer on all topics presented in this basic electrical power course.

- This material has not been checked for accuracy. It should be assumed to be out of date.

- This material is again for educational purposes only. No profits have been made in the making of this course or in its presentation. This course is solely to help educate our engineers and society on electrical power topics.

Understanding Power Concepts

- This REV 0 April 2013 course covers Parts 1, 2, and 3.

- Part 4 will be added at a later date, REV 1.

Understanding Power Concepts

- Part 1
  - Introduction
  - Formulas (AC/DC Basics)
  - Standards
  - Codes/Personal Safety
  - Grounding

Understanding Power Concepts

Part 2

- Electrical Studies
  - One lines
  - SC
  - LF
  - I2T
- Transfer Schemes
- Cable types
- Feeder Designs

Understanding Power Concepts

Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

Understanding Power Concepts

Part 4 ***(has not been added as of REV 0)***

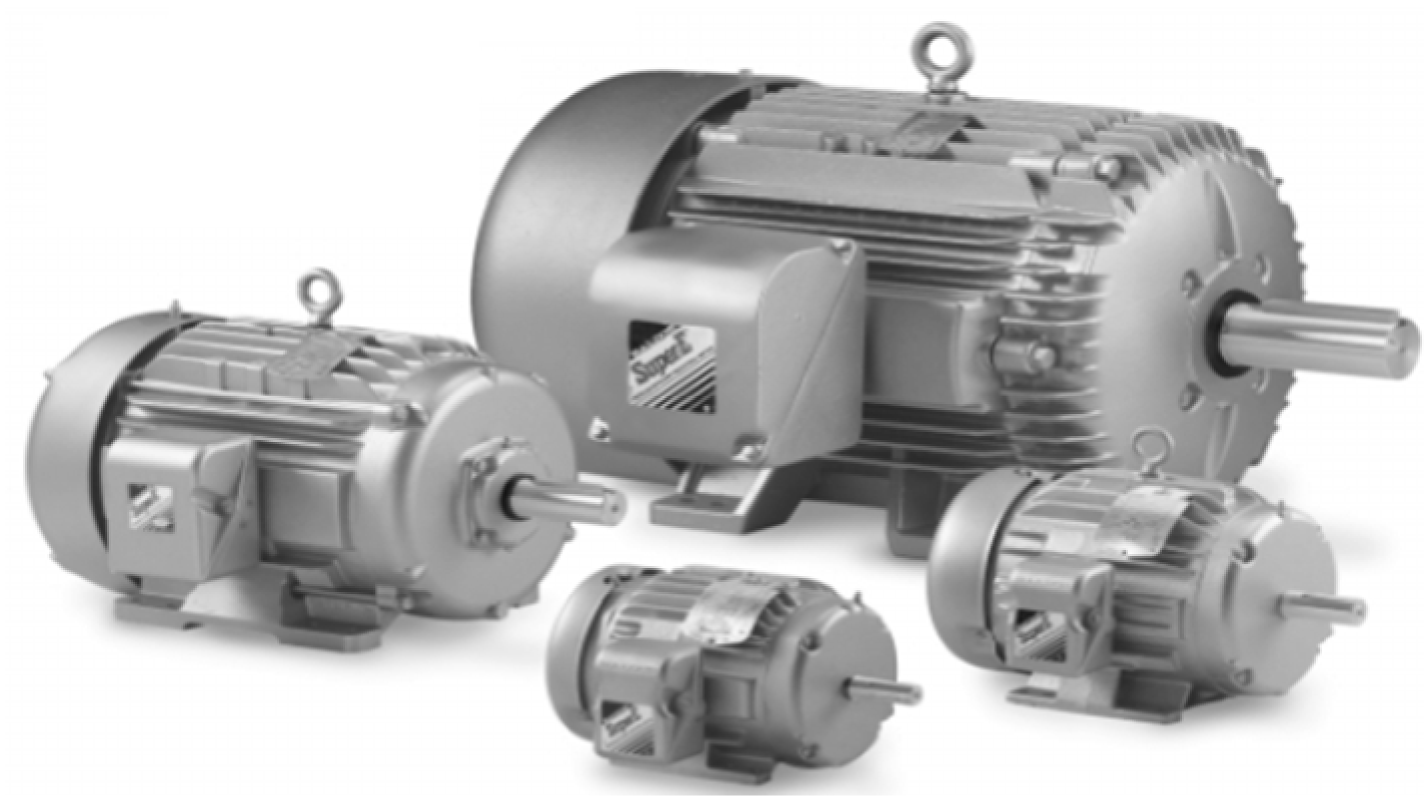
- Protective Relaying
  - Bus
  - Feeders
  - Motors
  - Generators
  - Transformers

Understanding Power Concepts

Part 3

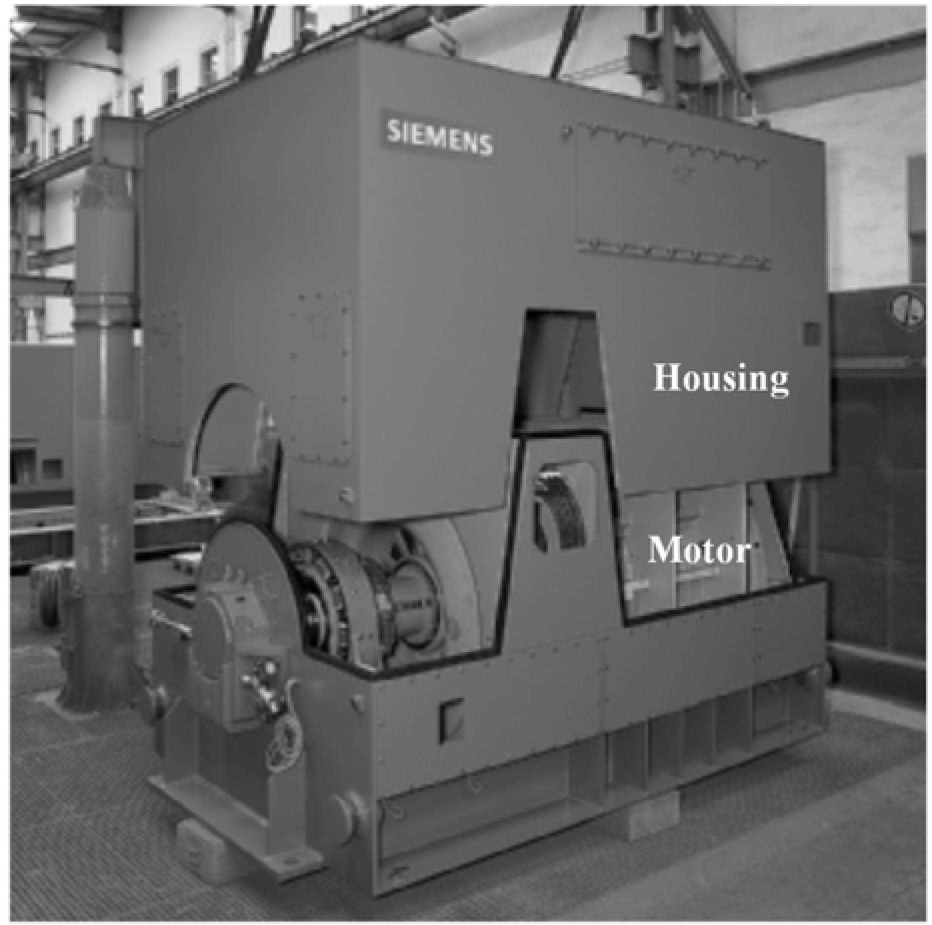
- ***<u>Motors</u>***
  - ***<u>AC Induction Motors</u>***
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

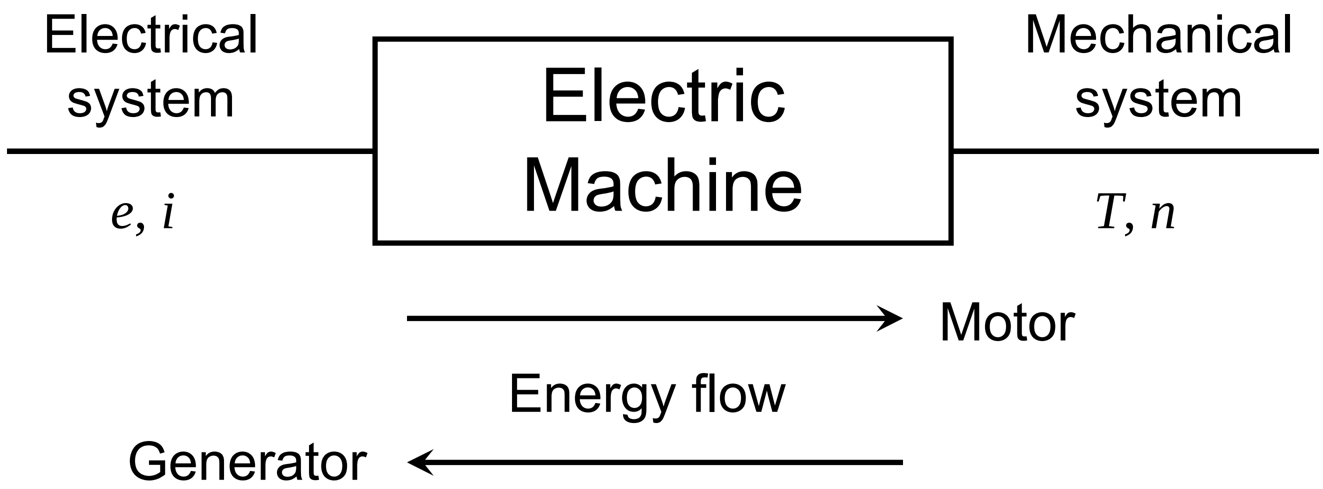
AC motors convert AC electrical energy to Mechanical energy.



Induction Motors

- **For industrial applications, the three-phase induction motor is used to drive machines**
- **Large three-phase induction motor. (Courtesy Siemens**).





- An electrical machine is link between an electrical system and a mechanical system.
- Conversion from mechanical to electrical: generator
- Conversion from electrical to mechanical: motor

Single Phase Induction Motors Three Types of Capacitor Start Motors

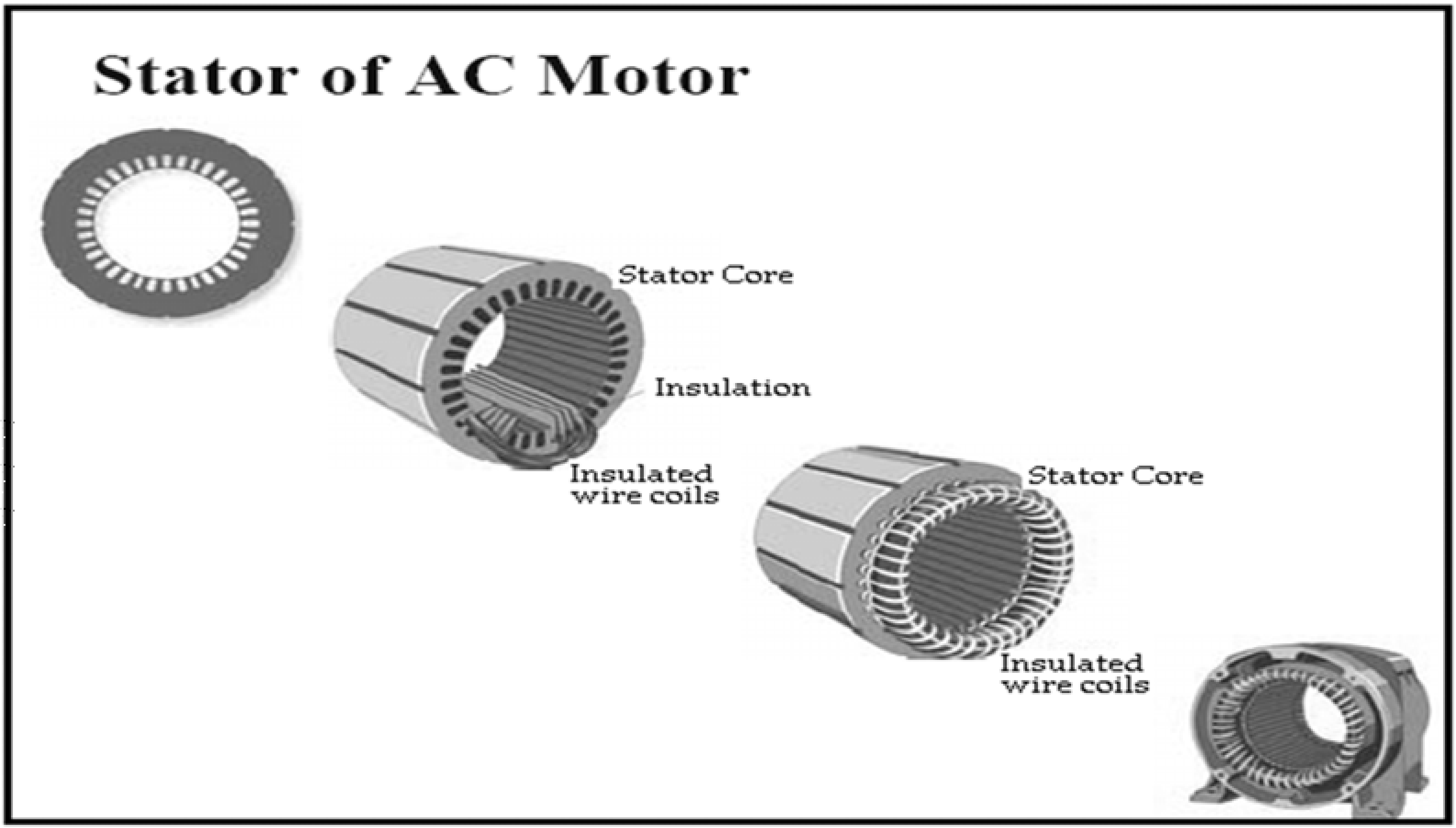
1. **Capacitor Start** (disconnects capacitor after motor speed picks up)

2. **Capacitor Run** (Keeps the capacitor connected during the operation of the motor, in order to keep the electric power consumption low)

3. **Capacitor Start-Run** (uses two capacitors, one for starting and one for running. This further improves Power Consumption)

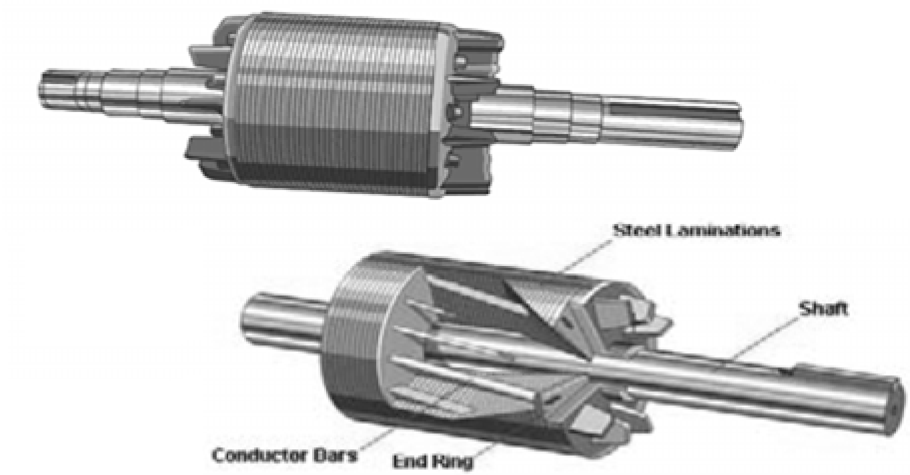
Motor Construction
The Stator

- The stator forms a hollow cylinder with coils of insulated wire inserted into slots of the stator core.
- The coils, plus the steel core form the electromagnets.



Motor Construction The Rotor

- There are two types of motor rotors:
- The wound rotor
- The squirrel cage
- The wound rotor has coils of wire wound in the slots of the rotor (Similar to generator coils).
- The “Squirrel cage” consists of bars of copper or aluminum electrically connected at each end with conducting rings.
- ***As the rotor rotates inside a magnetic field, it receives electromagnetic induction, then current flows and form the rotor electromagnet***.



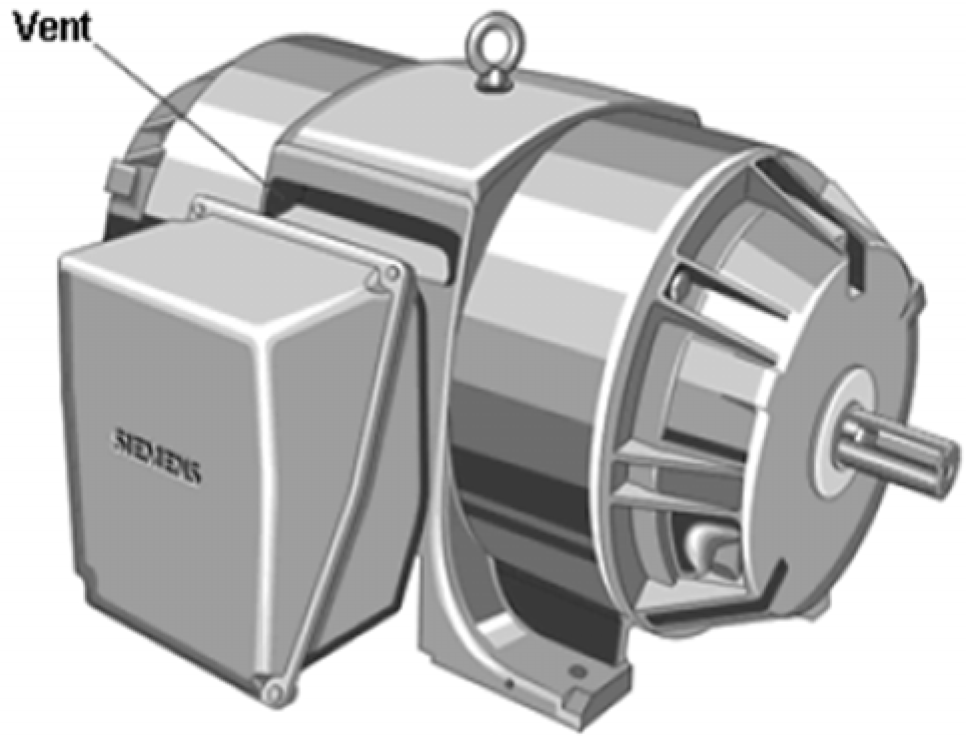
Squirrel Cage Rotor of an AC Motor

Types of Motor Enclosures

1. ODP – Open Drip Proof
2. TENV – Totally Enclosed Non-Ventilating
3. TEFC – Totally enclosed Fan Cooled
4. XP – Explosion Proof

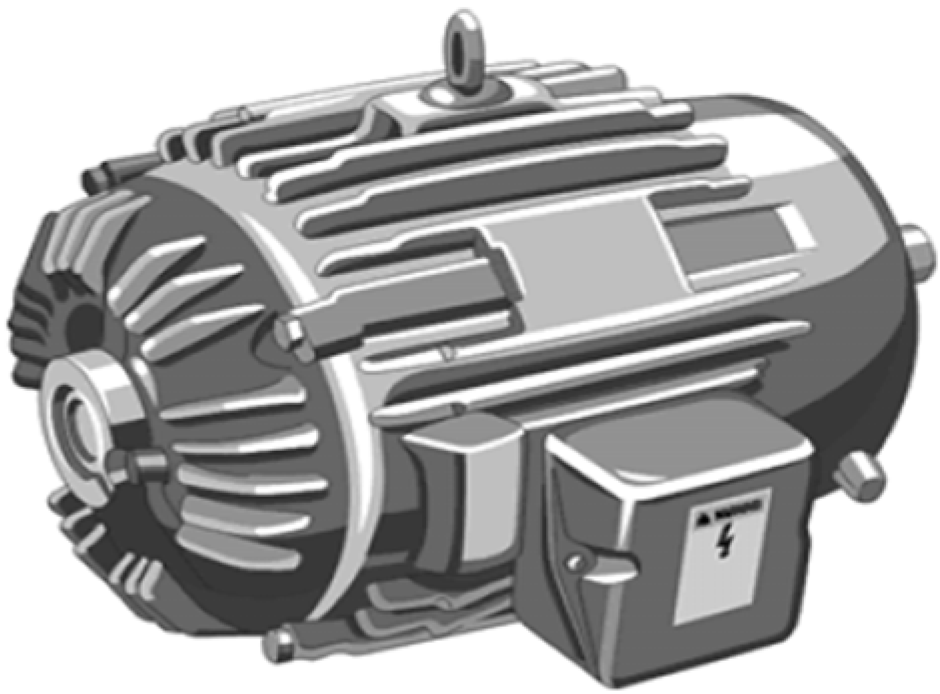
Types of Motor Enclosures

- ODP – Open Drip Proof
  - Air flows through motor (fan blades help flow)
  - Used in environments free from contaminants



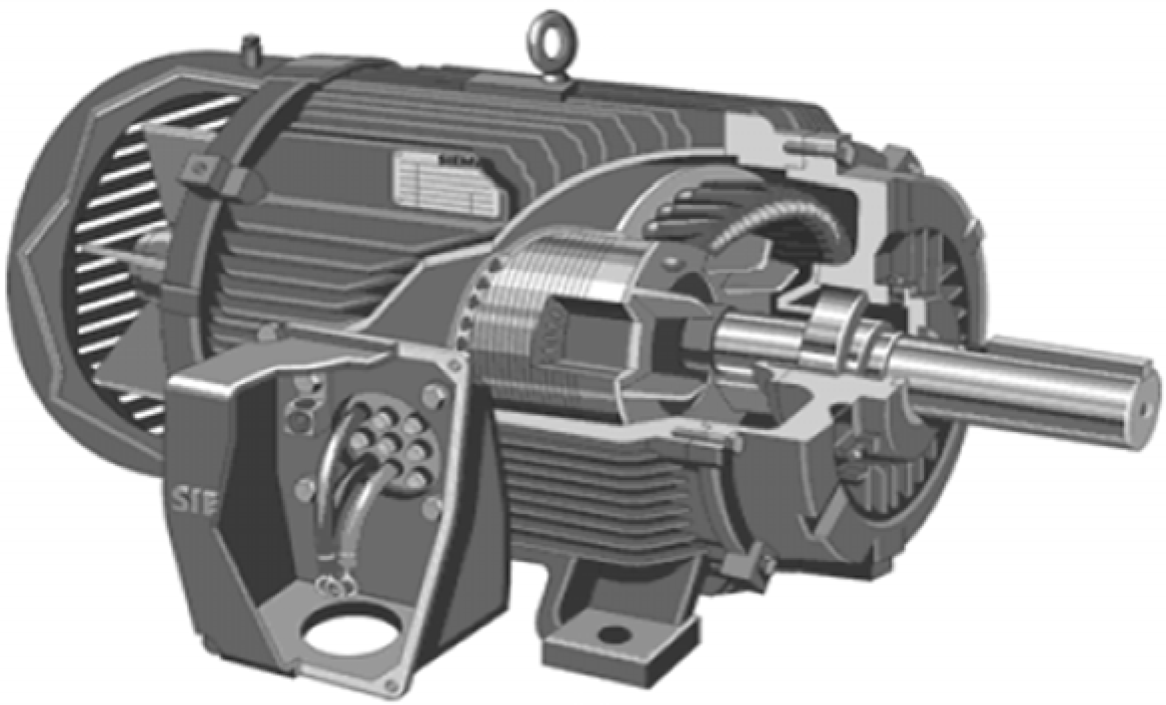
Types of Motor Enclosures

- TENV – Totally Enclosed Non-Ventilating
  - Protect motor from corrosive and harmful elements
  - Frame fins help to dissipate heat



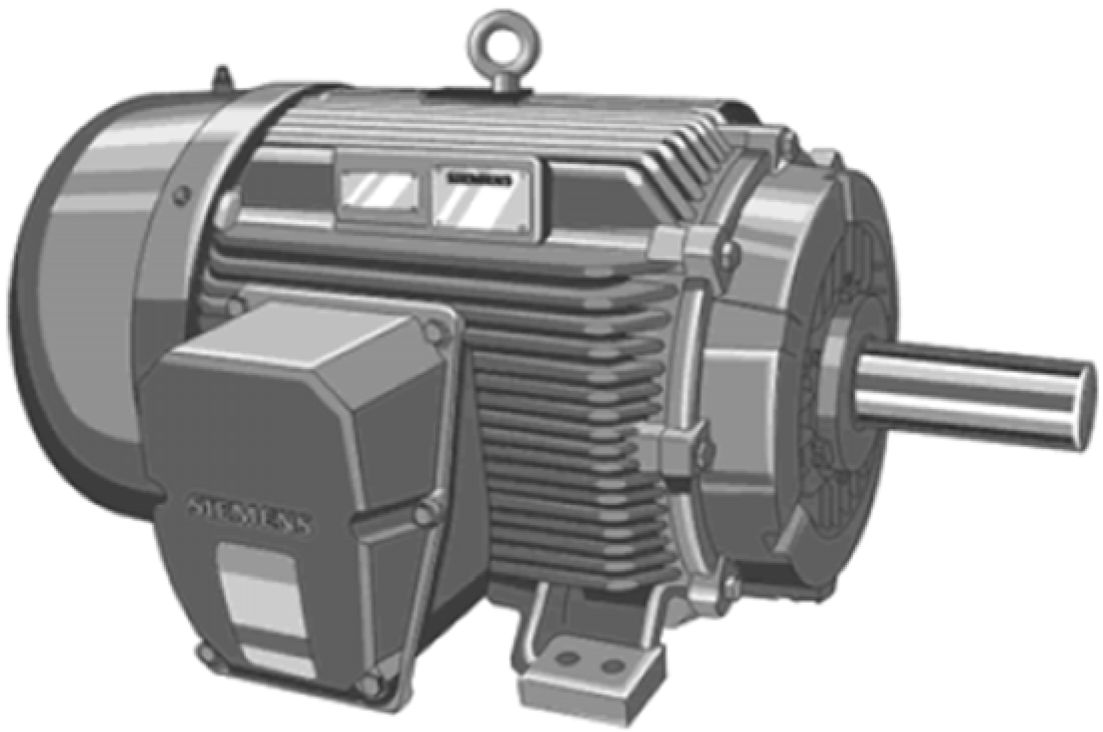
Types of Motor Enclosures

- TEFC – Totally enclosed Fan Cooled
  - Similar to TENV except has external fan for cooling



Types of Motor Enclosures

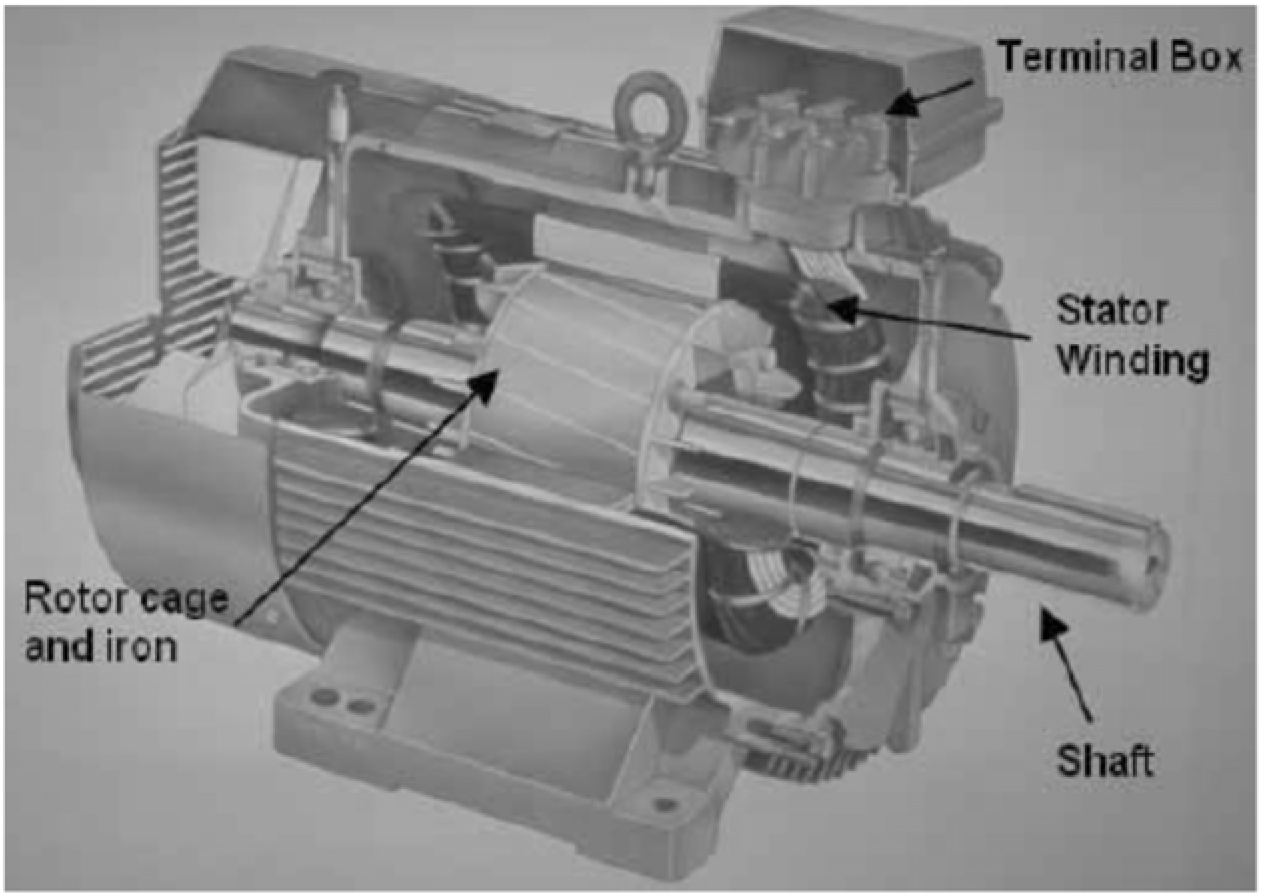
- XP – Explosion Proof
  - Similar to TEFC but enclosures are cast iron



Three Phase AC Motor

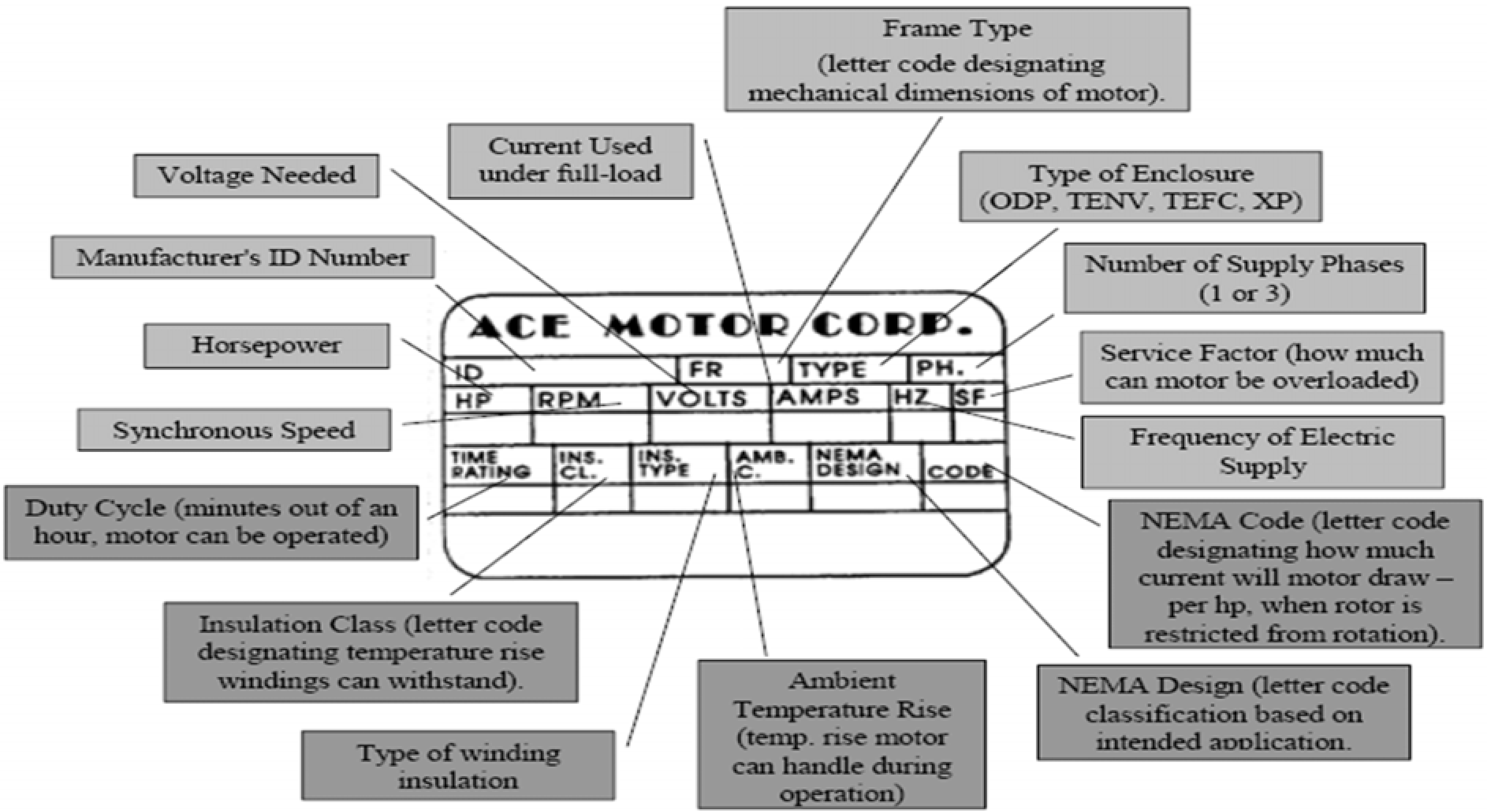
- It has three pairs of electromagnets, connected to one of the three phases of the power supply.
- It provides a lot higher power that what single phase motor can deliver.

Induction Machines Construction



AC Motor Data Plate

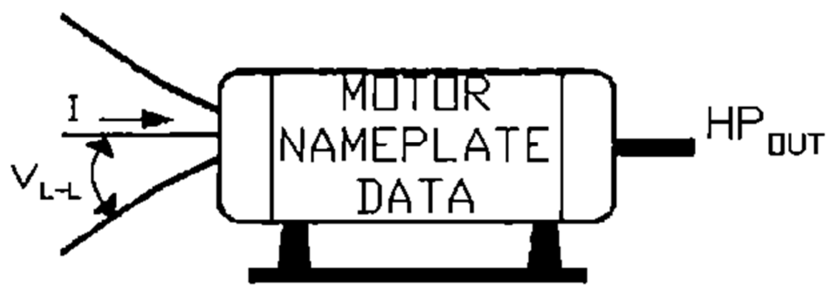
- Each motor has a plate mounted on its frame, with electrical and mechanical information.



MOTOR I/O RELATIONSHIPS

$$KVA_{IN} = \frac{\sqrt{3} \times V_{L-L} \times I}{1000} = \frac{KW_{IN}}{\text{POWER FACTOR}}$$

$$KW_{IN} = \frac{\sqrt{3} \times V_{L-L} \times I \times PF}{1000} = \frac{HP_{OUT} \times .746}{\text{EFFICIENCY}}$$



$$HP_{OUT} = \frac{\text{TORQUE (FT.LB.)} \times RPM}{5250} = \frac{KW_{IN} \times \text{EFF.}}{.746}$$

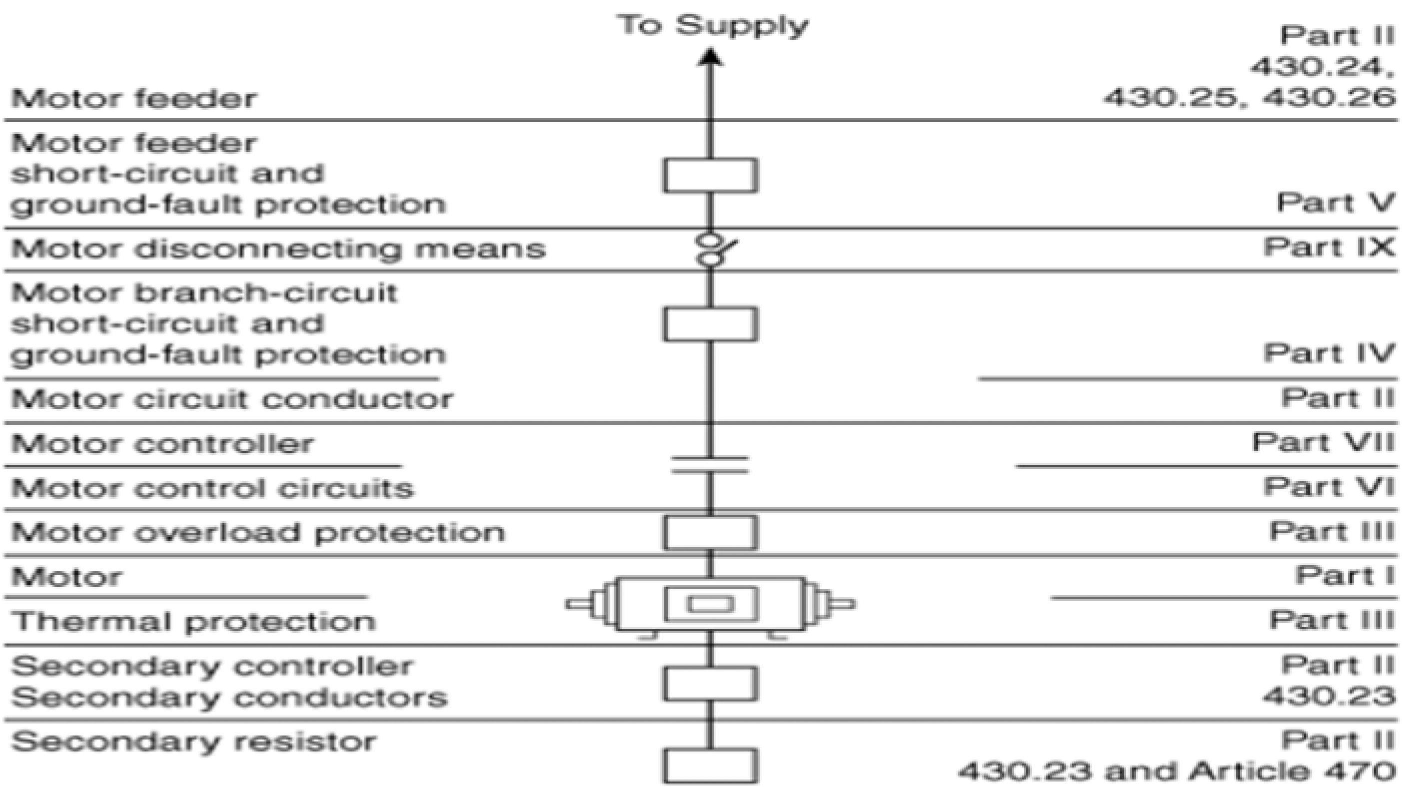


Figure 430.1 **Article 430 Contents**

Table 430.7(B) **Locked-Rotor Indicating Code Letters**

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor	Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0–3.14	L	9.0–9.99
B	3.15–3.54	M	10.0–11.19
C	3.55–3.99	N	11.2–12.49
D	4.0–4.49	P	12.5–13.99
E	4.5–4.99	R	14.0–15.99
F	5.0–5.59	S	16.0–17.99
G	5.6–6.29	T	18.0–19.99
H	6.3–7.09	U	20.0–22.39
J	7.1–7.99	V	22.4 and up
K	8.0–8.99		

Table 430.52 **Maximum Rating or Setting of Motor Branch-Circuit Short-Circuit and Ground-Fault Protective Devices**

Type of Motor	Percentage of Full-Load Current			
	Non-time Delay Fuse	Dual Element (Time-Delay) Fuse	Instantaneous Trip Breaker	Inverse Time Breaker
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor				
Squirrel cage other than Design B energy-efficient	300	175	800	250
Design B energy-efficient	300	175	1100	250
Synchronous	300	175	800	250
Wound rotor	150	150	800	150
Direct current (constant voltage)	150	150	250	150

Table 430.91 Motor Controller Enclosure Selection

For Outdoor Use										
Provides a Degree of Protection Against the Following Environmental Conditions	Enclosure Type Number[1]									
	3	3R	3S	3X	3RX	3SX	4	4X	6	6P
Incidental contact with the enclosed equipment	X	X	X	X	X	X	X	X	X	X
Rain, snow, and sleet	X	X	X	X	X	X	X	X	X	X
Sleet[2]	—	—	X	—	—	X	—	—	—	—
Windblown dust	X	—	X	X	—	X	X	X	X	X
Hosedown	—	—	—	—	—	—	X	X	X	X
Corrosive agents	—	—	—	X	X	X	—	X	—	X
Temporary submersion	—	—	—	—	—	—	—	—	X	X
Prolonged submersion	—	—	—	—	—	—	—	—	—	X

For Indoor Use										
Provides a Degree of Protection Against the Following Environmental Conditions	Enclosure Type Number1									
	1	2	4	4X	5	6	6P	12	12K	13
Incidental contact with the enclosed equipment	X	X	X	X	X	X	X	X	X	X
Falling dirt	X	X	X	X	X	X	X	X	X	X
Falling liquids and light splashing	—	X	X	X	X	X	X	X	X	X
Circulating dust, lint, fibers, and flyings	—	—	X	X	—	X	X	X	X	X
Settling airborne dust, lint, fibers, and flyings	—	—	X	X	X	X	X	X	X	X
Hosedown and splashing water	—	—	X	X	—	X	X	—	—	—
Oil and coolant seepage	—	—	—	—	—	—	—	X	X	X
Oil or coolant spraying and splashing	—	—	—	—	—	—	—	—	—	X
Corrosive agents	—	—	—	X	—	—	X	—	—	—
Temporary submersion	—	—	—	—	—	X	X	—	—	—
Prolonged submersion	—	—	—	—	—	—	X	—	—	—

1Enclosure type number shall be marked on the motor controller enclosure.
2Mechanism shall be operable when ice covered.
FPN: The term *raintight* is typically used in conjunction with Enclosure Types 3, 3S, 3SX, 3X, 4, 4X, 6, 6P. The term *rainproof* is typically used in conjunction with Enclosure Type 3R, 3RX. The term *watertight* is typically used in conjunction with Enclosure Types 4, 4X, 6, 6P. The term *driptight* is typically used in conjunction with Enclosure Types 2, 5, 12, 12K, 13. The term *dusttight* is typically used in conjunction with Enclosure Types 3, 3S, 3SX, 3X, 5, 12, 12K, 13.

Table 430.251(B) Conversion Table of Polyphase Design B, C, and D Maximum Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating and Design Letter

Rated Horsepower	Maximum Motor Locked-Rotor Current in Amperes, Two- and Three-Phase, Design B, C, and D*					
	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts
	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
½	40	23	22.1	20	10	8
¾	50	28.8	27.6	25	12.5	10
1	60	34.5	33	30	15	12
1½	80	46	44	40	20	16
2	100	57.5	55	50	25	20
3	—	73.6	71	64	32	25.6
5	—	105.8	102	92	46	36.8
7½	—	146	140	127	63.5	50.8
10	—	186.3	179	162	81	64.8
15	—	267	257	232	116	93
20	—	334	321	290	145	116
25	—	420	404	365	183	146
30	—	500	481	435	218	174
40	—	667	641	580	290	232
50	—	834	802	725	363	290
60	—	1001	962	870	435	348
75	—	1248	1200	1085	543	434
100	—	1668	1603	1450	725	580
125	—	2087	2007	1815	908	726
150	—	2496	2400	2170	1085	868
200	—	3335	3207	2900	1450	1160
250	—	—	—	—	1825	1460
300	—	—	—	—	2200	1760
350	—	—	—	—	2550	2040
400	—	—	—	—	2900	2320
450	—	—	—	—	3250	2600
500	—	—	—	—	3625	2900

*Design A motors are not limited to a maximum starting current or locked rotor current.

These tables for use only with 430.110, 440.12, 440.41 and 455.8(C).

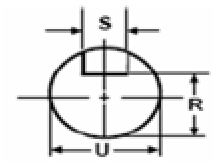
NEMA Table 11 **Typical Characteristics and Applications of Fixed Frequency Small and Medium AC Squirrel-Cage Induction Motors**

Design Letter	**Locked Rotor Torque**	**Pull-up Torque**	**Break-down Torque**	**Locked Rotor Current**	**Slip**	**Typical Applications**	**Relative Efficiency**
Polyphase Characteristics	**Percent Rated Load Torque***	**Percent Rated Load Torque**	**Percent Rated Load Torque**	**Percent Rated Load Current**	**Percent Sync Speed**		
Design A High locked rotor torque High locked rotor current	70-275	65-190	175-300	Not defined	0.5-5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or high
Design B Normal locked rotor torque Normal locked rotor current	70-275	65-190	175-300	600-700	0.5-5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or high
Design C High locked rotor torque Normal locked rotor current	200-285	140-195	190-225	600-700	1-5%	Conveyors, crushers, stirring motors, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
Design D High locked rotor torque High slip	275	NA	275	600-700	5-8%	High peak loads with or without flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wire-drawing motors	Low
Design N Small motor	-	NA	-	-	-	Centrifugal loads where starting torque requirements are relatively low.	Low
Design 0 Small motor	-	NA	-	-	NA		
Design L Medium motor	-	100%	-	-	NA	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or low
Design M Medium motor	-	100%	-	-	NA	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or low

*Higher values are for motors having lower horsepower ratings.

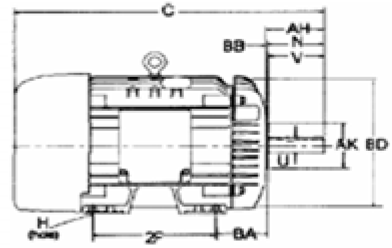
NEMA MOTOR DIMENSIONS

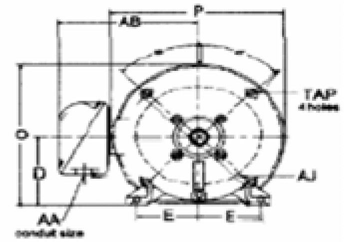
Shaft – Key Dimensions



NEMA Shaft (U)	Key (R)	Dimen (S)
3/8	21/64	flat
1/2	29/64	flat
5/8	33/64	3/16
7/8	49/64	3/16
1-1/8	63/64	1/4
1-3/8	1-13/64	5/16
1-5/8	1-13/32	3/8
1-7/8	1-19/32	1/2
2-1/8	1-27/32	1/2
2-3/8	2-1/64	5/8
2-1/2	2-3/16	5/8
2-7/8	2-29/64	3/4
3-3/8	2-7/8	7/8
3-7/8	3-5/16	1

Frame Dimensions





Frame	D	E	2F	H	N*	O*	P*	U	V	AA	AB*	AH	AJ	AK	BA	BB	BD*	TAP
42	2-5/8	1-3/4	1-11/16	9/32 slot	1-1/2	5	4-11/16	3/8	1-1/8	3/8	4-1/32	1-5/16	3-3/4	3	2-1/16	1/8	4-5/8	1/4-20
48	3	2-1/8	2-3/4	11/32 slot	1-7/8	5-7/8	5-11/16	1/2	1-1/2	1/2	4-3/8	1-11/16	3-3/4	3	2-1/2	1/8	5-5/8	1/4-20
56	3-1/2	2-7/16	3	11/32 slot	2-7/16	6-7/8	6-5/8	5/8	1-7/8	1/2	5	2-1/16	5-7/8	4-1/2	2-3/4	1/8	6-1/2	3/8-16
56H			5		2-1/8													
143T	3-1/2	2-3/4	4	11/32	2-1/2	6-7/8	6-5/8	7/8	2-1/4	3/4	5-1/4	2-1/8	5-7/8	4-1/2	2-1/4	1/8	6-1/2	3/8-16
145T			5															
182			4-1/2		2-11/16			7/8	2-1/4			2-1/8	5-7/8	4-1/2		1/8	6-1/2	3/8-16
184	4-1/2	3-3/4	5-1/2	13/32	2-11/16	8-11/16	7-7/8	7/8	2-1/4	3/4	5-7/8	2-1/8	5-7/8	4-1/2	2-3/4	1/8	6-1/2	3/8-16
182T			4-1/2		3-9/16			1-1/8	2-3/4			2-5/8	7-1/4	8-1/2		1/4	9	1/2-13
184T			5-1/2		3-9/16			1-1/8	2-3/4			2-5/8	7-1/4	8-1/2		1/4	9	1/2-13
213			5-1/2		3-1/2			1-1/8	3			2-3/4						
215	5-1/4	4-1/4	7	13/32	3-1/2	10-1/4	9-9/16	1-1/8	3	3/4	7-3/8	2-3/4	7-1/4	8-1/2	3-1/2	1/4	9	1/2-13
213T			5-1/2		3-7/8			1-3/8	3-3/8			3-1/8						
215T			7		3-7/8			1-3/8	3-3/8			3-1/8						
254U			8-1/4		4-1/16			1-3/8	3-3/4			3-1/2						
256U	6-1/4	5	10	17/32	4-1/16	12-7/8	12-15/16	1-3/8	3-3/4	1	9-5/8	3-1/2	7-1/4	8-1/2	4-1/4	1/4	10	1/2-13
254T			8-1/4		4-5/16			1-5/8	4			3-3/4						
256T			10		4-5/16			1-5/8	4			3-3/4						
284U			9-1/2		5-1/8			1-5/8	4-7/8			4-5/8						
286U			11		5-1/8			1-5/8	4-7/8			4-5/8						
284T	7	5-1/2	9-1/2	17/32	4-7/8	14-5/8	14-5/8	1-7/8	4-5/8	1-1/2	13-1/8	4-3/8	9	10-1/2	4-3/4	1/4	11-1/4	1/2-13
286T			11		4-7/8			1-7/8	4-5/8			4-3/8						
284TS			9-1/2		3-3/8			1-5/8	3-1/4			3						
286TS			11		3-3/8			1-5/8	3-1/4			3						
324U			10-1/2		5-7/8			1-7/8	5-5/8			5-3/8						
326U			12		5-7/8			1-7/8	5-5/8			5-3/8						
324T	8	6-1/4	10-1/2	21/32	5-1/2			2-1/8	5-1/4	2	14-1/8	5	11	12-1/2	5-1/4	1/4	13-3/8	5/8-11
326T			12		5-1/2	16-1/2	16-1/2	2-1/8	5-1/4			5						
324TS			10-1/2		3-15/16			1-7/8	3-3/4			3-1/2						
326TS			12		3-15/16			1-7/8	3-3/4			3-1/2						
364U			11-1/4		6-3/4			2-1/8	6-3/8			6-1/8						
365U			12-1/4		6-3/4			2-1/8	6-3/8			6-1/8						
364T	9	7	11-1/4	21/32	6-1/4	18-1/2	18-1/4	2-3/8	5-7/8	2-1/2	15-1/16	5-5/8	11	12-1/2	5-7/8	1/4	13-3/8	5/8-11
365T			12-1/4		6-1/4			2-3/8	5-7/8			5-5/8						
364TS			11-1/4		4			1-7/8	3-3/4			3-1/2						
365TS			12-1/4		4			1-7/8	3-3/4			3-1/2						
404U			12-1/4		7-3/16			2-3/8	7-1/8			6-7/8						
405U			13-3/4		7-3/16			2-3/8	7-1/8			6-7/8						
404T	10	8	12-1/4	13/16	7-5/16	20-5/16	20-1/8	2-7/8	7-1/4	3	18	7	11	12-1/2	6-5/8	1/4	13-7/8	5/8-11
405T			13-3/4		7-5/16			2-7/8	7-1/4			7						
404TS			12-1/4		4-1/2			2-1/8	4-1/4			4						
405TS			13-3/4		4-1/2			2-1/8	4-1/4			4						
444U			14-1/2		8-5/8	22-7/8	22-3/8	2-7/8	8-5/8		19-9/16	8-3/8						
445U			16-1/2		8-5/8	22-7/8	22-3/8	2-7/8	8-5/8		19-9/16	8-3/8						
444T			14-1/2		8-1/2	22-7/8	22-3/8	3-3/8	8-1/2		19-9/16	8-1/4						
445T	11	9	16-1/2	13/16	8-1/2	22-7/8	22-3/8	3-3/8	8-1/2		19-9/16	8-1/4						
447T			20		8-15/16	22-15/16	22-3/4	3-3/8	8-1/2	3	21-11/16	8-1/4	14	16	7-1/2	1/4	16-3/4	5/8-11
449T			25		8-15/16	22-15/16	22-3/4	3-3/8	8-1/2		21-11/16	8-1/4						
444TS			14-1/2		5-3/16	22-7/8	22-3/8	2-3/8	4-3/4		19-9/16	4-1/2						
445TS			16-1/2		5-3/16	22-7/8	22-3/8	2-3/8	4-3/4		19-9/16	4-1/2						
447TS			20		4-15/16	22-15/16	22-3/4	2-3/8	4-3/4	4NPT	21-11/16	4-1/2						
449TS			25		4-15/16	22-15/16	22-3/4	2-3/8	4-3/4	4NPT	21-11/16	4-1/2						

NEMA Motor Enclosure Type

Type	Abbreviation	Description	Designed for use in
Open Drip Proof	ODG	Open Drip-Proof, Guarded	non-hazardous, relatively clean areas, most common type,
	ODG-FV	Open Drip-Proof, Force Ventilated	
	ODG-SV	Open Drip-Proof, Separately Ventilated	
	ODP	Open Drip-Proof	
Totally Enclosed	TEAO	Totally-Enclosed, Air-Over	extremely wet, dirty, or dusty areas
	TEBC	Totally-Enclosed, Blower-Cooled	
	TECACA	Totally-Enclosed, Closed Circuit,, Air to Air	
	TEDC-A/A	Totally-Enclosed, Dual Cooled, Air to Air	
	TEDC-A/W	Totally-Enclosed, Dual Cooled, Air to Water	
	TEFC	Totally-Enclosed, Fan-Cooled	
	TENV	Totally-Enclosed Non-Ventilated	
	TETC	Totally-Enclosed, Tube Cooled	
	TEWAC	Totally-Enclosed, Water/Air Cooled	
	TEXP	Totally-Enclosed, Explosion-Proof	
Weather Protected	WPI	Weather Protected, Type I	adverse outdoor conditions
	WPII	Weather Protected Type II	
Special	XE	Premium Efficient	improved efficiency
	XL	Extra Life	
	XP	Explosion-Proof	withstanding an explosion of a specified dust, gas, or vapor
	XT	Extra Tough	
		Dust ignition proof	preventing the ignition of a dust, gas, or vapor surrounding the motor
IEC	IP-22	Open Drip-Proof	representative IEC designations
	IP-44	Totally-Enclosed	
	IP-54	Splash Proof	
	IP-55	Washdown	

Electrical Power System Design Example

Pump:	20 Hp, 300 RPM, 18" sheave	Pump:	
Motor:	3Φ, 460 V	Motor:	
Power:	3Φ, 7200 LN	Power:	
Environment:	ambient 98F, outdoor	Environment:	

#	Measure Parameter	Standard Table or Reference	Example Factor	Example Result	Problem Factor	Problem Result
1	Motor horsepower	NEC 430.250	-	20		
2	Full load Amps - FLA	NEC 430.250	-	27		
3	Lock letter code & kVA/hp	NEC 430.7(B)	F 5.59	112		
4	Lock rotor amp calculate	kVA*1000/1.732 V	112,000/1.732*460	141		
5	Lock rotor amp for disconnect	NEC 430.251(B)	-	145		
6	Wire rating:1.25*largest+other	NEC 430.24	1.25*27 + 0	34		
7	Insulation type	NEC 310-16	-	THHN		
8	Insulation temperature	NEC 310-16	-	90C		
9	AWG / kcmil	NEC 310-16	-	10 AWG		
10	Temperature correction amp	NEC 310-16	0.91	36		
11	Max breaker rating & type	NEC 430.52	800 instant	216		
12	Actual breaker size	NEC 240.6(A)	-	200		
13	Controller enclosure	NEC 430.91	-	3R		
14	Controller size	NEMA Controller	-	2		
15	Controller max closing amp	NEMA Controller	-	483		
16	Overload setting % - Amp	-	105	28.4		
17	Motor enclosure	NEMA Enclosure		TEFC		
18	Motor NEMA design	NEMA 11	-	B		
19	Motor sync speed	120 * freq / poles	120*60/4	1800		
20	Motor slip - shaft speed	NEMA 11	2%	1764		
21	Motor frame	NEMA Dimension 2	-	256T		
22	Shaft diameter	NEMA Dimensions	U	1-5/8		
23	Sheave diameter	P(n*dia) = M(n*dia)	300*18/1800	3"		
24	# wires	-	3Φ + N	4		
25	Conduit type & size	NEC C4 et al	1/2	3/4		
26	Total kVA	1.732 V * I / 1000	1.732*480*27/1000	22.5		
26	Transformer kVA size	NEMA	-	3 – 7.5		
28	Secondary volt & Y-Δ	-		277 / 480 Y		
29	Primary volt & Y-Δ	-		12470 Δ		
30	Transformers taps			two 2-1/2 ±		
31	Transformer impedance PU					

1. Which of the following is least likely to be found on an induction motor nameplate:

a) frequency

b) motor weight

c) full load current

d) rpm

ANSWER b

7. Which of the following is least likely to be found on an induction motor nameplate?

a) full load p.f.

b) design code

c) frequency

d) full load current

ANSWER a

8. A 60 Hz AC motor is running at 1178 rpms at half load. The motor has how many poles?

a) 2

b) 4

c) 6

d) 8

ANSWER c

$$p = \frac{120f}{n} = \frac{7200}{1178} = 6.11 \text{ therefore poles} = 6$$

9. Which of the following is least likely to be found on an induction motor nameplate?

a) full load rpm

b) full load hp

c) full load current

d) full load torque

ANSWER d

- A motor nameplate indicates the following:

HP = 50 Service Factor= 1.25 Voltage= 460 Current= 53 RPM = 1145 Code Letter = B Phases = 3 Design Letter = B

Temperature Rise= 25° F Frequency 60Hz

10. This motor has how many poles?

a) 8
b) 6
c) 4
d) 2

ANSWER b

$$p = \frac{120f}{n} = \frac{7200}{1145} = 6.29 \text{ therefore poles} = 6$$

- A motor nameplate indicates the following:

HP = 50 Service Factor= 1.25 Voltage= 460 Current= 53 RPM = 1145 Code Letter = B Phases = 3 Design Letter = B

Temperature Rise= 25° F Frequency 60Hz

11. The motor maximum horse power is:

a) 50
b) 62.5
c) 70
d) 57.5

ANSWER b

$$hp_{max} = hp \times s.f. = 50 \times 1.25 = 62.5\,hp$$

- A motor nameplate indicates the following:

HP = 50 Service Factor= 1.25 Voltage= 460 Current= 53 RPM = 1145 Code Letter = B Phases = 3 Design Letter = B

Temperature Rise= 25° F Frequency 60Hz

12. Starting current at rated service factor is most nearly:

a) 175
b) 200
c) 225
d) 275

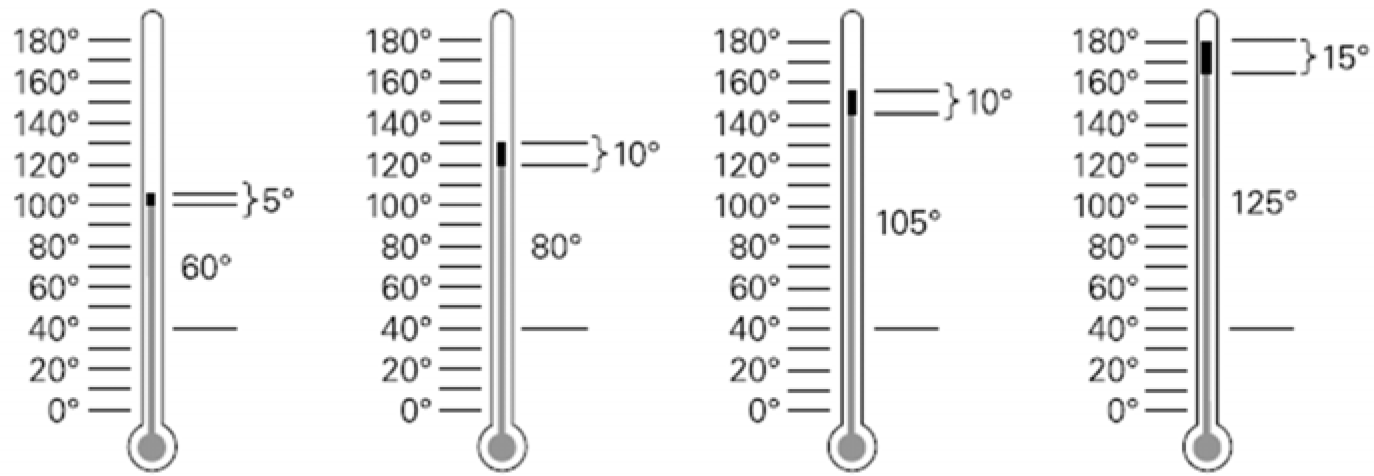
ANSWER c

Code Letter B = 3.54 kVA/Hp

$kVA_{STARTING}$ = 3.54*50=177 kVA

I = kVA/√3*460=222.4 A

The following illustration shows the **allowable temperature rise** for motors operated at a 1.0 service factor at altitudes no higher than 3300 ft. Each insulation class has a margin allowed to compensate for the motor's hot spot, a point at the center of the motor's windings where the temperature is higher. For motors with a service factor of 1.15, add 10° C to the allowed temperature rise for each motor insulation class.



Class A
60° C Rise
5° C Hot Spot

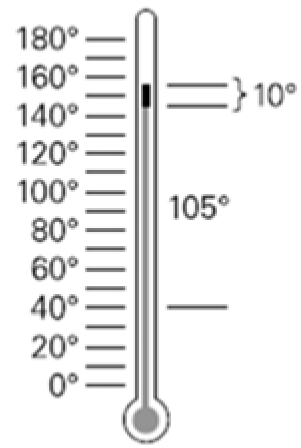
Class B
80° C Rise
10° C Hot Spot

Class F
105° C Rise
10° C Hot Spot

Class H
125° C Rise
15° C Hot Spot

- The motor has insulation class F and a service factor of 1.15.

- This means that its winding temperature is allowed to rise to 155° C with an additional 10° C hot spot allowance.



Motor Life vs. Temperature

- Most insulating materials have a negative temperature coefficient; that is, their resistance decreases as the temperature increases.

- Therefore, electrical stresses are more likely to cause insulation failure at elevated temperatures.

Motor Life vs. Temperature

- Insulation aging may be attributable, after years of service, to thermal weakening, even at rated nameplate temperatures.

- This process is greatly accelerated by operation at higher than normal current rating because heating increases as the square of the current. Continued operation at elevated temperatures produces embrittlement and mechanical deterioration of insulation.

- Hence, current nameplate values are exceeded at the expense of decreased insulation life.

Motor Life vs. Temperature

- Insulation degradation is a chemical action and higher temperatures accelerate this process.

- Arrhenius (IEEE C-57.91-1981 paragraph 3.4.3) expressed the chemical reaction rate by the following equation:

$$Log_{10}\ life(hrs.) = A + \frac{B}{T}$$

Motor Life vs. Temperature

$$Log_{10}\ life(hrs.) = A + \frac{B}{T}$$

- T = Absolute temperature in degrees kelvin, (C + 273) using the temperature at the hottest spot in the winding.
- A and B = Constants that vary with the type insulation system. Typical values for a Class A insulation would be A = -11.968 and B = 6328.8.

Motor Life vs. Temperature

$$Log_{10}\ life(hrs.) = A + \frac{B}{T}$$

- Although the above gives a general feel for life expectancy due to temperature changes, other variables such as vibration, moisture, switching surges, etc. must be factored in to determine the actual life.

NEMA Motor Design

- NEMA also uses letters (A, B, C, and D) to identify **motor designs** based on torque characteristics.
- The motor is a design B motor, the most common type.
- Motor design A is the least common type.
- The characteristics of motor designs B, C and D are discussed in this course.

Speed-Torque Curve for NEMA B Motor

- Because motor torque varies with speed, the relationship between speed and torque is often shown in a graph,

- called a speed-torque curve.

- This curve shows the motor’s torque, as a percentage of full-load torque, over the motor’s full speed range, shown as a percentage of its synchronous speed.

Torque and Magnetic Fields

- **Torque**, **moment** or **moment of force** is the tendency of a force to rotate an object about an axis, fulcrum, or pivot.

- Just as a force is a push or a pull, a torque can be thought of as a twist to an object.

- Mathematically, torque is defined as the cross product of the lever-arm distance and force, which tends to produce rotation.

Torque and Magnetic Fields

- Loosely speaking, torque is a measure of the turning force on an object such as a bolt or a flywheel.

- For example, pushing or pulling the handle of a wrench connected to a nut or bolt produces a torque (turning force) that loosens or tightens the nut or bolt.

Torque and Magnetic Fields

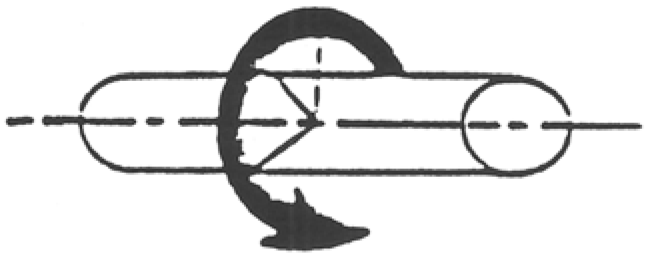
- The symbol for torque is typically τ, the Greek letter *tau*. When it is called moment, it is commonly denoted *M*.

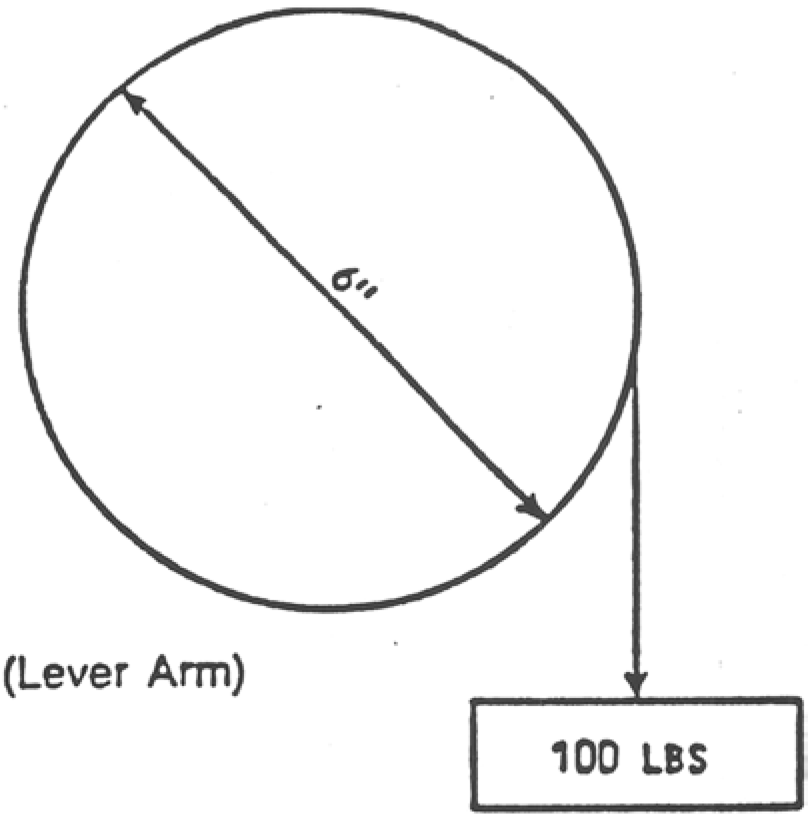
- The magnitude of torque depends on three quantities:
  - the force applied,
  - the length of the *lever arm* connecting the axis to the point of force application,
  - and the angle between the force vector and the lever arm. In symbols:

Machine torque

- Torque is part of the basic specification of an engine:
- the power output of an engine is expressed as its torque multiplied by its rotational speed of the axis.
- Internal-combustion engines produce useful torque only over a limited range of rotational speeds (typically from around 1,000–6,000 rpm for a small car).
- The varying torque output over that range can be measured with a dynamometer, and shown as a torque curve.

Torque and Magnetic Fields





FORMULA: Torque = Force x Radius (Lever Arm)

$$T = F \times R$$

EXAMPLE: Calculate Torque when:

$$T = F \times R$$

$$= 100 \text{ lbs.} \times 3 \text{ inches}$$

$$T = 300 \text{ pounds-inch}$$

Torque and Magnetic Fields

$$\text{Torque (pounds-inch)} = \frac{63025 \times \text{Horsepower}}{\text{Revolutions per Minute}}$$

$$\text{Torque (pounds-feet)} = \frac{5252 \times \text{HP}}{\text{RPM}}$$

EXAMPLE: Constant HP; Speed Decrease — Solve for Torque

1 HP @ 1750 RPM

$$T = \frac{63025 \times HP}{RPM} = \frac{63025 \times 1}{1750}$$

T = 36 pounds-inch

1 HP @ 875 RPM

$$T = \frac{63025 \times HP}{RPM} = \frac{63025 \times 1}{875}$$

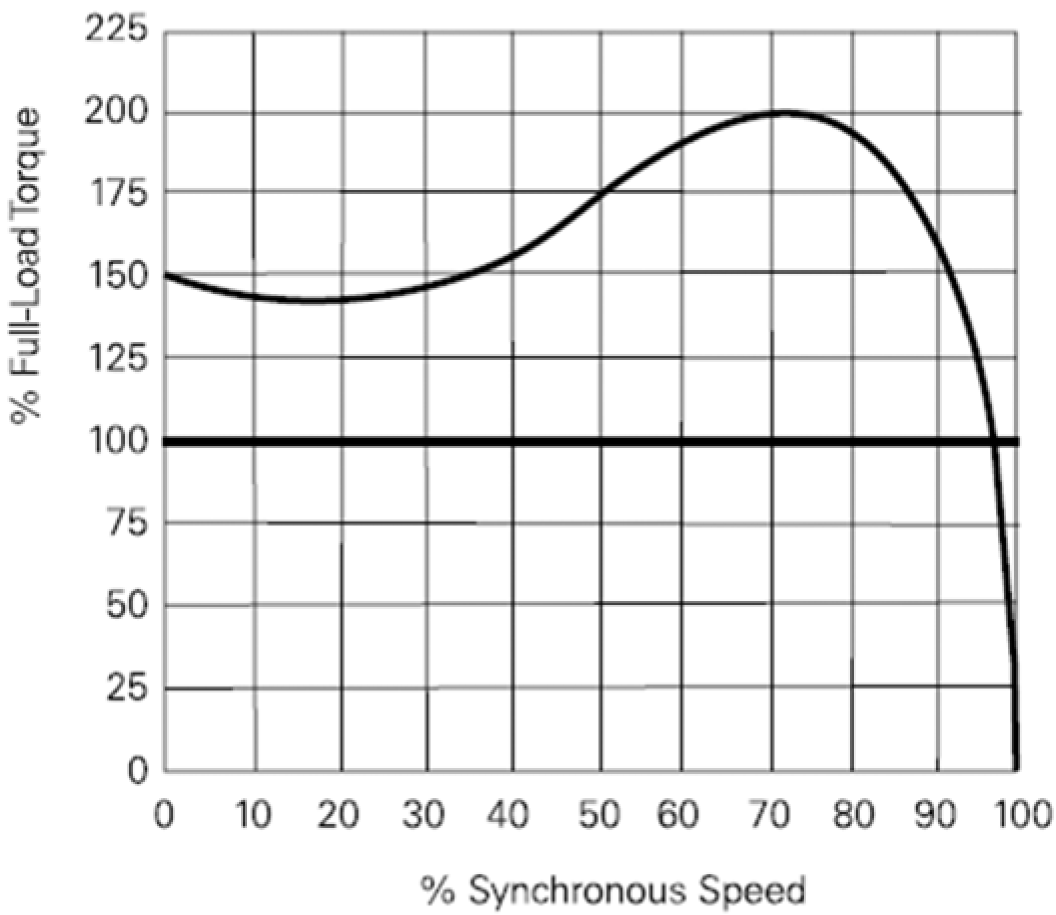
T = 72 pounds-inch

Speed was cut in half; torque value increased by same ratio or 2:1.

Torque multiplier

- A torque multiplier is a gear box with reduction ratios greater than 1. The given torque at the input gets multiplied as per the reduction ratio and transmitted to the output, thereby achieving greater torque, but with reduced rotational speed.

The following speed-torque curve is for a **NEMA B motor**. NEMA B motors are general purpose, single speed motors suited for applications that require normal starting and running torque, such as fans, pumps, lightly-loaded conveyors, and machine tools.

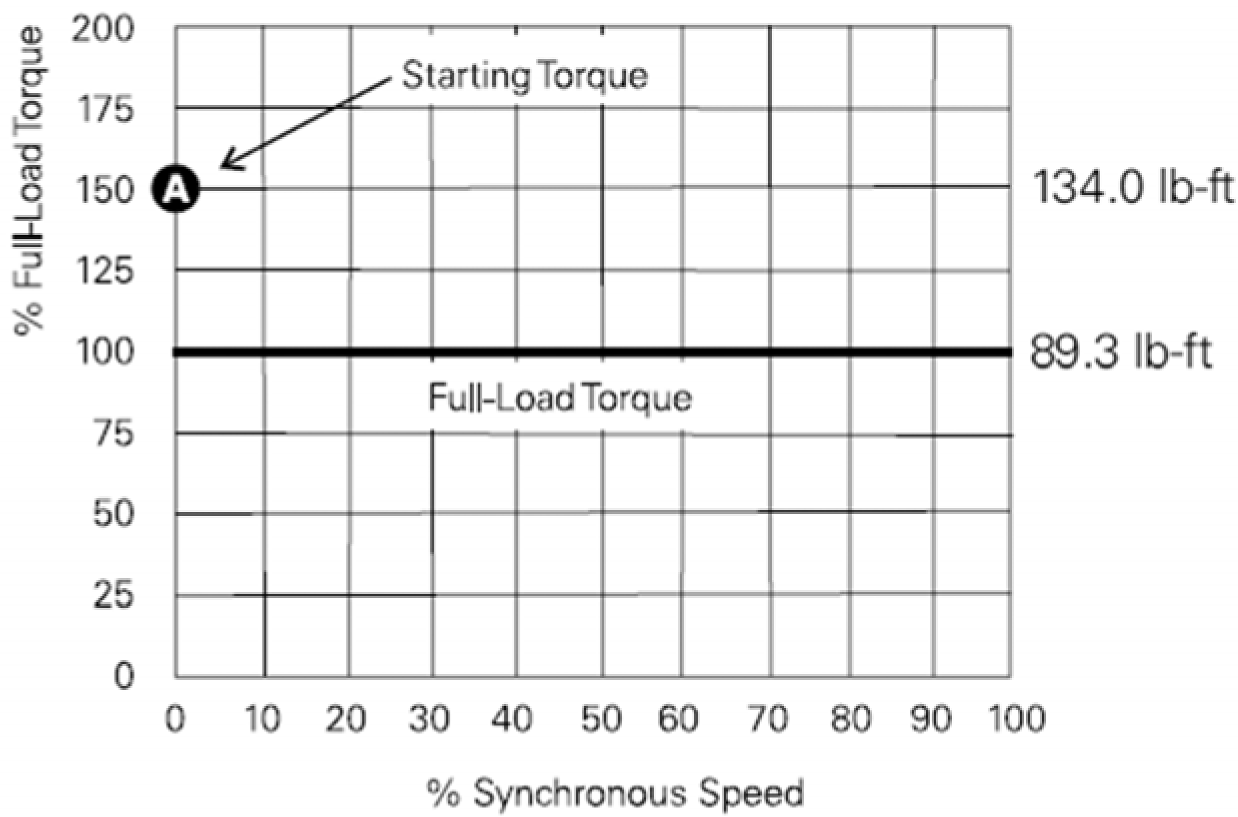


Using a 30 HP, 1765 RPM NEMA B motor as an example, full-load torque can be calculated by transposing the formula for horsepower.

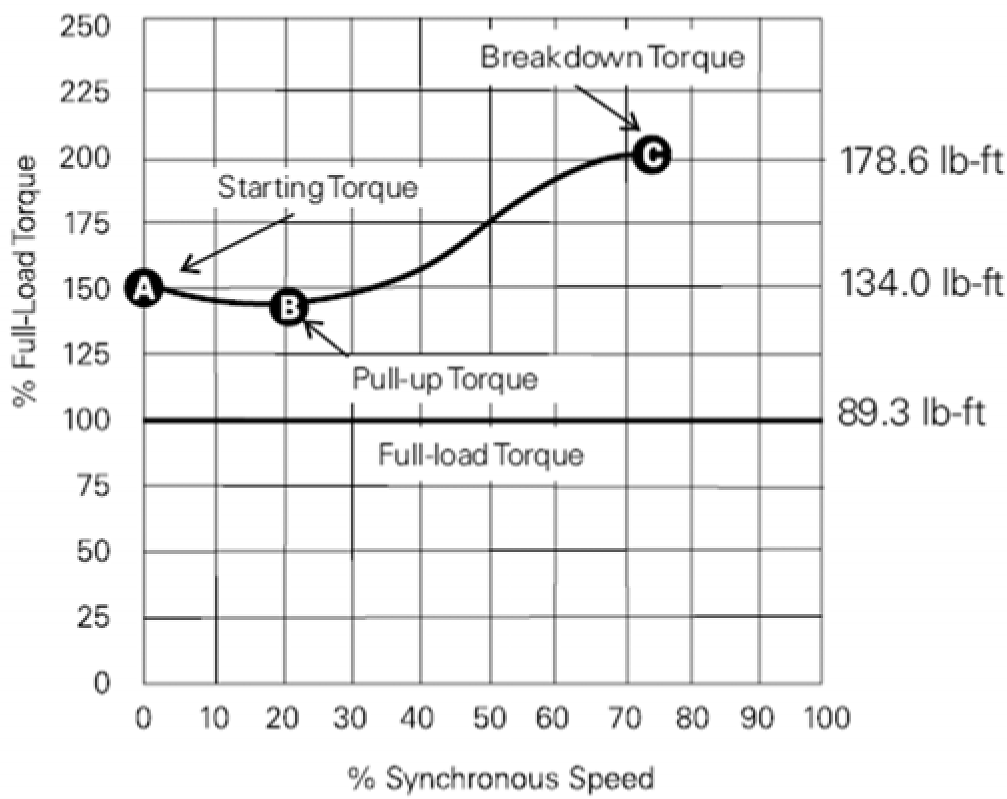
$$HP = \frac{\text{Torque (in lb-ft)} \times \text{Speed (in RPM)}}{5252}$$

$$\text{Torque (in lb-ft)} = \frac{HP \times 5252}{\text{Speed (in RPM)}} = \frac{30 \times 5252}{1765} = 89.3 \text{ lb-ft}$$

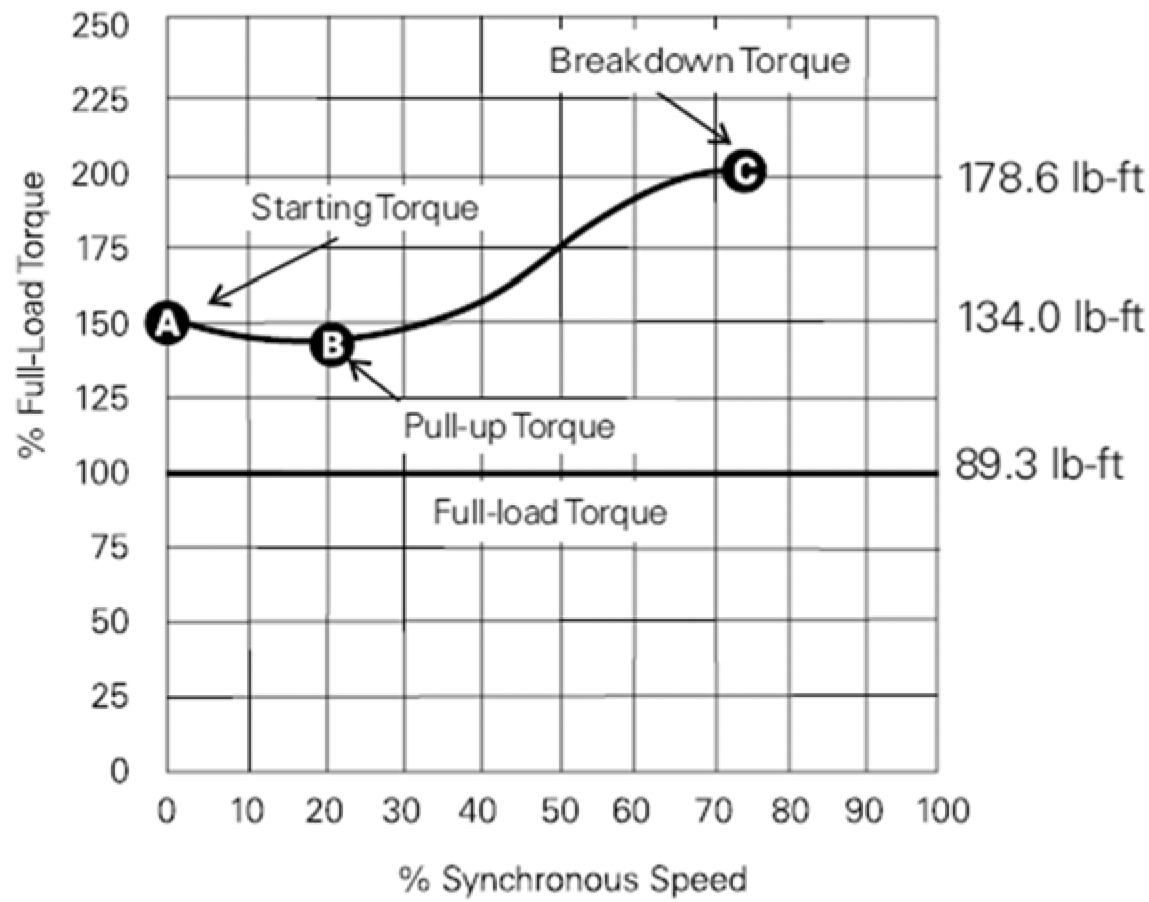
Starting torque, also referred to as **locked rotor torque,** is the torque that the motor develops each time it is started at rated voltage and frequency. When voltage is initially applied to the motor's stator, there is an instant before the rotor turns. At this instant, a NEMA B motor develops a torque approximately equal to 150% of full-load torque. For the 30 HP, 1765 RPM motor used in this example, that's equal to 134.0 lb-ft of torque.



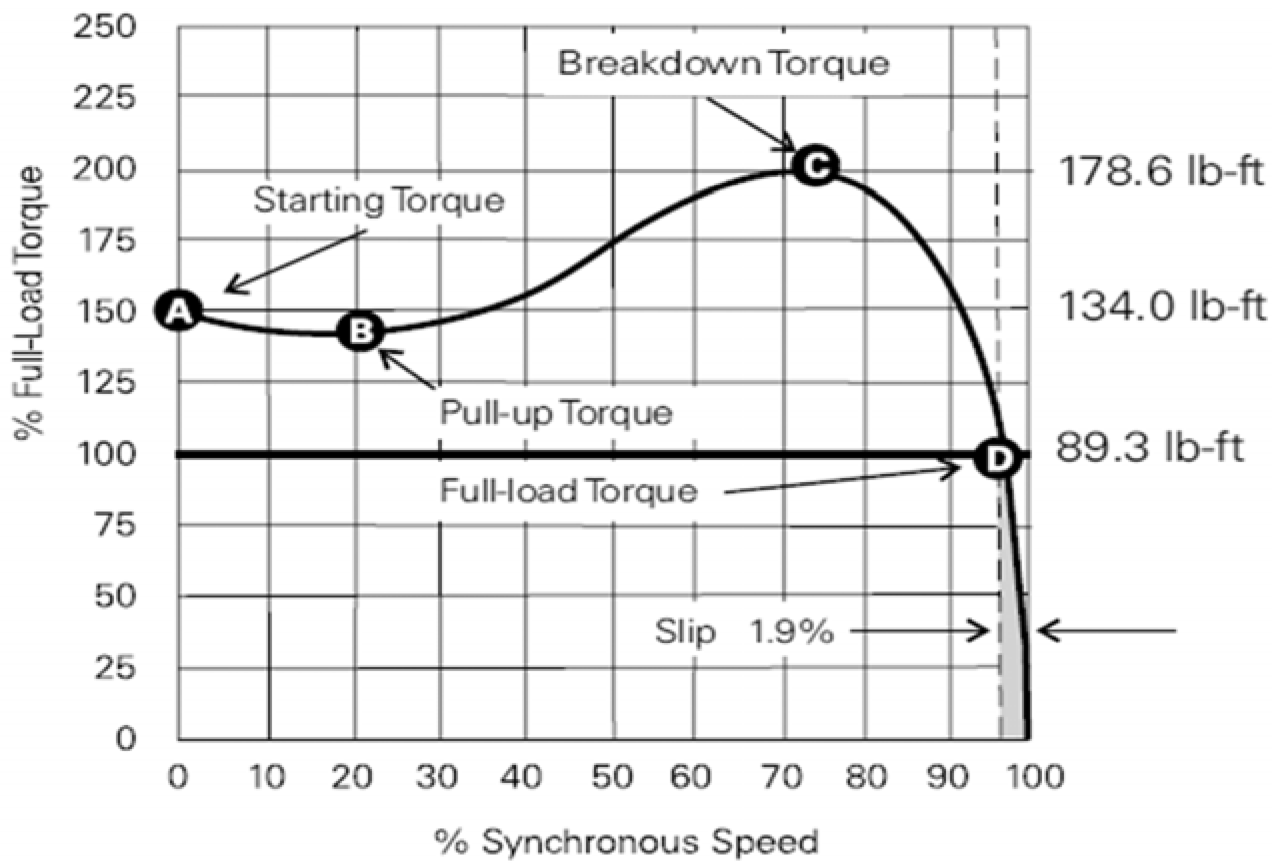
As the motor picks up speed, torque decreases slightly until point B on the graph is reached. The torque available at this point is called **pull-up torque**. For a NEMA B motor, this is slightly lower than starting torque, but greater than full-load torque.



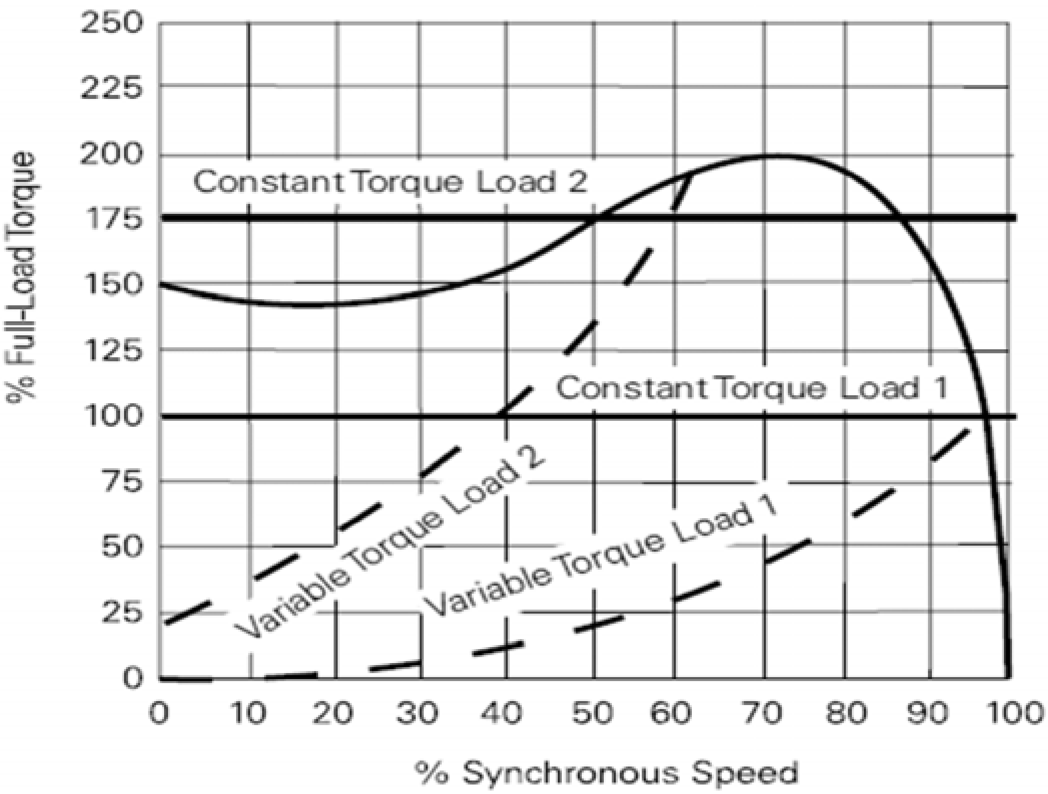
As speed continues to increase from point B to point C, torque increases up to a maximum value at approximately 200% of full-load torque. This maximum value of torque is referred to as **breakdown torque.** The 30 HP motor in this example has a breakdown torque of approximately 178.6 lb-ft.



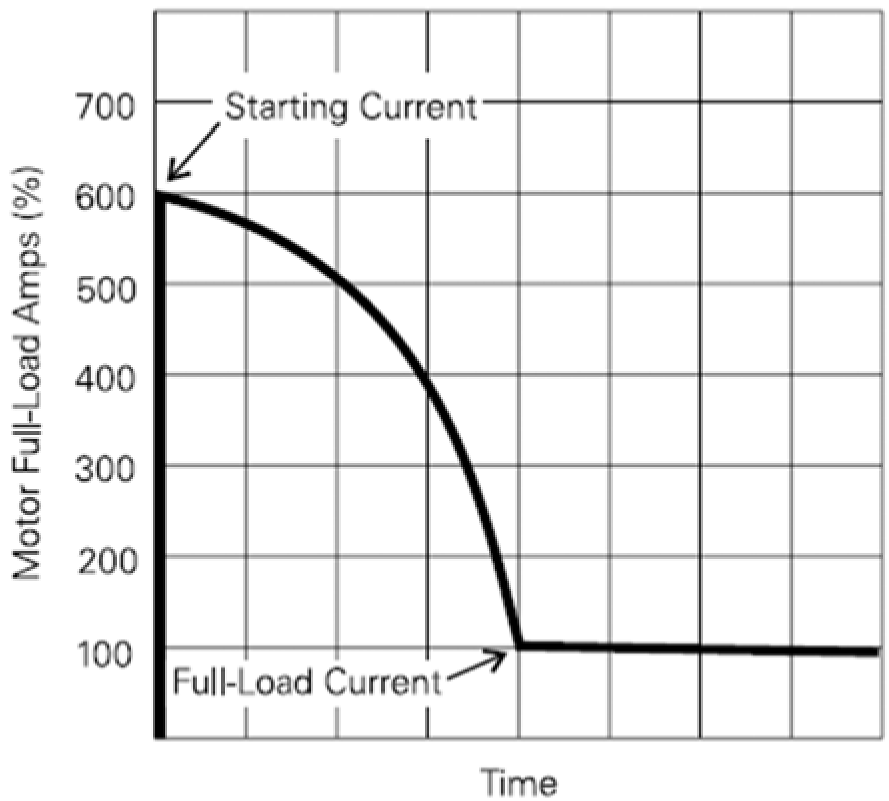
Torque decreases rapidly as speed increases beyond breakdown torque until it reaches **full-load torque** at a speed slightly less than 100% of synchronous speed. Full-load torque is developed with the motor operating at rated voltage, frequency, and load. The motor in this example has a synchronous speed of 1800 RPM and a full-load speed of 1765 RPM. Therefore, its slip is 1.9%.



Speed-torque curves are useful for understanding motor performance under load. The following speed-torque curve shows four load examples. This motor is appropriately sized for constant torque load 1 and variable torque load 1. In each case, the motor will accelerate to its rated speed. With constant torque load 2, the motor does not have sufficient starting torque to turn the rotor. With variable torque load 2, the motor cannot reach rated speed. In these last two examples, the motor will most likely overheat until its overload relay trips.



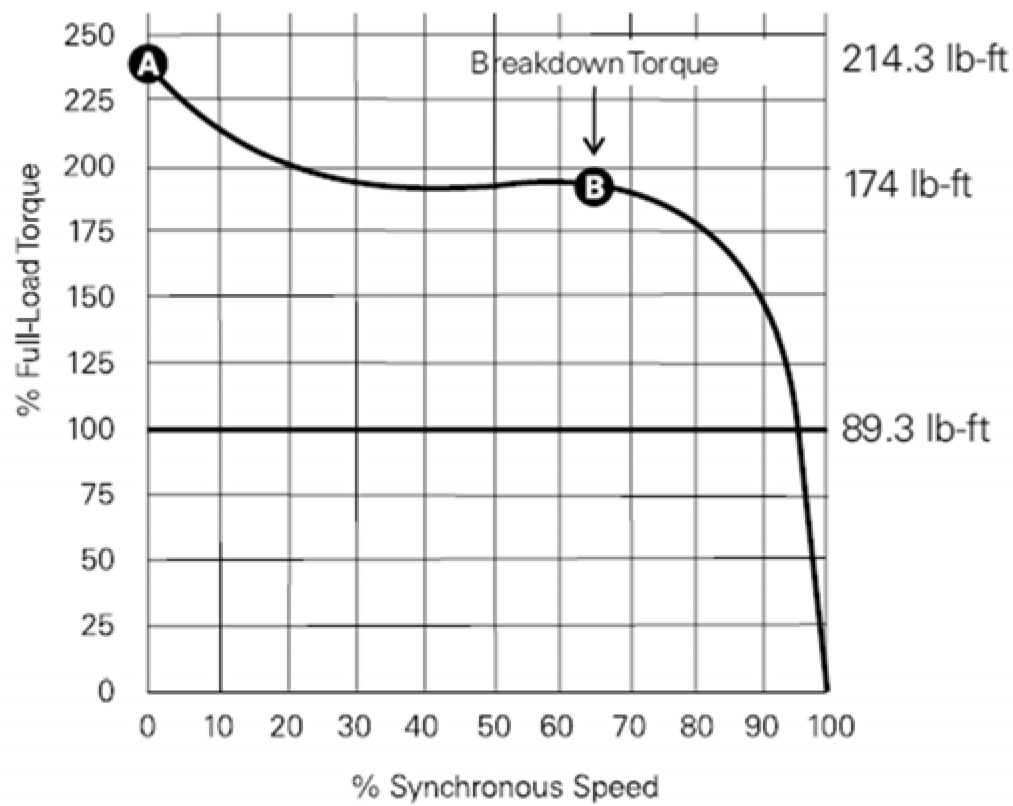
Starting current, also referred to as **locked rotor current**, is the current supplied to the motor when the rated voltage is initially applied with the rotor at rest. **Full-load current** is the current supplied to the motor with the rated voltage, frequency, and load applied and the rotor up to speed. For a NEMA B motor, starting current is typically 600-650% of full-load current. Knowledge of the current requirements for a motor is critical for the proper application of overcurrent protection devices.



NEMA A motors are the least common design. NEMA A motors have a speed-torque curve similar to that of a NEMA B motor, but typically have higher starting current. As a result, overcurrent protection devices must be sized to handle the increased current. NEMA A motors are typically used in the same types of applications as NEMA B motors.

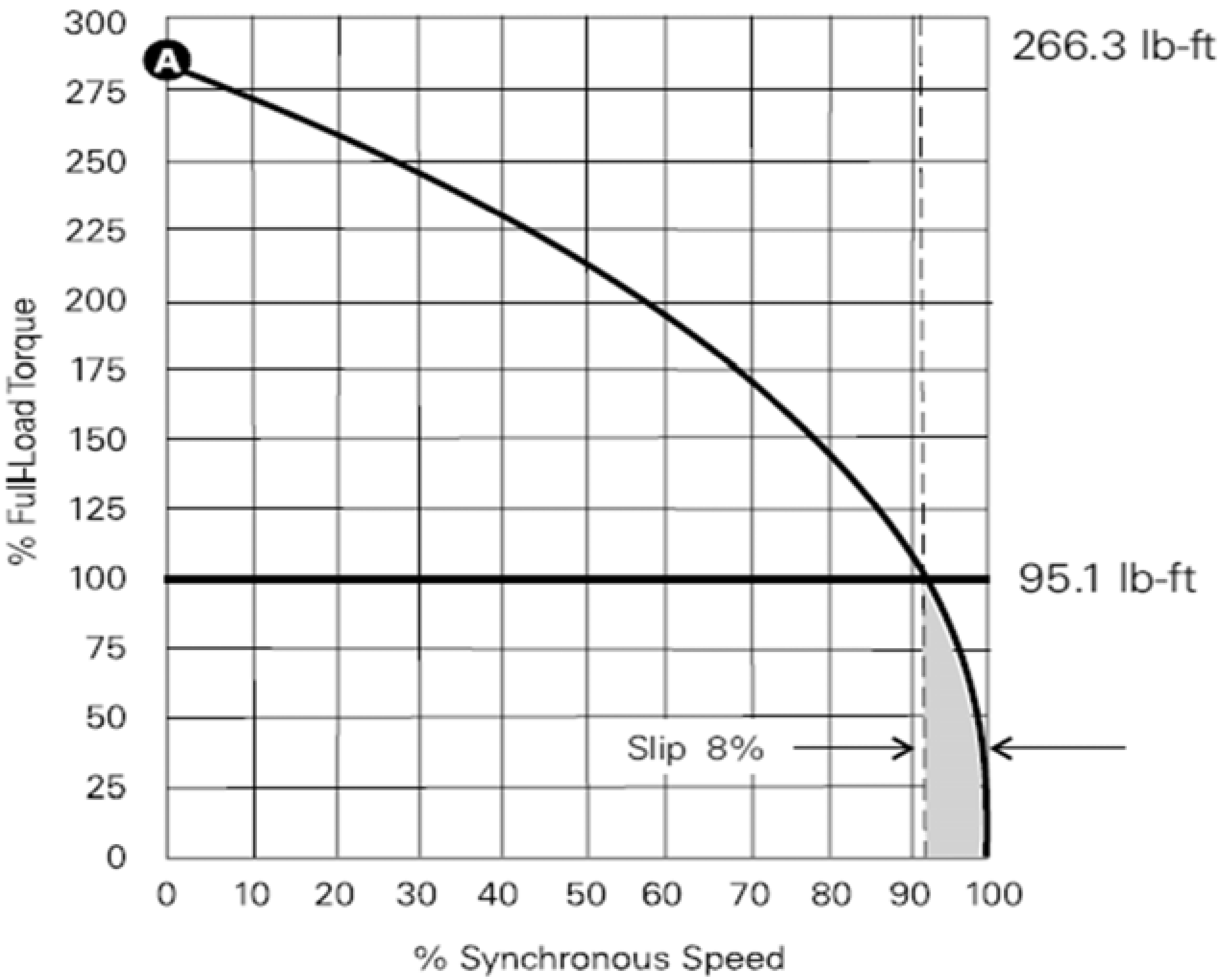
NEMA C motors are designed for applications that require a high starting torque for hard to start loads, such as heavily-loaded conveyors, crushers and mixers. Despite the high starting torque, these motors have relatively low starting current. Slip and full-load torque are about the same as for a NEMA B motor. NEMA C motors are typically single speed motors which range in size from approximately 5 to 200 HP.

The following speed-torque curve is for a 30 HP NEMA C motor with a full-load speed of 1765 RPM and a full-load torque of 89.3 lb-ft. In this example, the motor has a starting torque of 214.3 lb-ft, 240% of full-load torque and a breakdown torque of 174 lb-ft.



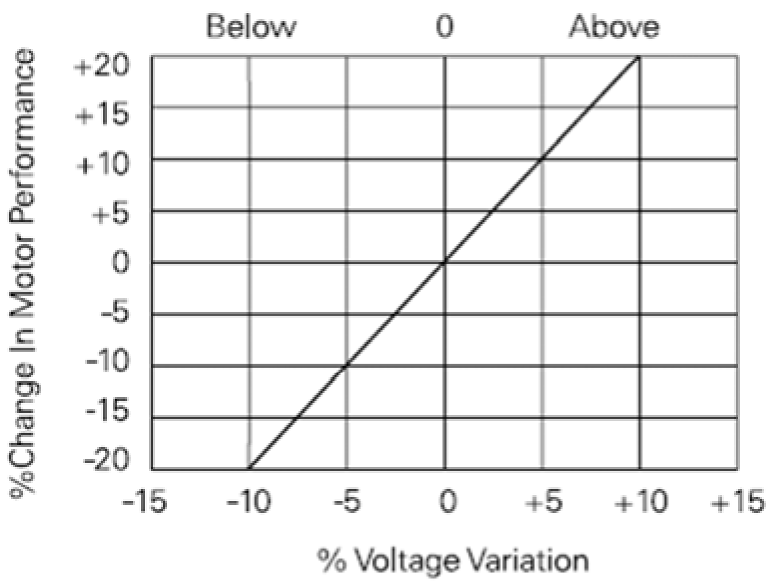
The starting torque of a **NEMA design D motor** is approximately 280% of the motor's full-load torque. This makes it appropriate for very hard to start applications such as punch presses and oil well pumps. NEMA D motors have no true breakdown torque. After starting, torque decreases until full-load torque is reached. Slip for NEMA D motors ranges from 5 to 13%.

The following speed torque curve is for a 30 HP NEMA D motor with a full-load speed of 1656 RPM and a full load torque of 95.1 lb-ft. This motor develops approximately 266.3 lb-ft of starting torque.



A small variation in supply voltage can have a dramatic affect on motor performance. In the following chart, for example, when voltage is 10% below the rated voltage of the motor, the motor has 20% less starting torque. This reduced voltage may prevent the motor from getting its load started or keeping it running at rated speed.

A 10% increase in supply voltage, on the other hand, increases the starting torque by 20%. This increased torque may cause damage during startup. A conveyor, for example, may lurch forward at startup. A voltage variation also causes similar changes in the motor's starting and full-load currents and temperature rise.



A variation in the frequency at which the motor operates causes changes primarily in speed and torque characteristics. A 5% increase in frequency, for example, causes a 5% increase in full-load speed and a 10% decrease in torque.

Frequency Variation	% Change Full-Load Speed	% Change Starting Torque
+5%	+5%	-10%
-5%	-5%	+11%

Standard motors are designed to operate below 3300 feet. Air is thinner, and heat is not dissipated as quickly above 3300 feet. Most motors must be **derated** for altitudes above 3300 feet. The following chart shows typical horsepower derating factors, but the derating factor should be checked for each motor. A 50 HP motor operated at 6000 feet, for example, would be derated to 47 HP, providing the 40°C ambient rating is still required.

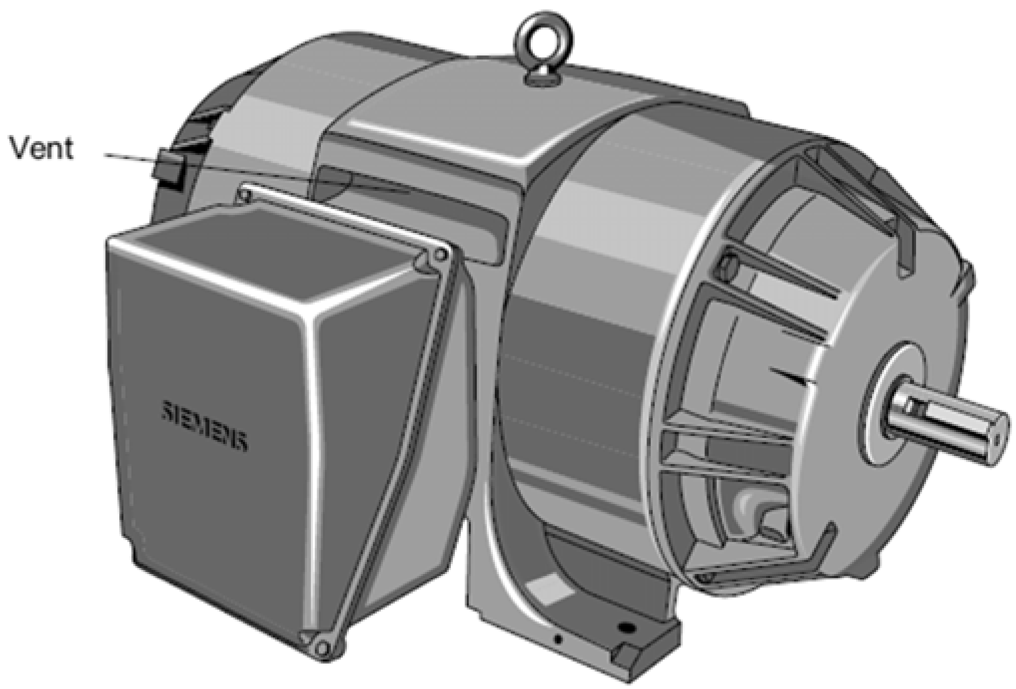
Altitude	Derating Factor
3300 - 5000	0.97
5001 - 6600	0.94
6601 - 8300	0.90
8301 - 9900	0.86
9901 - 11,500	0.82

50 HP X 0.94 = 47 HP

The ambient temperature may also have to be considered. The ambient temperature requirement may be reduced from 40°C to 30°C at 6600 feet on many motors. However, a motor with a higher insulation class may not require derating in these conditions.

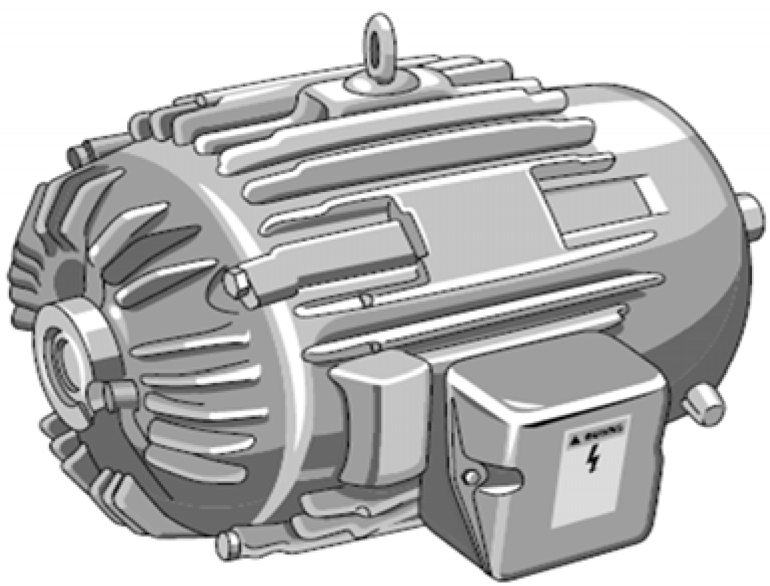
Ambient Temperature (°C)	Maximum Altitude (Feet)
40	3300
30	6600
20	9900

Open enclosures permit cooling air to flow through the motor. One type of open enclosure is the **open drip proof (ODP) enclosure**. This enclosure has vents that allow for air flow. Fan blades attached to the rotor move air through the motor when the rotor is turning. The vents are positioned so that liquids and solids falling from above at angles up to 15° from vertical cannot enter the interior of the motor when the motor is mounted on a horizontal surface. When the motor is mounted on a vertical surface, such as a wall or panel, a special cover may be needed. ODP enclosures should be used in environments free from contaminates.

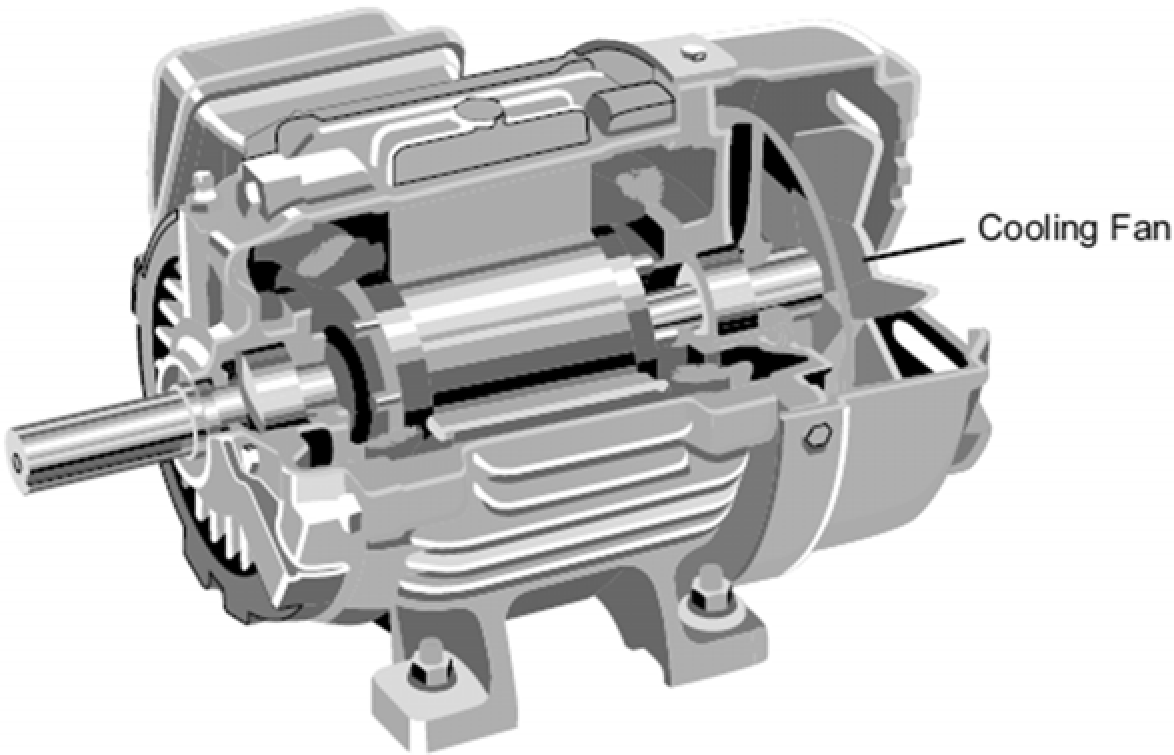


In some applications, the air surrounding the motor contains corrosive or harmful elements which can damage the internal parts of a motor. A **totally enclosed non-ventilated (TENV) motor** enclosure limits the flow of air into the motor, but is not airtight. However, a seal at the point where the shaft passes through the housing prevents water, dust, and other foreign matter from entering the motor along the shaft.

Most TENV motors are fractional horsepower. However, integral horsepower TENV motors are used for special applications. The absence of ventilating openings means that all the heat from inside the motor must dissipate through the enclosure by conduction. These larger horsepower TENV motors have an enclosure that is heavily ribbed to help dissipate heat more quickly. TENV motors can be used indoors or outdoors.

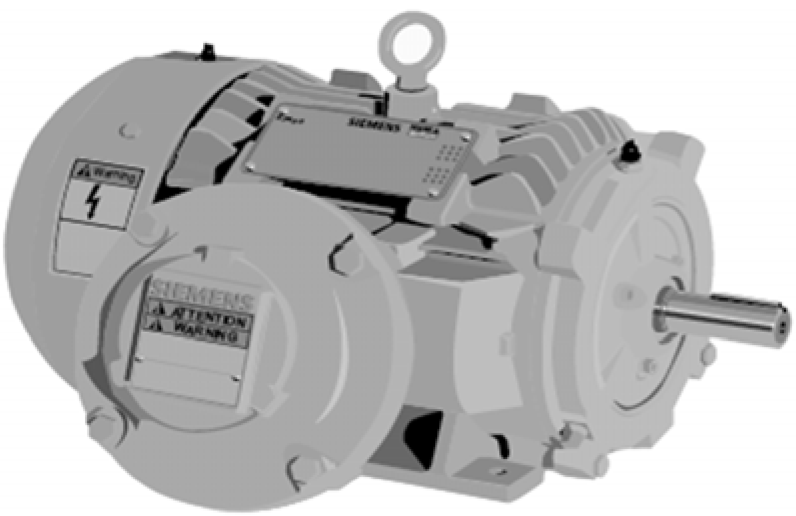


A **totally enclosed fan-cooled (TEFC) motor** is similar to a TENV motor, but has an external fan mounted opposite the drive end of the motor. The fan blows air over the motor's exterior for additional cooling. The fan is covered by a shroud to prevent anyone from touching it. TEFC motors can be used in dirty, moist, or mildly corrosive environments.



Hazardous duty applications are commonly found in chemical processing, mining, foundry, pulp and paper, waste management, and petrochemical industries. In these applications, motors have to comply with the strictest safety standards for the protection of life, machines and the environment. This often requires use of **explosion proof (XP) motors**.

An XP motor is similar in appearance to a TEFC motor, however, most XP enclosures are cast iron. In the United States, the application of motors in hazardous locations is subject to *National Electrical Code®* and standards set by Underwriters Laboratories and various regulatory agencies.



Understanding Power Concepts

Part 3

- ***<u>Motors</u>***
  - AC Induction Motors
  - ***<u>Motor Efficiency and Assessment</u>***
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

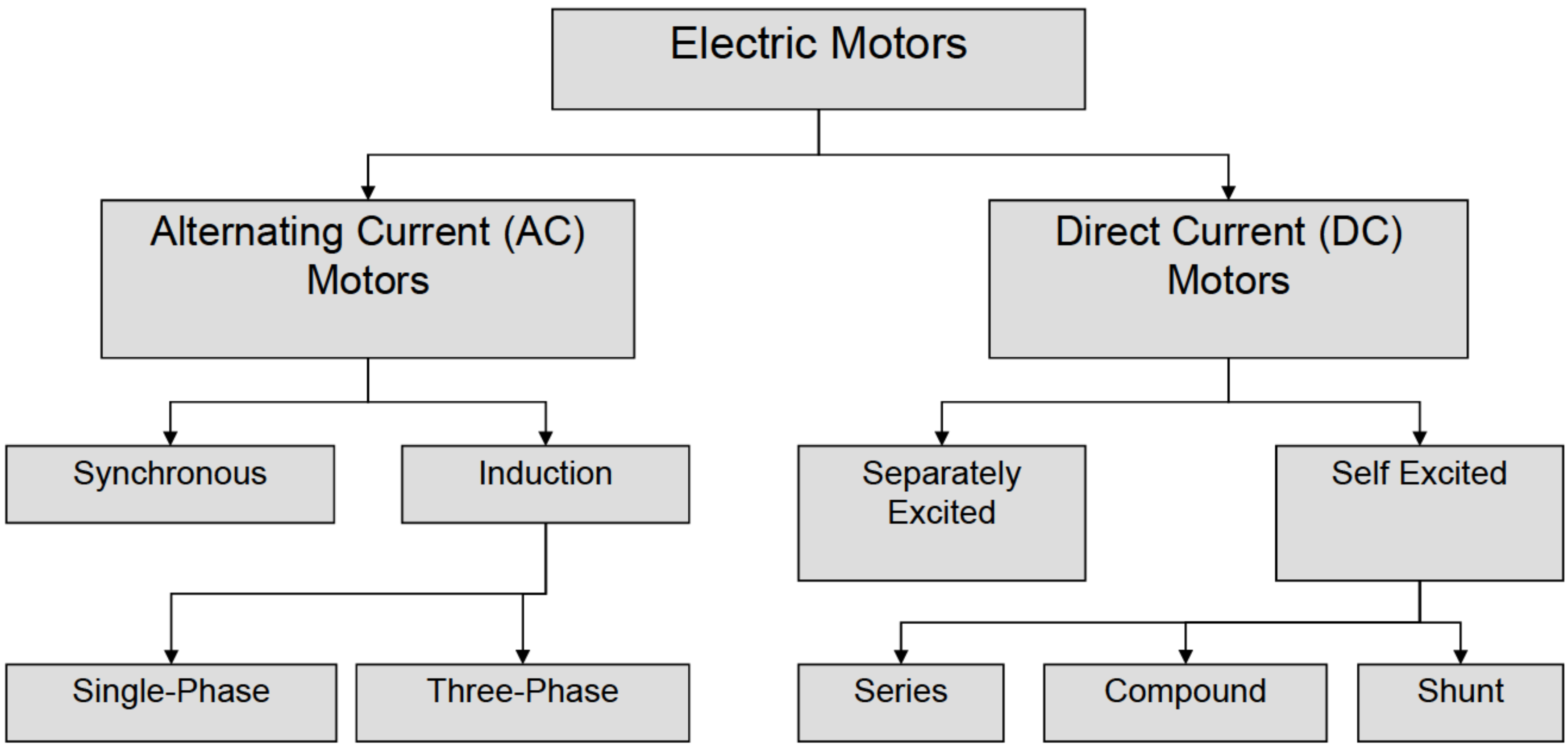
Three types of Motor Load

Introduction

Motor loads	**Description**	**Examples**
Constant torque loads	Output power varies but torque is constant	Conveyors, rotary kilns, constant-displacement pumps
Variable torque loads	Torque varies with square of operation speed	Centrifugal pumps, fans
Constant power loads	Torque changes inversely with speed	Machine tools

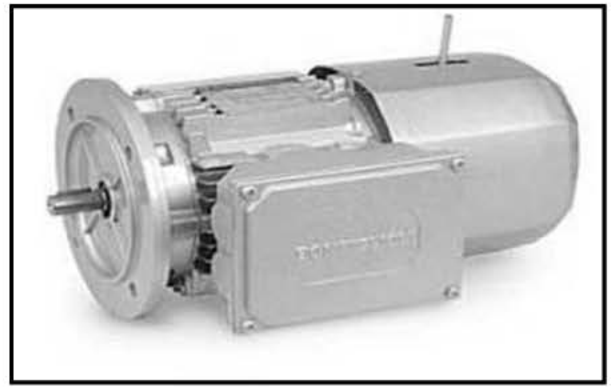
Type of Electric Motors

Classification of Motors



Type of Electric Motors

DC Motors – Components



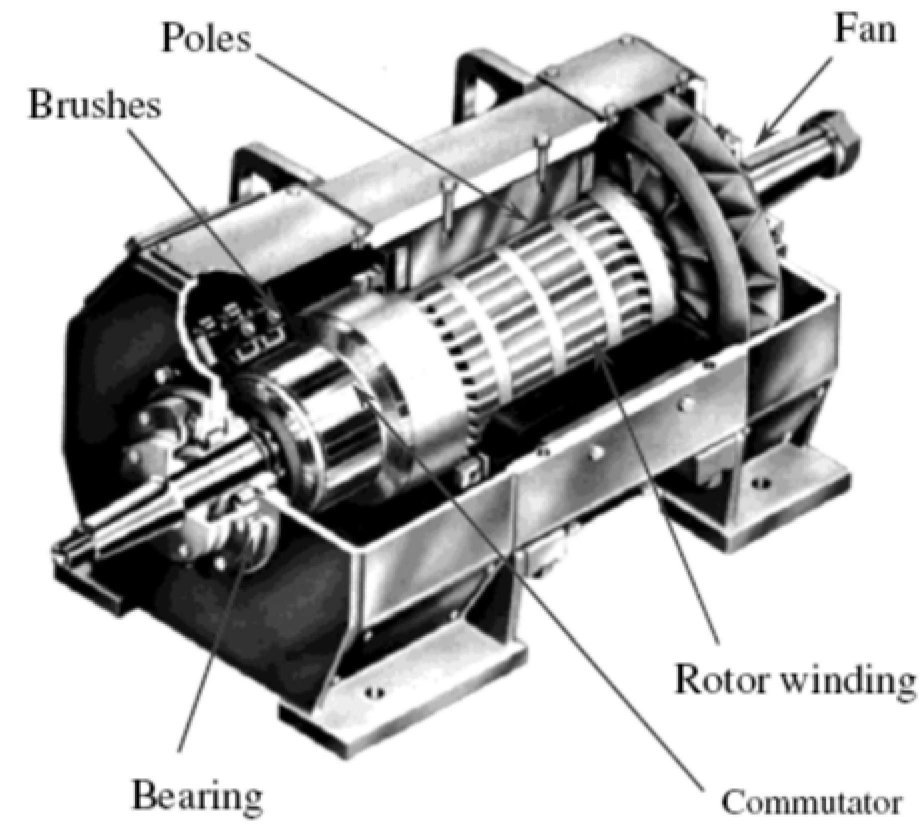
- Field pole
  - North pole and south pole
  - Receive electricity to form magnetic field
- Armature
  - Cylinder between the poles
  - Electromagnet when current goes through
  - Linked to drive shaft to drive the load
- Commutator
  - Overturns current direction in armature

Type of Electric Motors

DC motors

- Speed control without impact power supply quality
  - Changing armature voltage
  - Changing field current
- Restricted use
  - Few low/medium speed applications
  - Clean, non-hazardous areas
- Expensive compared to AC motors

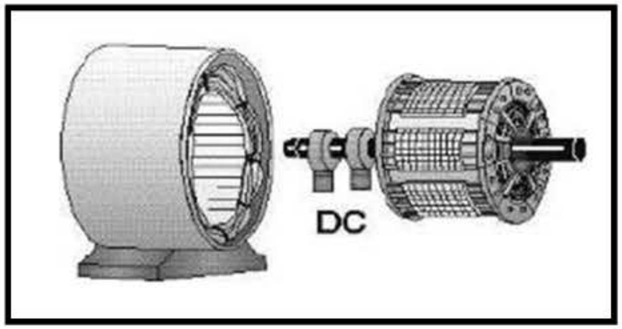
DC Machines Construction



Type of Electric Motors

AC Motors

- Electrical current reverses direction
- Two parts: stator and rotor
  - Stator: stationary electrical component
  - Rotor: rotates the motor shaft
- Speed difficult to control
- Two types
  - Synchronous motor
  - Induction motor



Type of Electric Motors

AC Motors – Synchronous motor

- Constant speed fixed by system frequency
- DC for excitation and low starting torque: suited for low load applications
- Can improve power factor: suited for high electricity use systems
- Synchronous speed (Ns):

$$Ns = 120\ f\ /\ P$$

F = supply frequency
P = number of poles

Type of Electric Motors

AC Motors – Induction motor

- Most common motors in industry
- Advantages:
  - Simple design
  - Inexpensive
  - High power to weight ratio
  - Easy to maintain
  - Direct connection to AC power source

Type of Electric Motors

AC Motors – Induction motor

- Single-phase induction motor
  - One stator winding
  - Single-phase power supply
  - Squirrel cage rotor
  - Require device to start motor
  - 3 to 4 HP applications
  - Household appliances: fans, washing machines, dryers

Type of Electric Motors

AC Motors – Induction motor

- Three-phase induction motor
  - Three-phase supply produces magnetic field
  - Squirrel cage or wound rotor
  - Self-starting
  - High power capabilities
  - 1/3 to hundreds HP applications: pumps, compressors, conveyor belts, grinders
  - 70% of motors in industry!

Type of Electric Motors

AC Motors – Induction motor

Speed and slip

- Motor never runs at synchronous speed but lower "base speed"
- Difference is "slip"
- Install slip ring to avoid this
- Calculate % slip:

$$\% \text{ Slip} = \frac{Ns - Nb}{Ns} \times 100$$

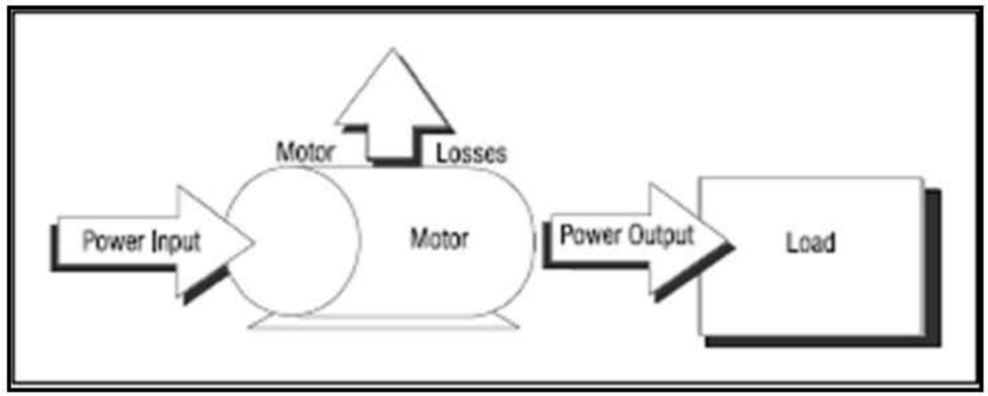
Ns = synchronous speed in RPM
Nb = base speed in RPM

Assessment of Electric Motors

Efficiency of Electric Motors

Motors loose energy when serving a load

- Fixed loss
- Rotor loss
- Stator loss
- Friction and rewinding
- Stray load loss



Assessment of Electric Motors

Efficiency of Electric Motors

Factors that influence efficiency

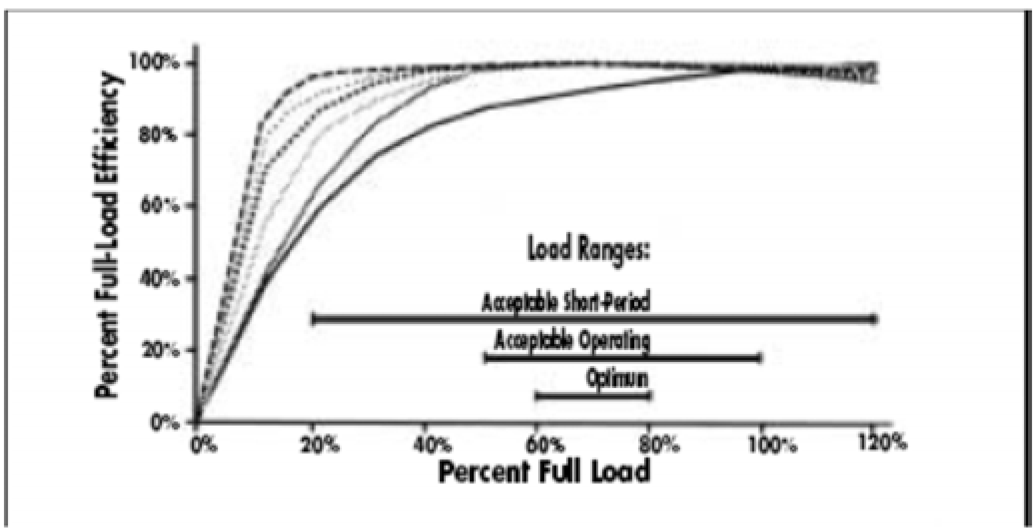
- Age
- Capacity
- Speed
- Type
- Temperature
- Rewinding
- Load

Assessment of Electric Motors

Efficiency of Electric Motors

Motor part load efficiency

- Designed for 50-100% load
- Most efficient at 75% load
- Rapid drop below 50% load



Assessment of Electric Motors

Motor Load

- Motor load is indicator of efficiency
- Equation to determine load:

$$\text{Load} = \frac{P_i \times \eta}{HP \times 0.7457}$$

η	= Motor operating efficiency in %
HP	= Nameplate rated horse power
Load	= Output power as a % of rated power
Pi	= Three phase power in kW

Assessment of Electric Motors

Motor Load

Three methods for individual motors

- Input power measurement
  - Ratio input power and rate power at 100% loading
- Line current measurement
  - Compare measured amperage with rated amperage
- Slip method
  - Compare slip at operation with slip at full load

Assessment of Electric Motors

Motor Load

Input power measurement

- Three steps for three-phase motors

Step 1. Determine the input power:

$$Pi = \frac{V \; x \; I \; x \; PF \; x \; \sqrt{3}}{1000}$$

Pi	= Three Phase power in kW
V	= RMS Voltage, mean line to line of 3 Phases
I	= RMS Current, mean of 3 phases
PF	= Power factor as Decimal

Assessment of Electric Motors

Motor Load

Input power measurement

Step 2. Determine the rated power:

$$P_r = hp \; x \; \frac{0.7457}{\eta_r}$$

Pr = Input Power at Full Rated load in kW
hp = Name plate Rated Horse Power
ηr = Efficiency at Full Rated Load

Step 3. Determine the percentage load:

$$Load = \frac{Pi}{P_r} \; x \; 100\%$$

Load = Output Power as a % of Rated Power
Pi = Measured Three Phase power in kW
Pr = Input Power at Full Rated load in kW

Assessment of Electric Motors

Motor Load

Result		Action
1. Significantly oversized and under loaded	→	Replace with more efficient, properly sized models
2. Moderately oversized and under loaded	→	Replace with more efficient, properly sized models when they fail
3. Properly sized but standard efficiency	→	Replace most of these with energy-efficient models when they fail

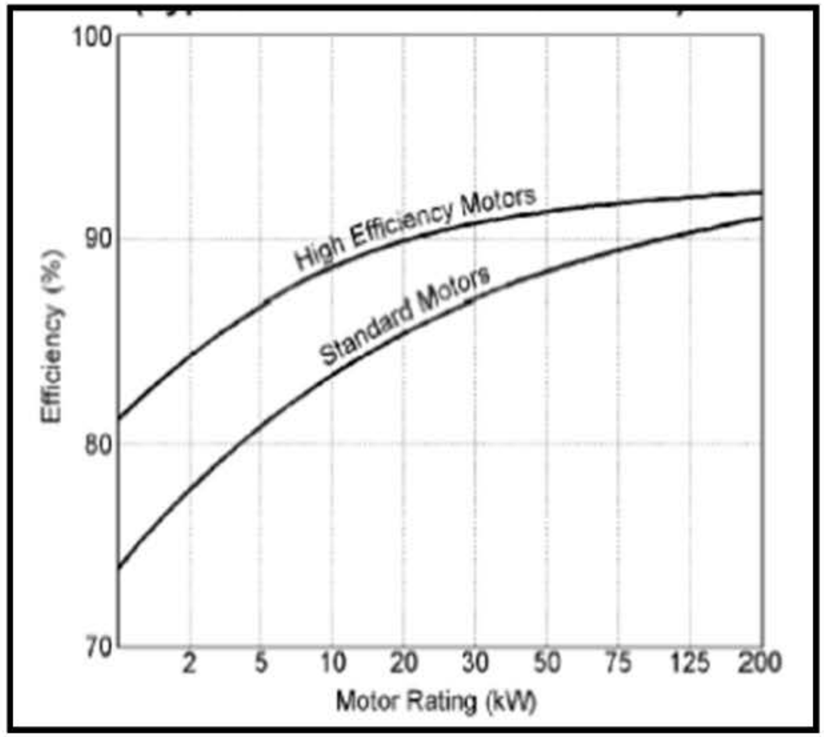
Energy Efficiency Opportunities

1. Use energy efficient motors
2. Reduce under-loading (and avoid over-sized motors)
3. Size to variable load
4. Improve power quality
5. Rewinding
6. Power factor correction by capacitors
7. Improve maintenance
8. Speed control of induction motor

Energy Efficiency Opportunities

Use Energy Efficient Motors

- Reduce intrinsic motor losses
- Efficiency 3-7% higher
- Wide range of ratings
- More expensive but rapid payback
- Best to replace when existing motors fail



Energy Efficiency Opportunities

Use Energy Efficient Motors

Power Loss Area	***Efficiency Improvement***
1. Fixed loss (iron)	Use of thinner gauge, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities.
2. Stator I2R	Use of more copper & larger conductors increases cross sectional area of stator windings. This lower resistance (R) of the windings & reduces losses due to current flow (I)
3 Rotor I2R	Use of larger rotor conductor bars increases size of cross section, lowering conductor resistance (R) & losses due to current flow (I)
4 Friction & Winding	Use of low loss fan design reduces losses due to air movement
5. Stray Load Loss	Use of optimized design & strict quality control procedures minimizes stray load losses

Energy Efficiency Opportunities

2. Reduce Under-loading

- Reasons for under-loading
  - Large safety factor when selecting motor
  - Under-utilization of equipment
  - Maintain outputs at desired level even at low input voltages
  - High starting torque is required
- Consequences of under-loading
  - Increased motor losses
  - Reduced motor efficiency
  - Reduced power factor

Energy Efficiency Opportunities

2. Reduce Under-loading

- Replace with smaller motor
  - If motor operates at <50%
  - Not if motor operates at 60-70%
- Operate in star mode
  - If motors consistently operate at <40%
  - Inexpensive and effective
  - Motor electrically downsized by wire reconfiguration
  - Motor speed and voltage reduction but unchanged performance

Energy Efficiency Opportunities

3. Sizing to Variable Load

- Motor selection based on
  - X Highest anticipated load: expensive and risk of under-loading
  - ✓ Slightly lower than highest load: occasional overloading for short periods
- But avoid risk of overheating due to
  - Extreme load changes
  - Frequent / long periods of overloading
  - Inability of motor to cool down

Motors have 'service factor' of 15% above rated load

Energy Efficiency Opportunities

4. Improve Power Quality

Motor performance affected by

- Poor power quality: too high fluctuations in voltage and frequency
- Voltage unbalance: unequal voltages to three phases of motor

	Example 1	Example 2	Example 3
Voltage unbalance (%)	**0.30**	**2.30**	**5.40**
Unbalance in current (%)	**0.4**	**17.7**	**40.0**
Temperature increase (oC)	**0**	**30**	**40**

Energy Efficiency Opportunities

4. Improve Power Quality

Keep voltage unbalance within 1%

- Balance single phase loads equally among three phases
- Segregate single phase loads and feed them into separate line/transformer

Energy Efficiency Opportunities

5. Rewinding

- Rewinding: sometimes 50% of motors
- Can reduce motor efficiency
- Maintain efficiency after rewinding by
  - Using qualified/certified firm
  - Maintain original motor design
  - Replace 40HP, >15 year old motors instead of rewinding
  - Buy new motor if costs are less than 50-65% of rewinding costs

Energy Efficiency Opportunities

6. Improve Power Factor (PF)

- Use capacitors for induction motors
- Benefits of improved PF
  - Reduced kVA
  - Reduced losses
  - Improved voltage regulation
  - Increased efficiency of plant electrical system
- Capacitor size not >90% of no-load kVAR of motor

Energy Efficiency Opportunities
7. Maintenance

Checklist to maintain motor efficiency

- Inspect motors regularly for wear, dirt/dust
- Checking motor loads for over/under loading
- Lubricate appropriately
- Check alignment of motor and equipment
- Ensure supply wiring and terminal box and properly sized and installed
- Provide adequate ventilation

Energy Efficiency Opportunities

8. Speed Control of Induction Motor

- Multi-speed motors
  - Limited speed control: 2 – 4 fixed speeds
- Wound rotor motor drives
  - Specifically constructed motor
  - Variable resistors to control torque performance
  - >300 HP most common

Energy Efficiency Opportunities

8. Speed Control of Induction Motor

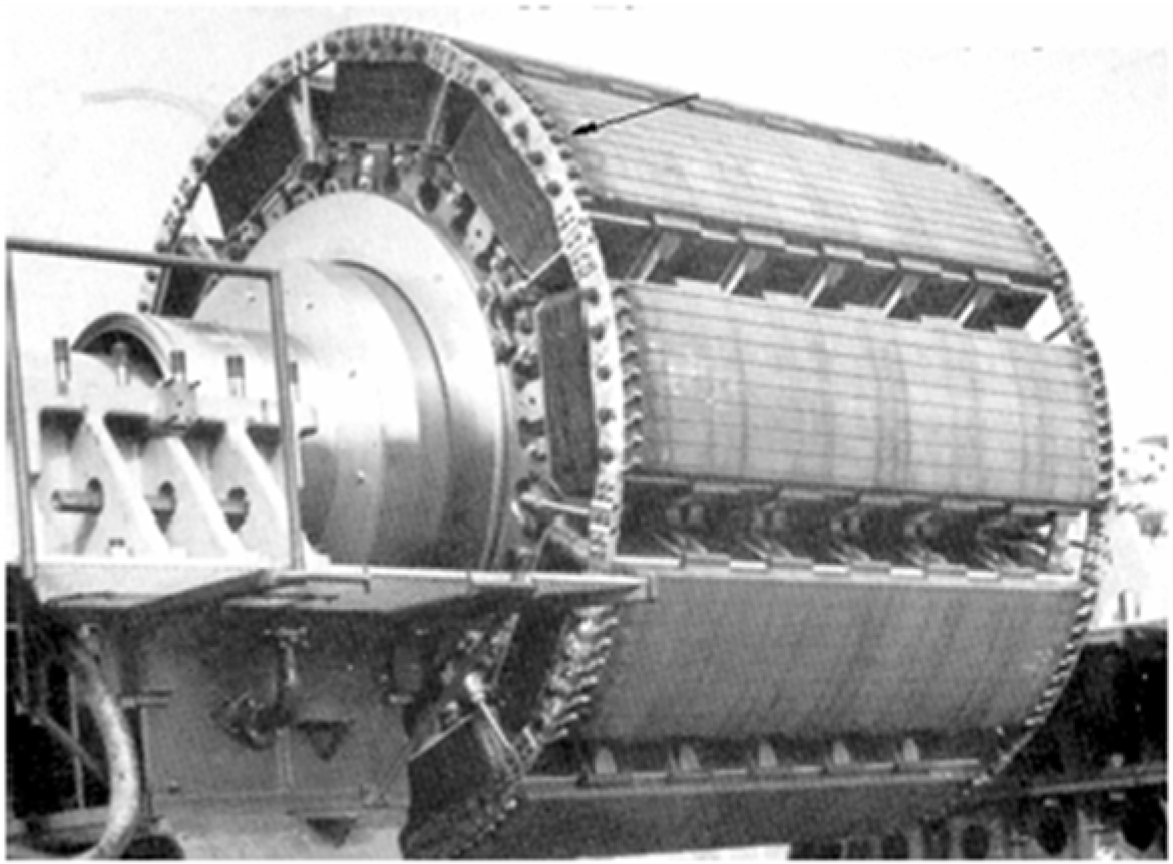
- Variable speed drives (VSDs)
  - Also called inverters
  - Several kW to 750 kW
  - Change speed of induction motors
  - Can be installed in existing system
  - Reduce electricity by >50% in fans and pumps
  - Convert 50Hz incoming power to variable frequency and voltage: change speed
  - Three types

Energy Efficiency Opportunities
8. Speed Control of Induction Motor

Direct Current Drives

- Oldest form of electrical speed control
- Consists of
  - DC motor: field windings and armature
  - Controller: regulates DC voltage to armature that controls motor speed
  - Tacho-generator: gives feedback signal to controlled

Synchronous Machines
Construction



Classification of AC Rotating Machines

Synchronous Machines:

Synchronous Generators: A primary source of electrical energy

Synchronous Motors: Used as motors as well as power factor compensators (synchronous condensers)

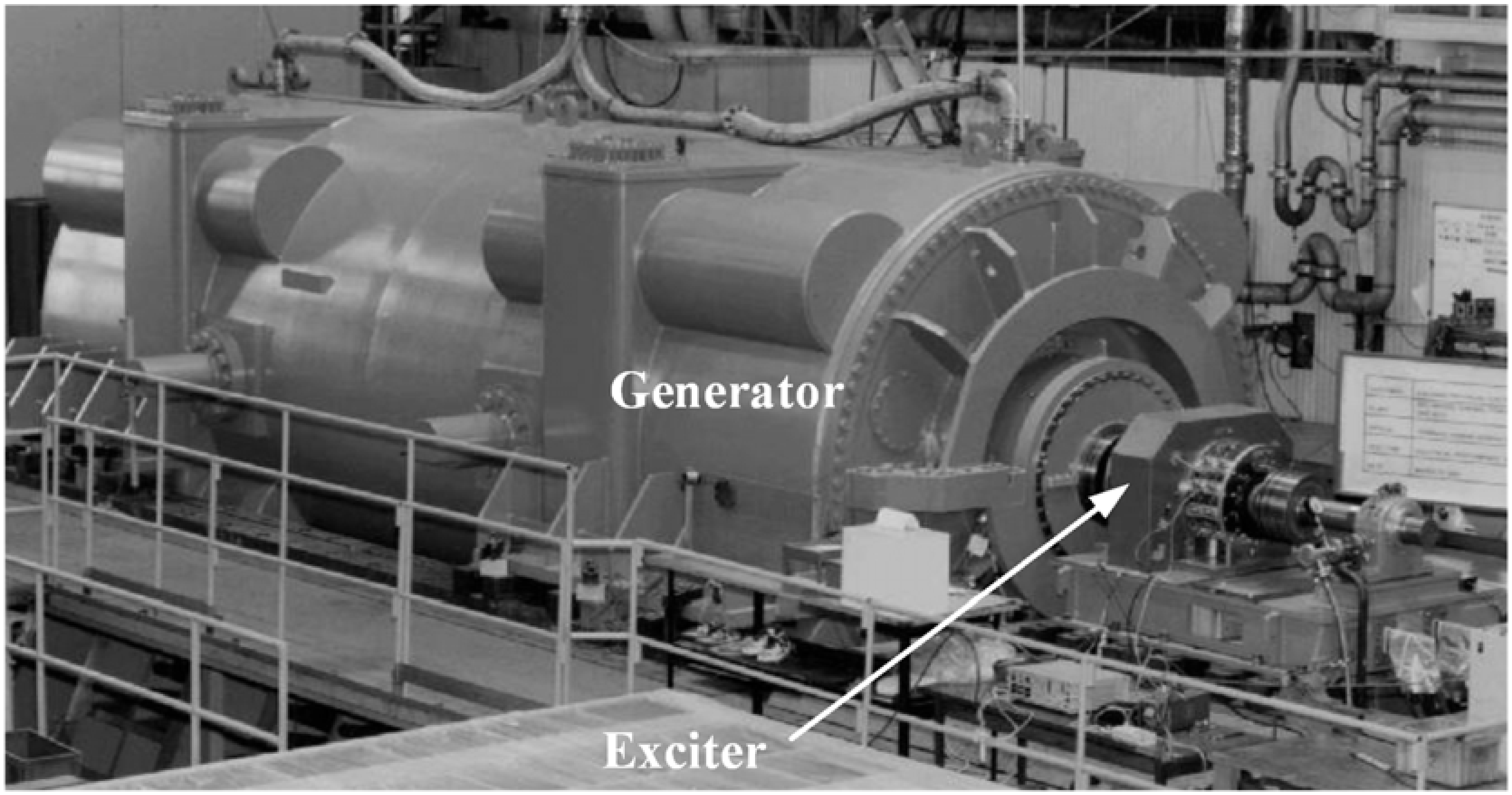
Asynchronous (Induction) Machines:

- Induction Motors: Most widely used electrical motors in both domestic and industrial applications.
- Induction Generators: Due to lack of a separate field excitation, these machines are rarely used as generators.

Synchronous Machine

- Unlike induction machines, the rotating air gap field and the rotor rotate at the same speed, called the synchronous speed.
- Synchronous machines are used primarily as generators of electrical power, called synchronous generators or alternators.
- They are usually large machines generating electrical power at hydro, nuclear, or thermal power stations.
- Application as a motor: pumps in generating stations, electric clocks, timers, and so forth where constant speed is desired.

Synchronous Machines

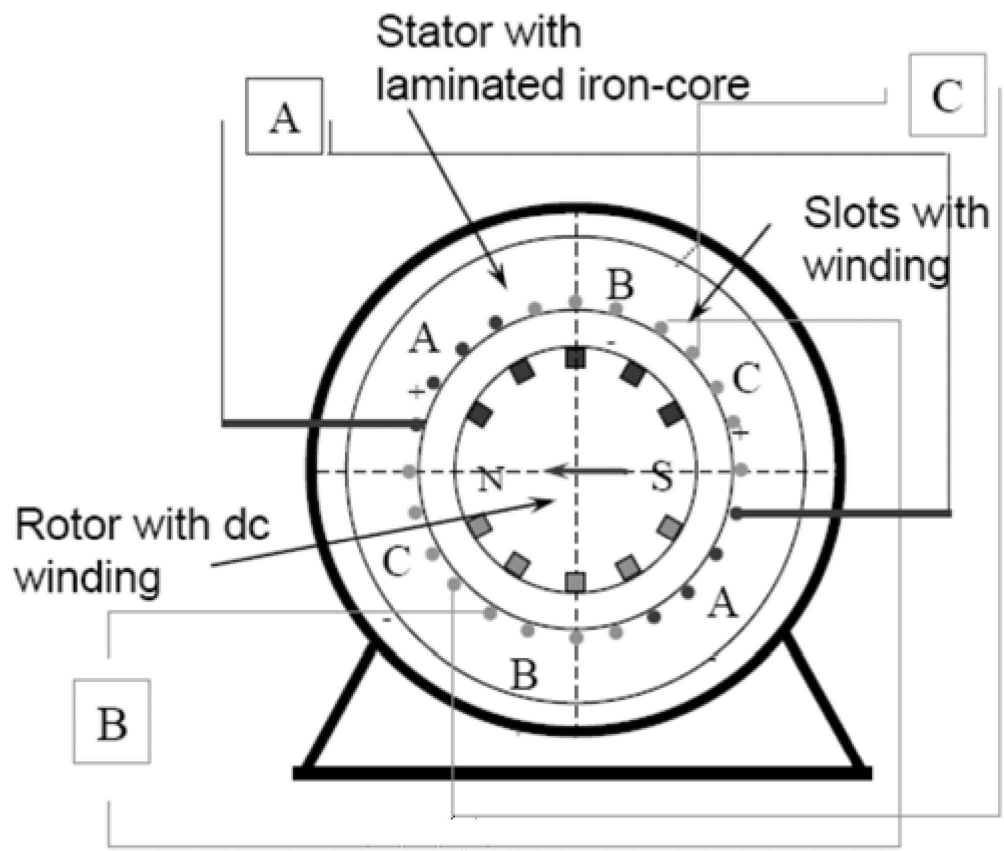


View of a two-pole round rotor generator and exciter

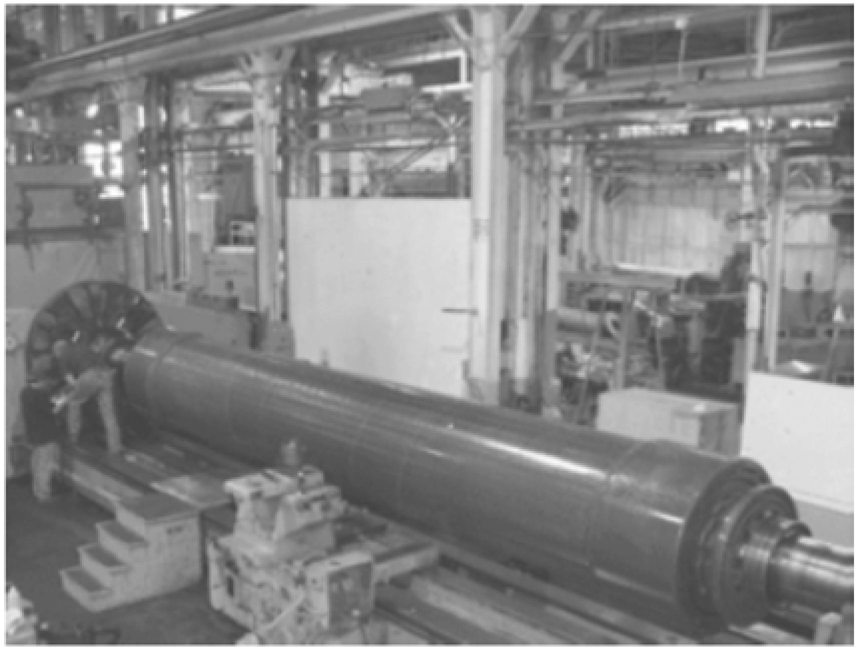
Synchronous Machine

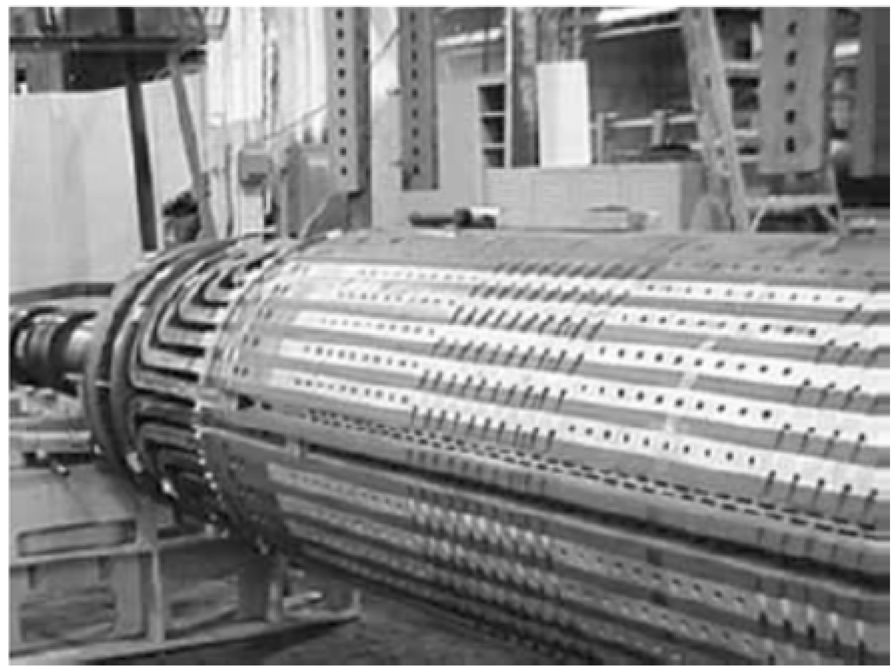
- <u>Round Rotor Machine</u>

- The stator is a ring shaped laminated iron-core with slots.
- Three phase windings are placed in the slots.
- Round solid iron rotor with slots.
- A single winding is placed in the slots. Dc current is supplied through slip rings.



Round Rotor Machine





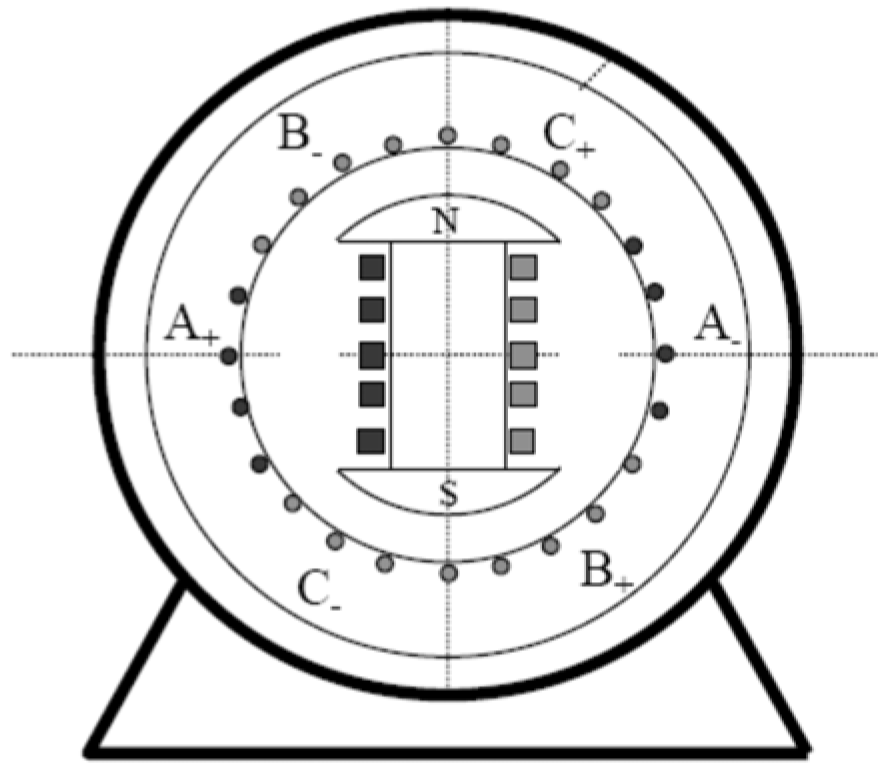
Synchronous Machine

- <u>Salient Rotor Machine</u>

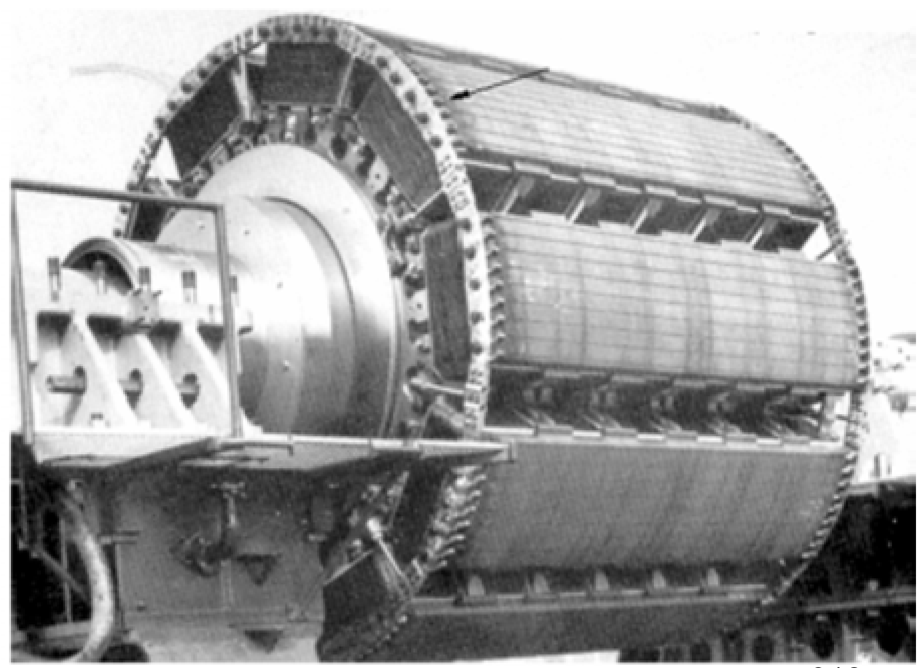
•The stator has a laminated iron-core with slots and three phase windings placed in the slots.

•The rotor has salient poles excited by dc current.

•DC current is supplied to the rotor through slip-rings and brushes.



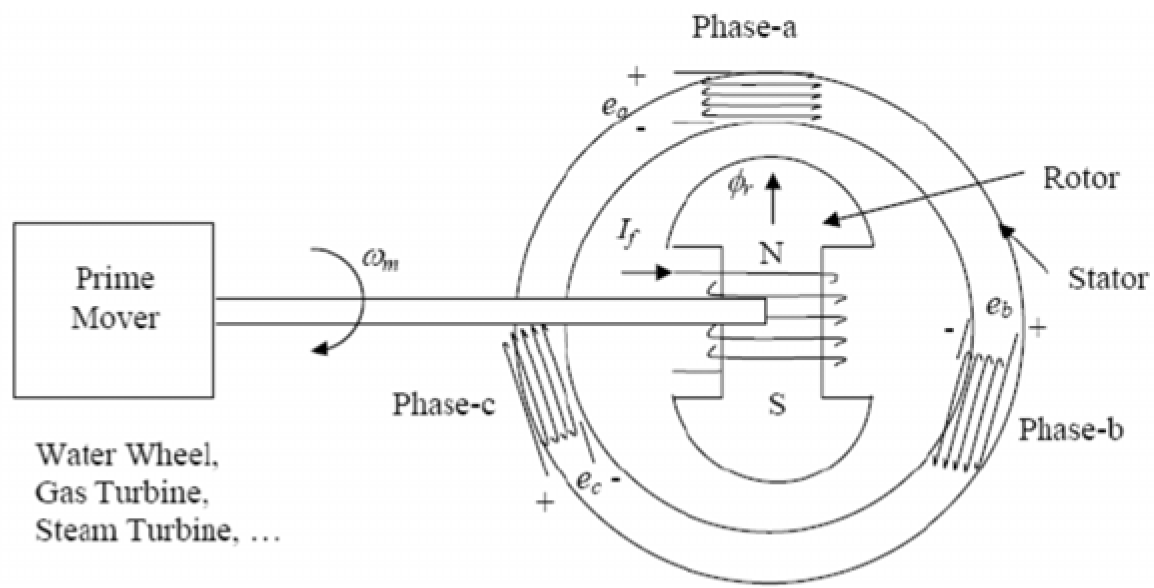
Salient Rotor Machine



Synchronous Generator

Principle of Operation

1) From an external source, the field winding is supplied with a DC current -> excitation.
2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



Parallel Operation of Synchronous Generator

Generators are rarely used in isolated situations. More commonly, generators are used in parallel, often massively in parallel, such as in the power grid. The following steps must be adhered to:

When adding a generator to an existing power grid:

1) RMS line voltages of the two generators must be the same.
2) Phase sequence must be the same.
3) Phase angles of the corresponding phases must be the same.
4) Frequency must be the same.

Synchronous Speed

$$n_s = \frac{120f}{p}$$

n_s = synchronous speed [r/min]
f = frequency of supply [hertz/Hz]
P = total of magnetic pole

Slip and Slip Speed

The slip s of an induction motor is the difference between the synchronous speed and the rotor speed, expressed as a Percent (per unit) of synchronous speed

The per-unit slip is given by the equation

$$S = \frac{n_s - n_r}{n_s}$$

S = slip
n_s = synchronous speed [r/min]
n_r = rotor speed [r/min]

Voltage and frequency induced in the rotor

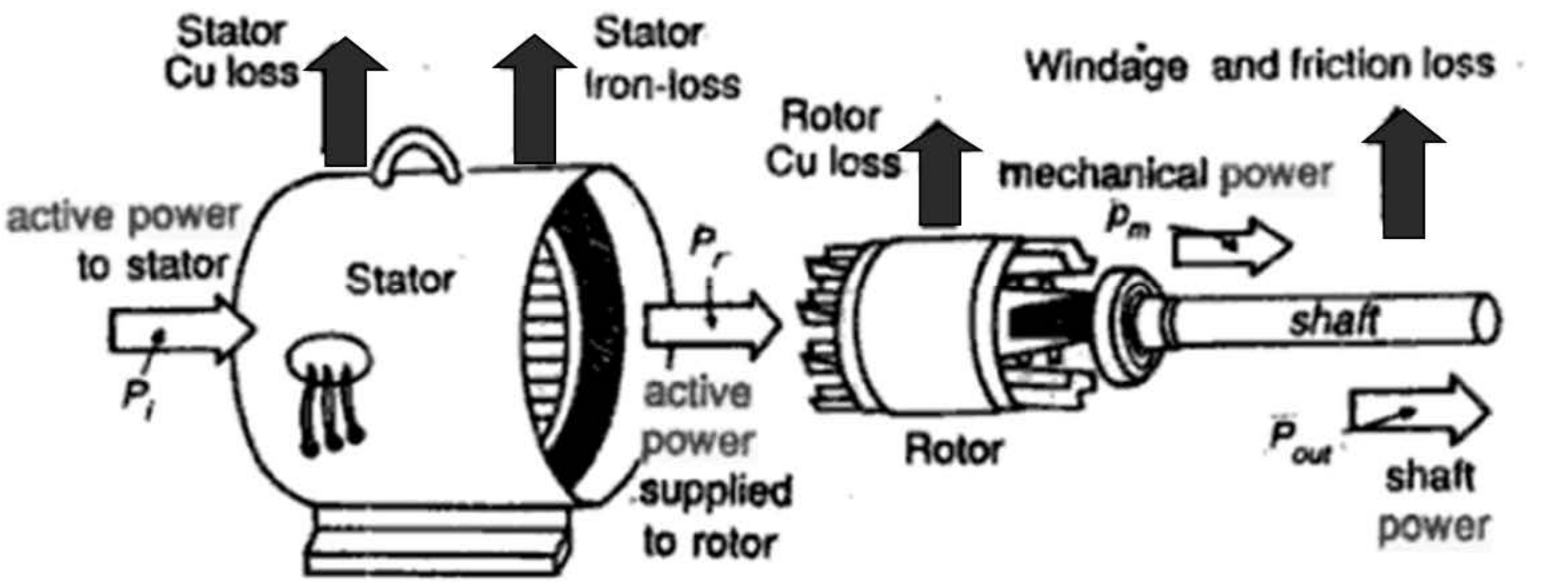
The voltage and frequency induced in the rotor both depend on the slip. They are given by the following equation

$$f_2 = s\,f$$

$$E_2 = s\,E_{oc} \text{ (approx.)}$$

f_2 = frequency of the voltage and current in the rotor [Hz]
f = frequency of the source connected to the stator [Hz]
s = slip
E_2 = voltage induced in the rotor at the slip s
E_{oc} = open-circuit voltage induced in the rotor when at rest [V]

Active Power in a Induction Motor



$$\text{Efficiency } (\eta) = \frac{P_{output}}{P_{input}}$$

Motor Torque

$$T_m = \frac{9.55 \; P_m}{n}$$

$$= \frac{9.55 \; (1 - s) \, P_r}{n_s \, (1 - s)}$$

$$= 9.55 \; P_r / n_s$$

➡ $T_m = 9.55 \; P_r / n_s$

I^2R losses in the rotor

$$P_{jr} = s\,P_r$$

P_{jr} = rotor I^2R losses [W]

s = slip

P_r = power transmitted to the rotor [W]

Mechanical Power

$$P_m = P_r - P_{jr}$$
$$= P_r - s\,P_r$$
$$= (1 - s)\,P_r$$

Example 1

Calculate the synchronous speed of a 3-phase induction motor having 20 poles when it is connected to a 50 Hz source.

Knowing quantities:

Source frequency = 50 Hz, number of poles = 20

$$\text{Synchronous speed } n_s = \frac{120\ f}{p}$$

$$= \frac{120 \times 50}{20}$$

$$n_s = \underline{\underline{300 \text{ r/min}}}$$

Example 2

A 0.5 hp, 6-pole induction motor is excited by a 3-phase, 60 Hz source. If the full-load is 1140 r/min, calculate the slip.

Knowing quantities:

Source frequency = 60 Hz, number of poles = 6

Full load/rotor speed = 1140 r/min

Synchronous speed $n_s = \dfrac{120\ f}{p}$

$$= \frac{120 \times 60}{6}$$

$$n_s = 1200 \text{ r/min}$$

Slip speed: $n_s - n = 1200 - 1140 = 60$ r/min

Slip: $s = (n_s - n) / n_s$

$= 60/1200$

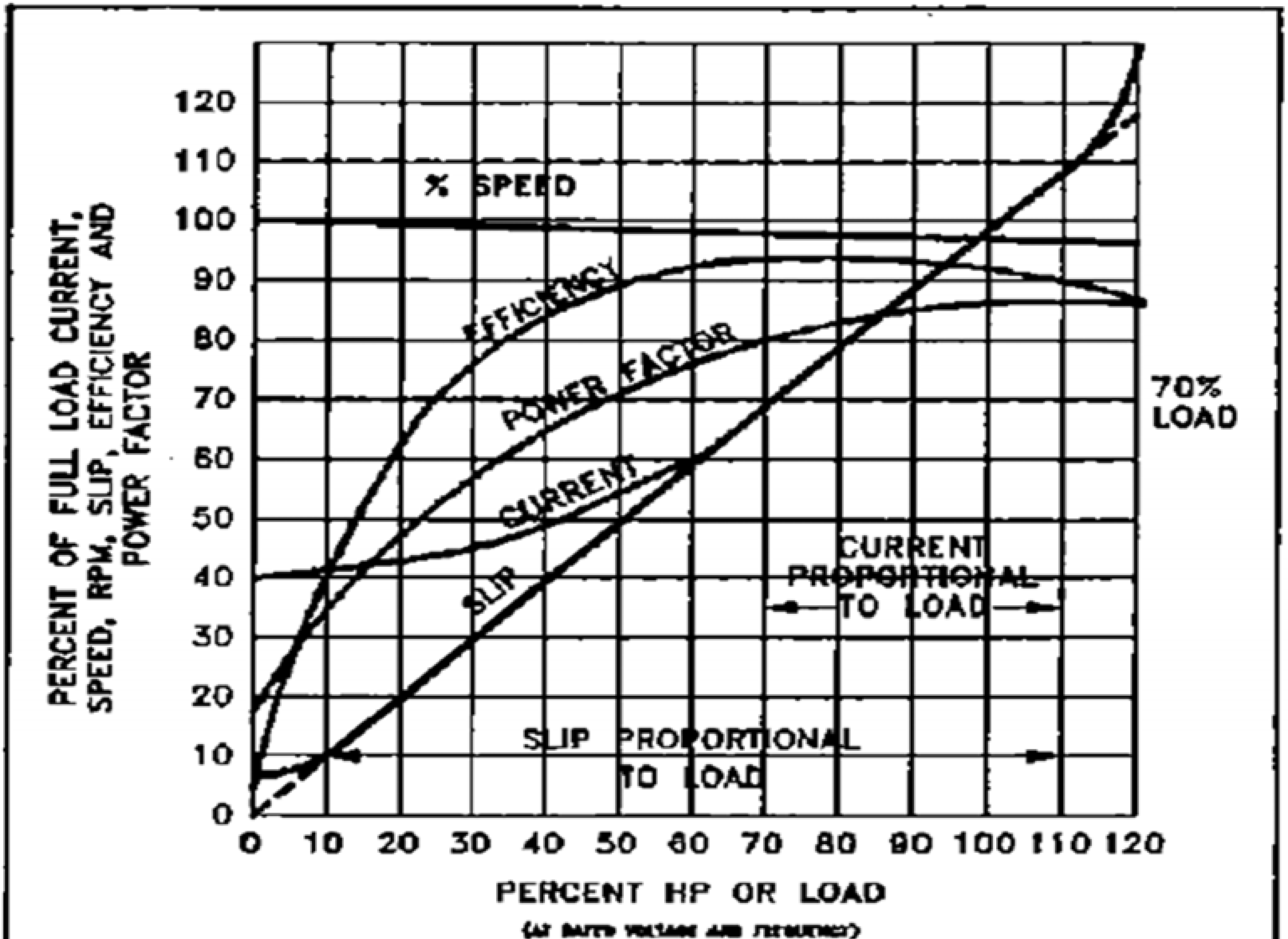
$= 0.05$ or 5%

able 4. The affects of voltage and frequency variation on induction motors

Variation	Starting & max running torque	Synchronous speed	%Slip	Full-load speed	Full-load efficiency	Full-load power factor	Full-load current	Starting current	Temp rise, full-load	Max Overload Capacity	Magnetic noise no-load in particular
Voltage variation: 120%	Increase 44%	No change	Decrease 30%	Increase 1.5%	0-6%Decrease	Decrease 5-15 points	Increase 12%	Increase 20%	Increase 5-6°C	Increase 44%	Noticeable Increase
110%voltage	Increase 21%	No change	Decrease 17%	Increase 1%	Slight decrease	Decrease 5-10 points	Increase 2-4%	Increase 10-12%	Increase 3-4°C	Increase 21%	Increase slightly
Functions of voltage	$(\text{Voltage})^2$	Constant	$\frac{1}{(\text{Voltage})^2}$	(Synchronous speed slip)	—	—	—	Voltage	—	$(\text{Voltage})^2$	—
90% voltage	Decrease 19%	No change	Increase 23%	Decrease 1½%	Decrease 2 points	Increase 5 points	Increase 10-11%	Decrease 10-12%	Increase 6-7°C	Decrease 19%	Decrease slightly
Freq. variation: 105%freq.	Decrease 10%	Increase 5%	Practically no change	Increase 5%	Slight increase	Slight increase	Decrease slightly	Decrease 5-6%	Decrease slightly	Decrease slightly	Decrease slightly
Function of frequency	$\frac{1}{(\text{Frequency})^2}$	Frequency	—	(Synchronous speed slip)	—	—	—	$\frac{1}{\text{Frequency}}$	—	—	—
95%frequency	Increase 11%	Decrease 5%	Practically no change	Decrease 5%	Slight decrease	Slight decrease	Increase slightly	Increase 5-6%	Increase slightly	Increase slightly	Increase slightly
1%Unbalance	Slight decrease	Slight decrease	—	Slight decrease	2%Decrease	5-6% Decrease	1½%Increase	Slight decrease	2%Increase	—	—
2%Unbalance	Slight decrease	Slight decrease	—	Slight decrease	8%Decrease	7%Decrease	3%Increase	Slight decrease	8%Increase	—	—

NOTE: This table shows general effects, which will vary somewhat for specific ratings. From Engineers Digest September 1989.

Measurement of motor output is based on the principle that slip RPM is linear from ten percent load to 110 percent load



Typical NEMA Design "B" Induction Motor Curve.

For example, if a four-pole, 10 hp motor with a full load slip of 80 RPM was found to be running at 1770 RPM. What is the approximate output at that time?

Full-load slip = 1800 - 1720 = 80 RPM = 100 % load.

Running slip = 1800 - 1770 = 30 RPM.

$$\text{Running load} = \frac{\text{Running slip}}{\text{Full-load slip}} = \frac{30}{80} = 0.375$$

Output load = 10hp x 0.375 = 3.75hp.

This method of estimating motor loads assumes nameplate voltage is applied to the unit. As shown in Table 4, a motor's slip will vary inversely proportional to the square of the voltage deviation from nameplate. Unless nameplate voltage is applied to the unit, a significant error can be made in estimating the motor loads based only on slip.

Note that below about 60% of full-load amperes, the motor current is not a valid measurement of motor load. Due to the decrease in motor power factor, more and more of the apparent current is reactive amperes as the motor load decreases.

Understanding Power Concepts

Part 3

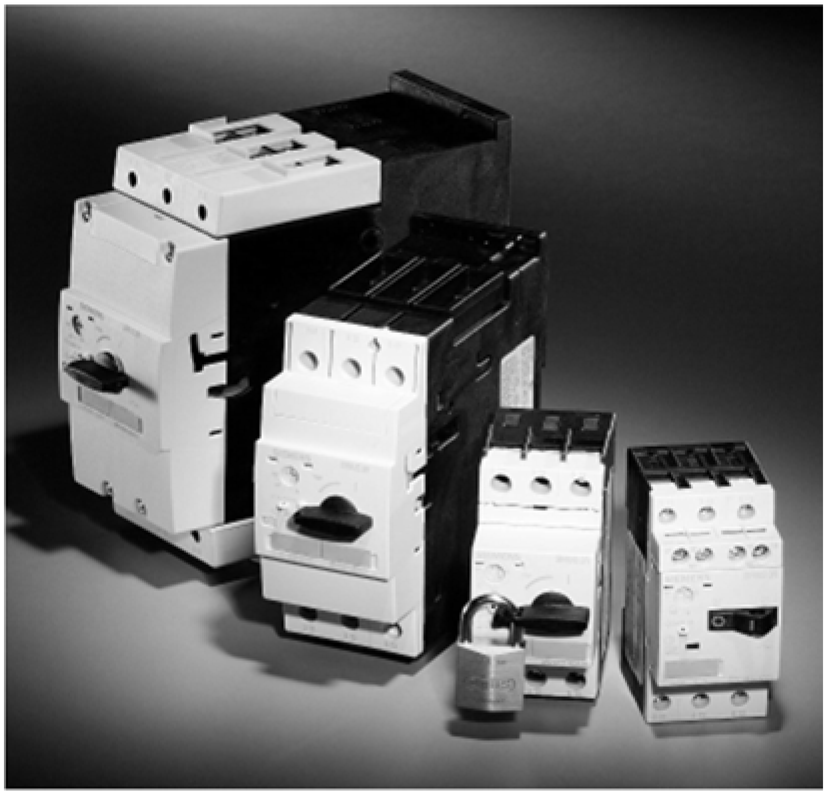
- ***Motors***
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - ***Motor Controllers*** (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

Control of Electric Motors

Types of Motor Controllers

- Magnetic Units
  - Contactors
  - Motor Starters
- Solid State
- Programmable
- VFD

Magnetic Controllers



Magnetic Controllers

- Universally used.

- Made up of components such as:

  - Relays or Contactors:
    - ✓ Magnetic Coils
    - ✓ Electromagnets and Moving Armatures
    - ✓ Contacts and Arcing Horn
  - Spring loaded components (Pushbuttons)
  - Fuses
  - Timers
  - Interlocks
  - Switches

- Main Operation:

  - Opens and Closes an Electrical Circuit by means of contacts

MOTOR STARTER

- Basically Made up of:
    - Contactor → Special Relay containing coils, contacts, pressure spring, arching horn, armature
    - Overload Protection
    - Undervoltage Release / Protection
- Difference between a Contactor and a Motor Starter is the added Overload Protection or Undervoltage release protection in the Motor Starter.

Overload Protection

- Implemented when overheating occurs.
- Overheating causes:
  - Stalled Rotor
  - Low Voltage
  - Low Frequency (in the case of AC motor)
  - Unbalanced Voltages

THERMAL RELAY

- Consists of:
  - Heater Element → connected in series with Motor
  - Bimetallic Element → Deflected by high heater temperature
  - Contacts → Open when bimetallic element deflects
  - Reset Button → manually closes contacts

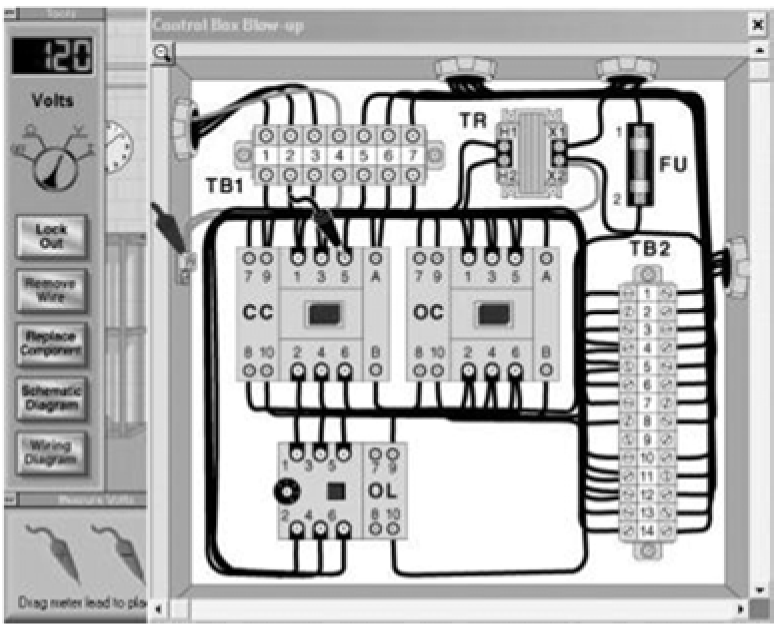
See Current – Time characteristics of a typical Thermal –Overload Relay

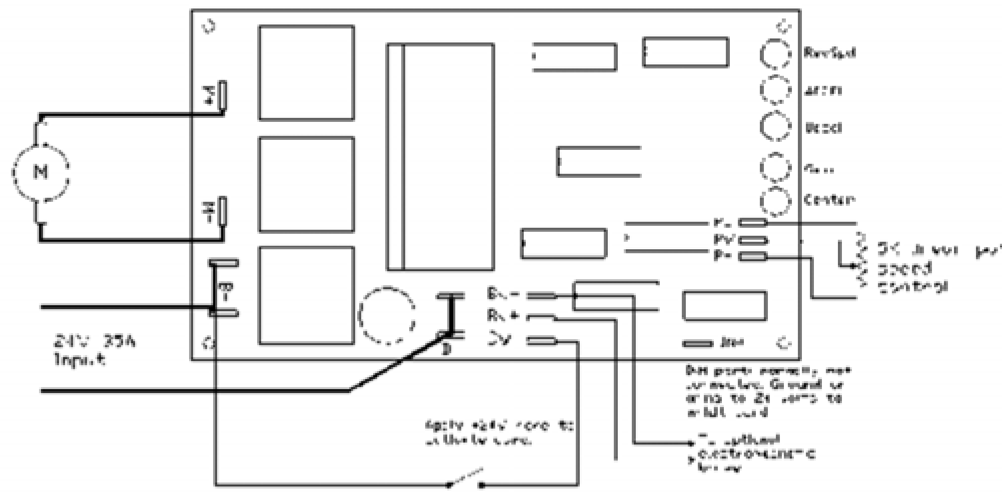
Undervoltage Release and Under-voltage Protection

- Implemented when loss of power of low voltage occurs.
- Undervoltage Release allows for the voltage to be restored automatically.
- Undervoltage Protection prevents automatic restarting when voltage is restored.

Connection Wiring Diagram

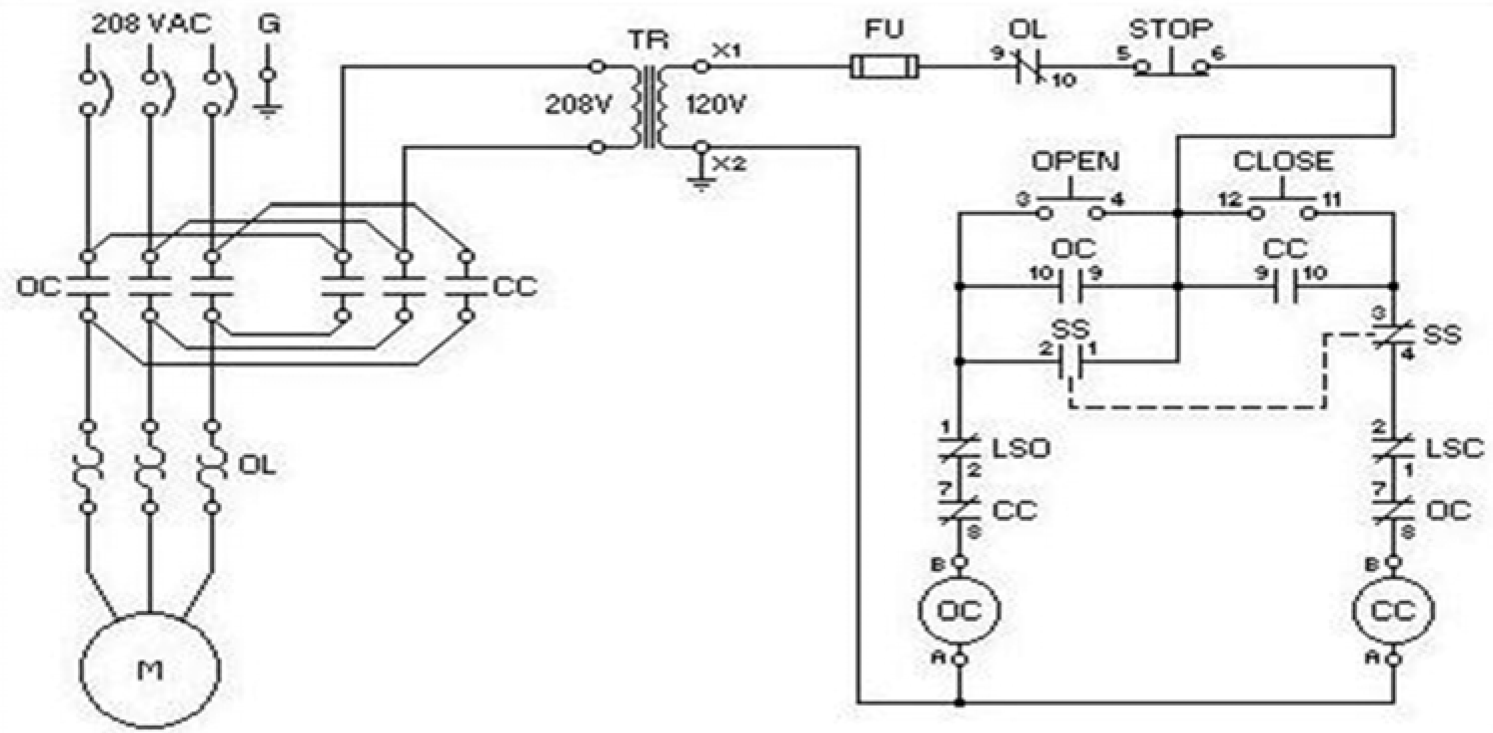
- It shows the Physical Layout.
- It shows the Wire Connector numbers.
- Darker lines usually depicts the power circuit.





Elementary Wiring or Ladder Diagram

- It shows the power on vertical lines called RAILS.
- It shows the components on horizontal lines called RUNGS.
- Two sections:
  - o Power Circuit
  - o Control or Logic Circuit



GARAGE DOOR - ELEMENTARY WIRING DIAGRAM

Diagram Symbols

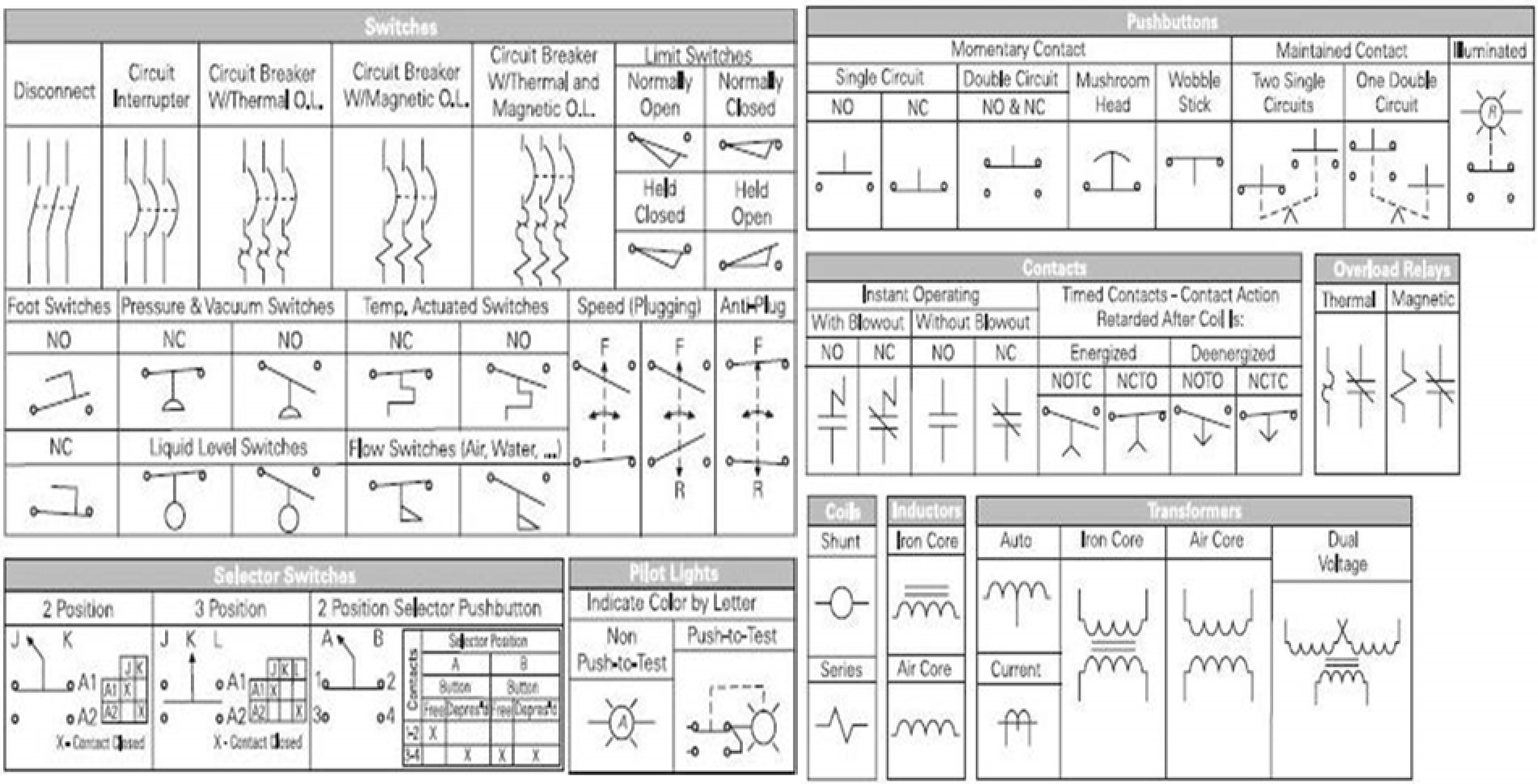
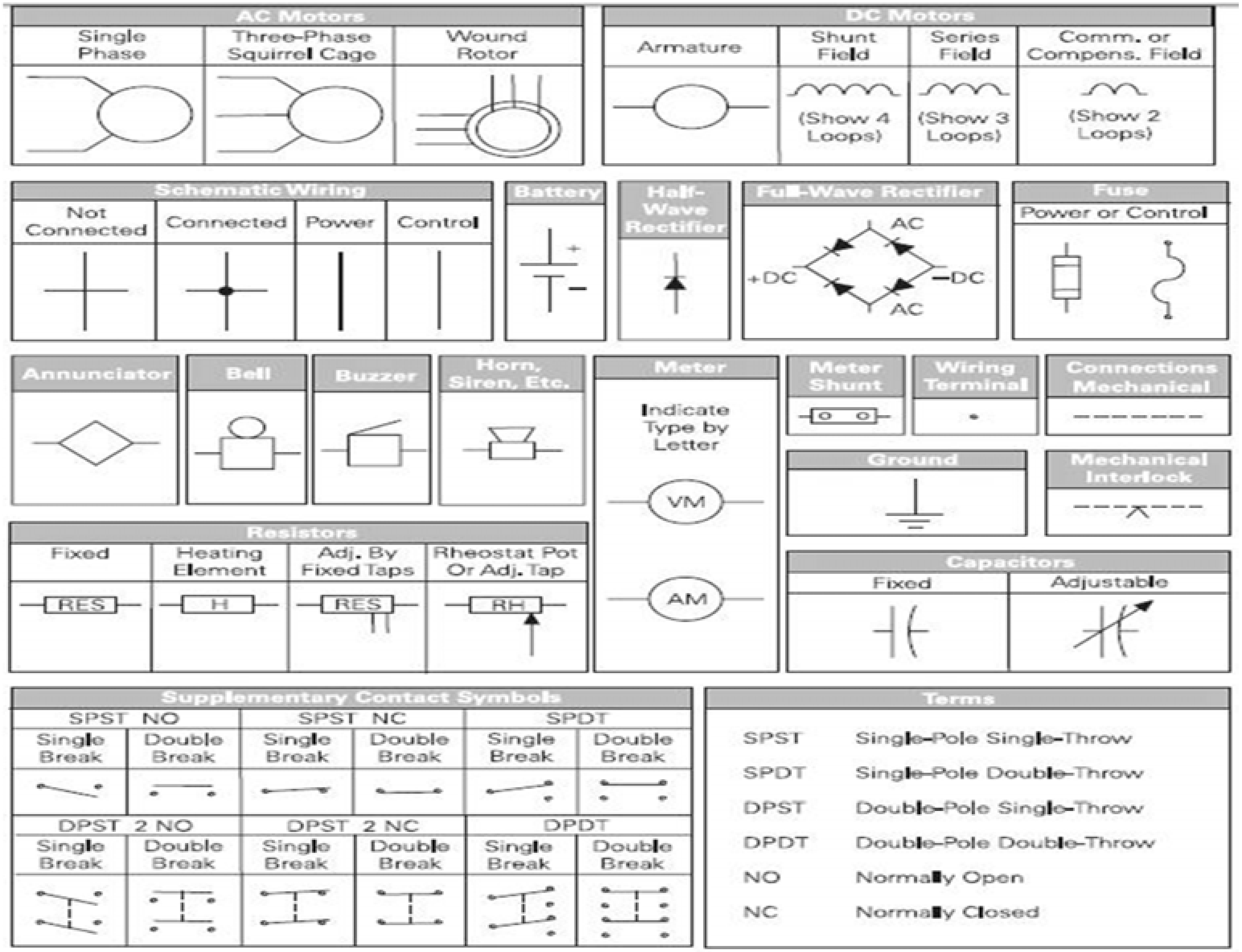
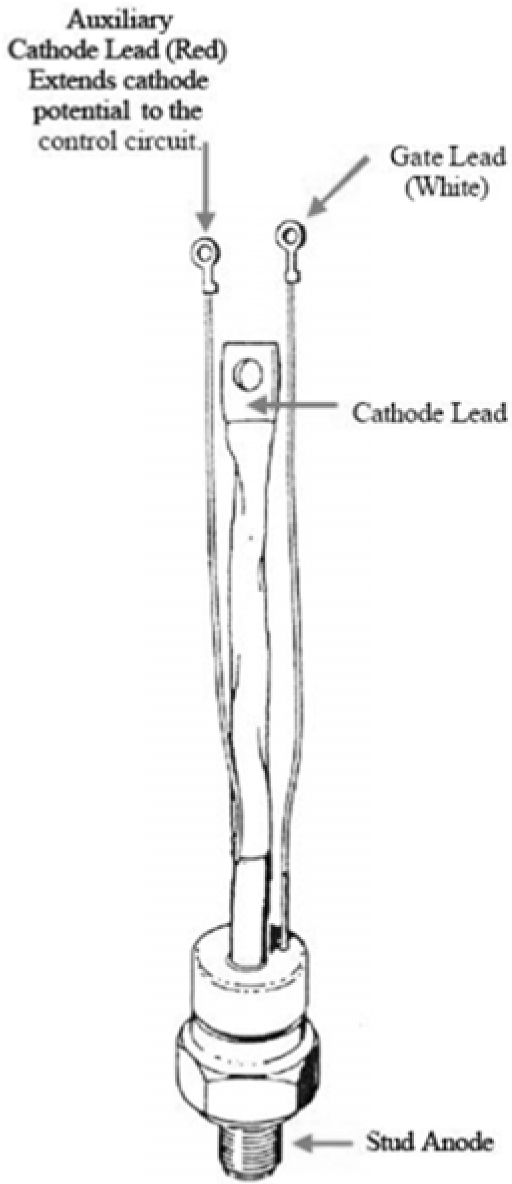


Diagram Symbols (Cont’d)



The Silicon Controlled Rectifier (SCR)



- A semiconductor device that is a member of a family of control devices known as Thyristors.
- The workhorse of the industrial control industry.
- Its evolution over the years has yielded a device that is less expensive, more reliable, and smaller in size than ever before.

Typical applications include :

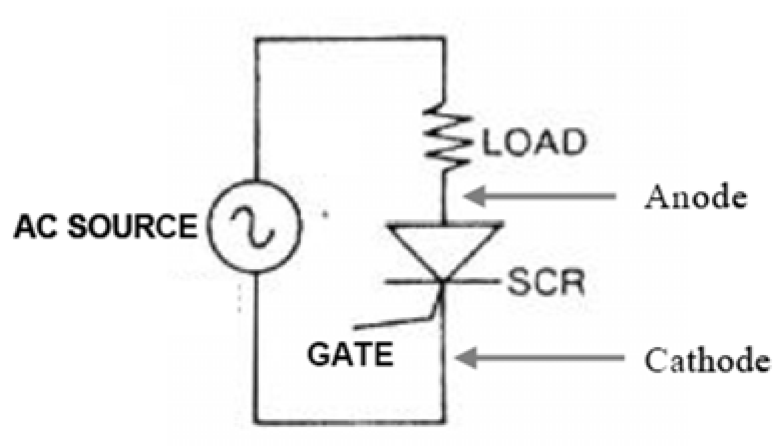
- DC Motor Control
- Generator Field Regulation
- Variable Frequency Drive
- Lighting System Control

The Silicon Controlled Rectifier (SCR)

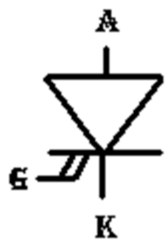
- A three-lead device with an anode and a cathode (as with a standard diode) plus a third control lead or *gate. As the name implies, it is a rectifier* which can be controlled - or more correctly - one that can be triggered to the "ON" state by applying a small positive voltage to the gate lead.

- Once gated ON, the trigger signal may be removed and the SCR will remain conducting as long as current flows through the device.

- The load to be controlled by the SCR is normally placed in the anode circuit. See drawing below.



The Gate-Turn-Off Device (GTO)



- Another member of the Thyristor Family is the GTO, or *Gate-Turn-Off Device.*

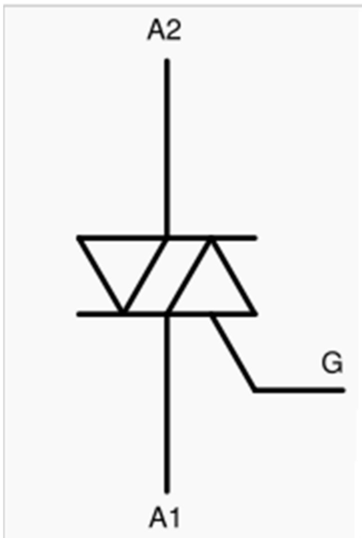
- *While this component has* been around for many years, it has just recently evolved to the point where it is capable of carrying the high currents required for motor control circuitry.

- Unlike the SCR, the GTO can be turned ON *and OFF* with a signal applied to the gate.

- The turn-on signal is a small positive voltage; the turn-off signal is a negative current pulse.

- It is now finding applications in the output stage of medium-voltage, high horsepower, Variable Frequency Drives.

The TRIAC (Triode for Alternating Current)

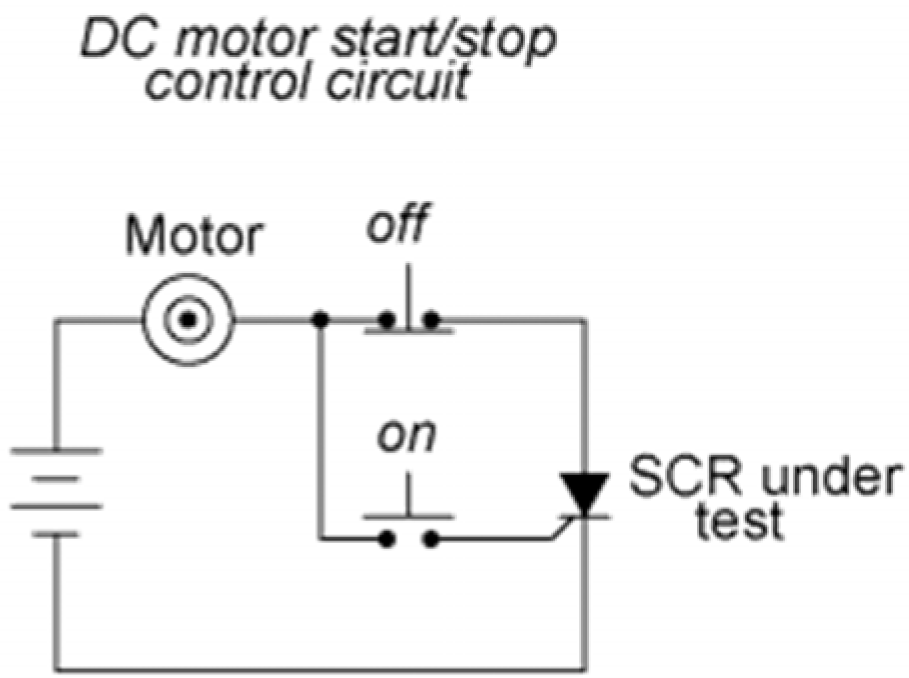


The TRIAC Symbol

- It’s just a Bidirectional SCR.
- It represents SCRs connected back to back.
- AC Motor Control utilizes TRIAC instead of SCRs for control.

Circuits using SCR

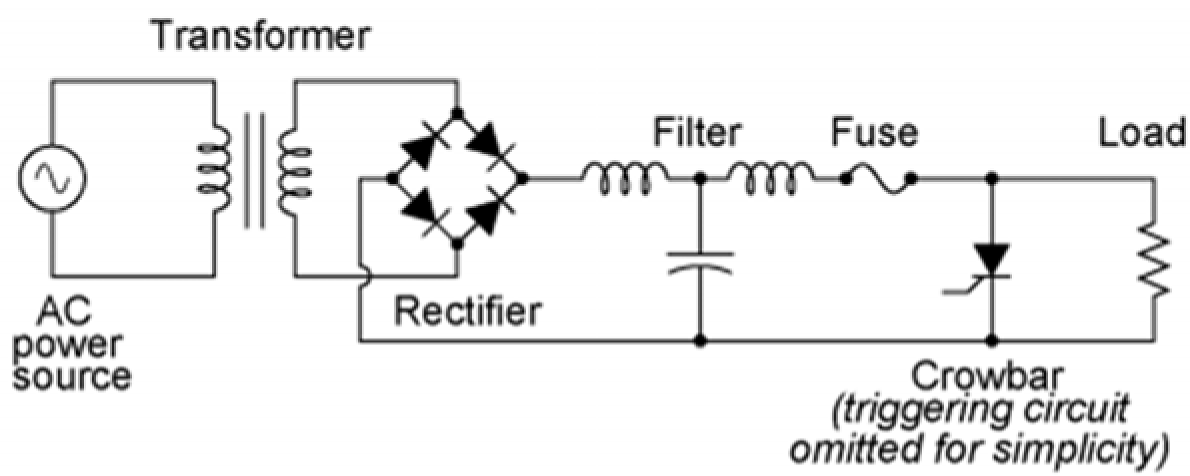
Circuit below shows an SCR controlling a Load in a DC Circtui.



Circuits using SCR (Cont'd)

AC-DC "Crowbar"

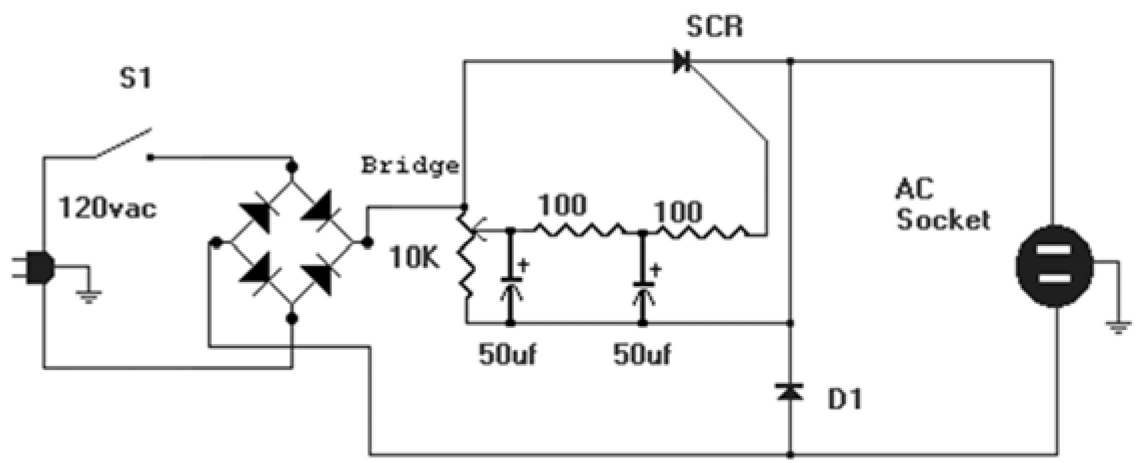
- It is used for overvoltage protection.
- It consists of an SCR placed in parallel with the output of a DC power supply, for the purpose of placing a direct short-circuit on the output of that supply to prevent excessive voltage from reaching the load.
- Damage to the SCR and power supply is prevented by the judicious placement of a fuse or substantial series resistance ahead of the SCR to limit short-circuit current.



Circuits using SCR (Cont' d)

AC Motor Speed Control

- This circuit will allow you to control the speed of an AC motor, for example an electric drill.
- The bridge rectifier produces dc voltage from the 120vac line. A portion on this current passes through the 10K ohm pot.
- The circuit comprised of the 10k pot, the two 100 ohm resistors and the 50uf capacitors delivers gate drive of the SCR.
- The diode D1 protects the circuit from reverse voltage spikes. The ratings of the bridge rectifier and the SCR should be 25 amps and PIV 600 volts. The diode D1 should be rated for 2 amps with PIV of 600 volts.
- The circuit can handle a load up to 10 amps. The SCR should be very well heat-sink.



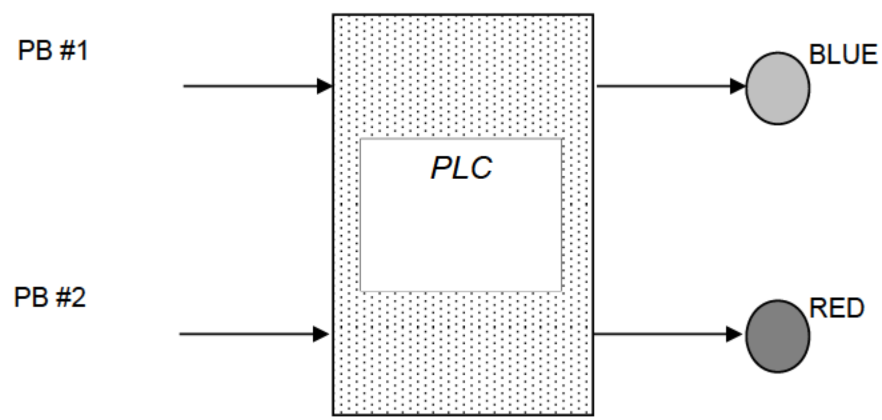
PLC Introductory Laboratory

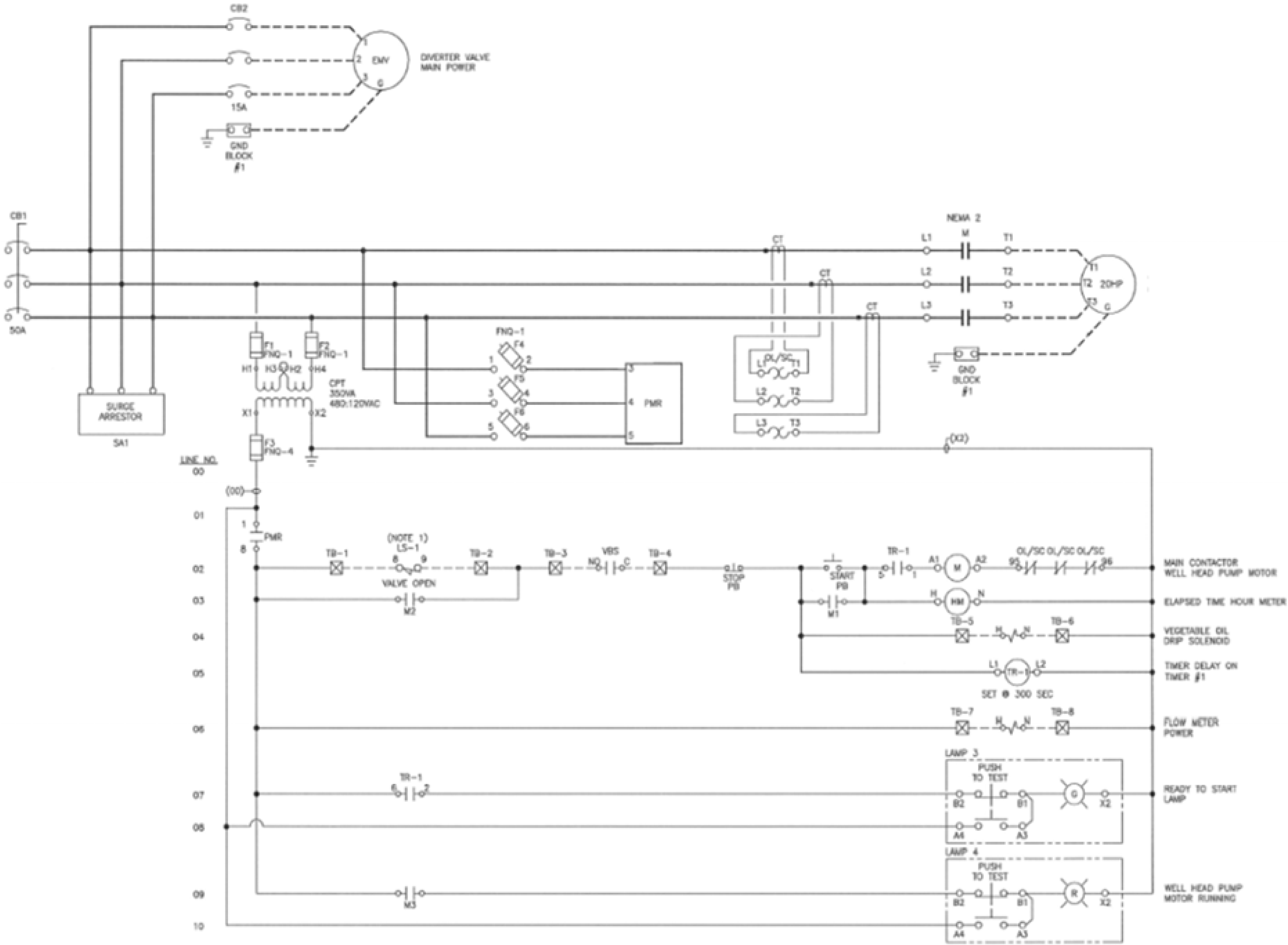
Design the ladder logic to control the system shown

1. When Pushbutton 1 is ON AND pushbutton 2 is OFF, the blue light turns ON.

2. As long as Pushbutton 2 is ON, the red light turns on. (independently whether pushbutton 1 is ON of OFF).

3. If both Pushbuttons are OFF, neither light turns on.





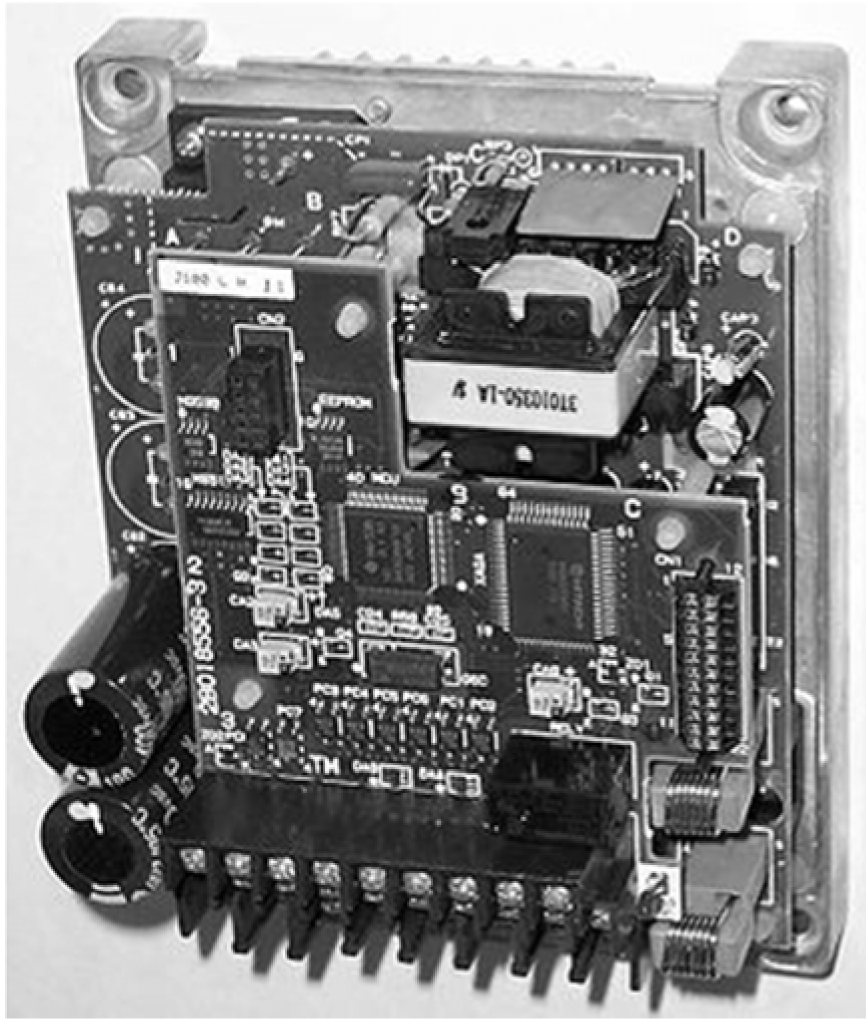
CB2
EMV
DIVERTER VALVE MAIN POWER
15A
GND BLOCK #1
CB1
50A
NEMA 2
CT
L1
L2
L3
M
T1
T2
T3
20HP
SURGE ARRESTOR
SA1
F1 FNQ-1
F2 FNQ-1
H1 H3 H2 H4
CPT 350VA 480:120VAC
X1 X2
F3 FNQ-4
FNQ-1
F4
F5
F6
PMR
OL/SC
LINE NO.
00
01
02
03
04
05
06
07
08
09
10
(00)
(X2)
TB-1
(NOTE 1) LS-1
VALVE OPEN
M2
TB-2
TB-3
VBS
TB-4
STOP PB
START PB
M1
TR-1
A1 A2
HM
TB-5
TB-6
SET @ 300 SEC
TB-7
TB-8
LAMP 3
PUSH TO TEST
B2 B1 A4 A3 X2
LAMP 4
M3
MAIN CONTACTOR WELL HEAD PUMP MOTOR
ELAPSED TIME HOUR METER
VEGETABLE OIL DRIP SOLENOID
TIMER DELAY ON TIMER #1
FLOW METER POWER
READY TO START LAMP
WELL HEAD PUMP MOTOR RUNNING

Understanding Power Concepts

Part 3

- ***Motors***
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (***VFD*** and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

POWER
FUNC.
RUN
STOP/RESET
WARNING

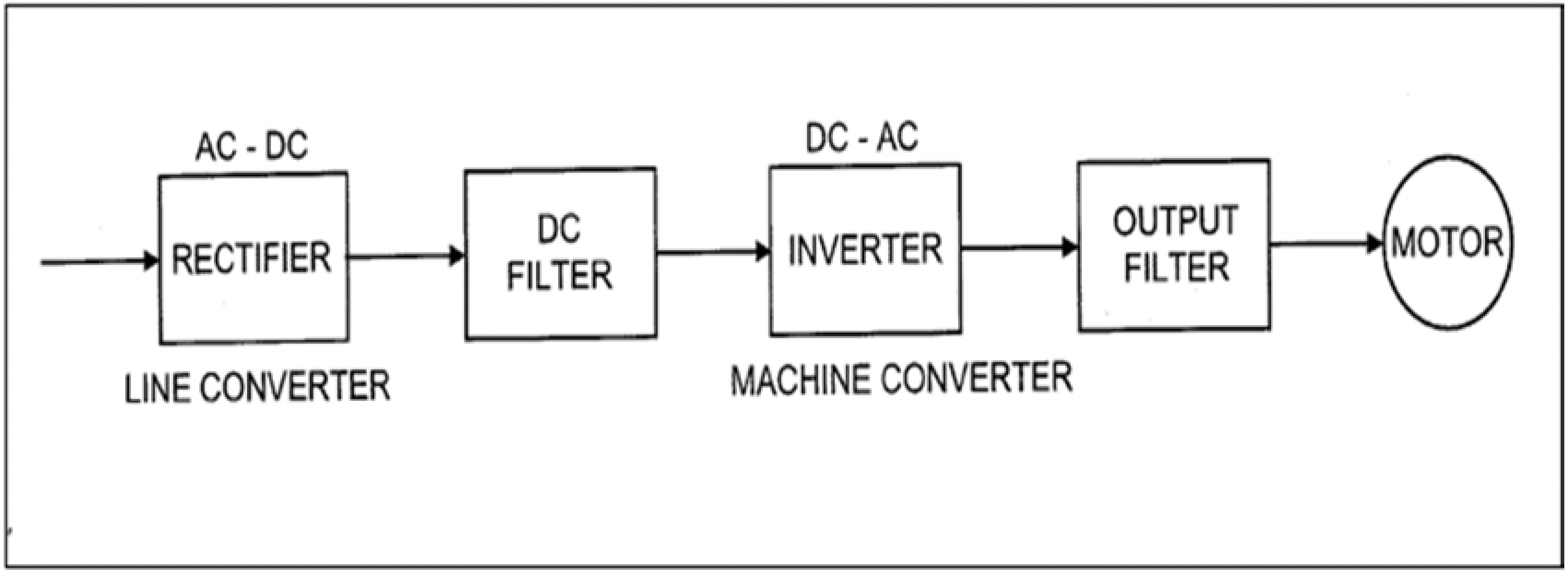



TOSHIBA
G9

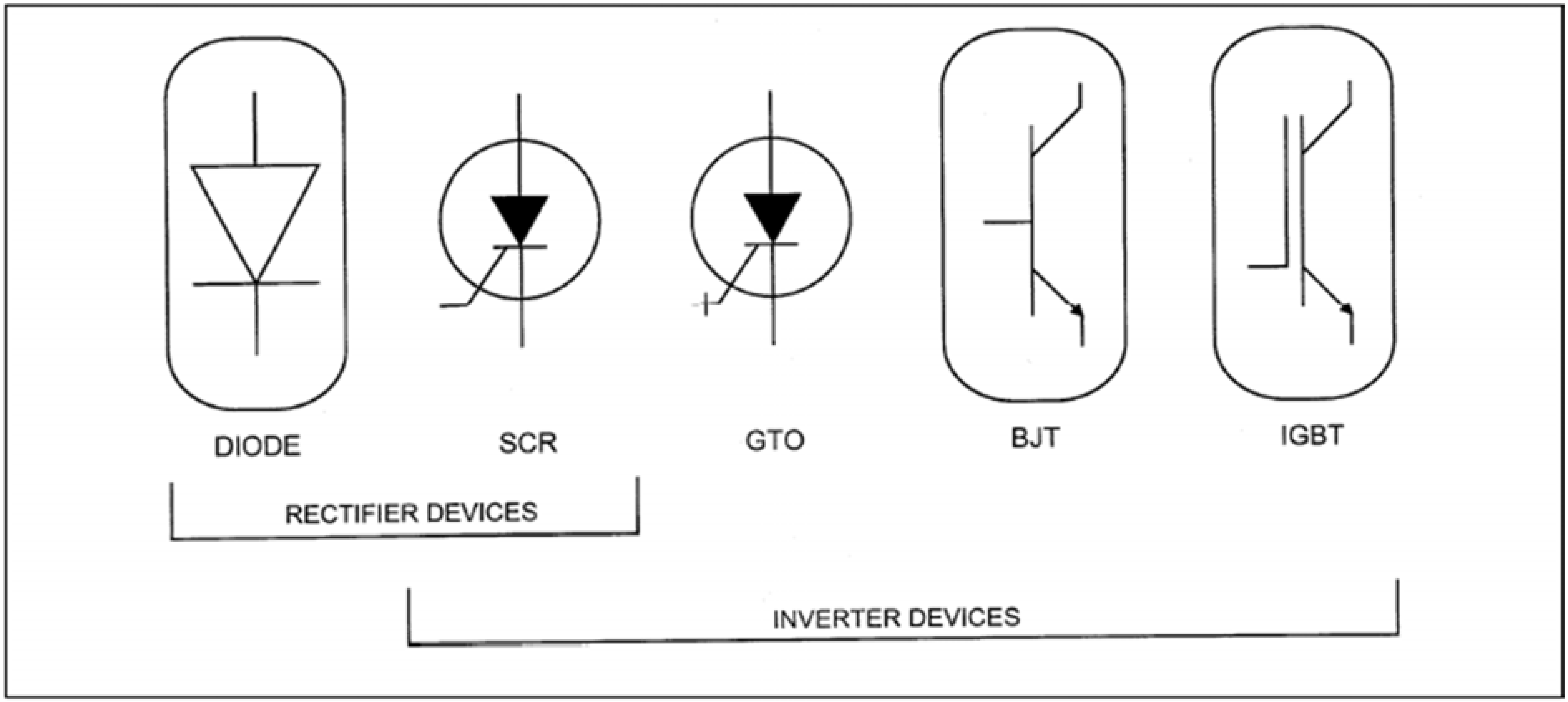

TOSHIBA
P9

Course Contents

- System description and operation
  - What is a Variable Frequency Drive
  - AC Motor
  - Controller
  - Operator interface
  - Drive operation
- Benefits
  - Energy savings
  - Control performance
- VFD types and ratings
  - Generic topologies
  - Control platforms
  - Load torque and power characteristics
  - Available power ratings
  - Drives by machines & detailed topologies
- Application considerations
  - AC line harmonics
  - Long lead effects
  - Motor bearing currents
  - Dynamic braking
  - Regenerative drives


AC - DC
RECTIFIER
LINE CONVERTER
DC
FILTER
DC - AC
INVERTER
MACHINE CONVERTER
OUTPUT
FILTER
MOTOR

Commonly Used Solid State Switching Devices for Power Converters.



Variable-frequency drive

- A **variable-frequency drive (VFD)**
  - adjustable-frequency drive
  - variable-speed drive
  - AC drive
  - micro drive
  - inverter drive

- is a type of adjustable-speed drive used in electro-mechanical drive systems to control
  - AC motor speed
  - torque by varying motor input frequency and voltage.

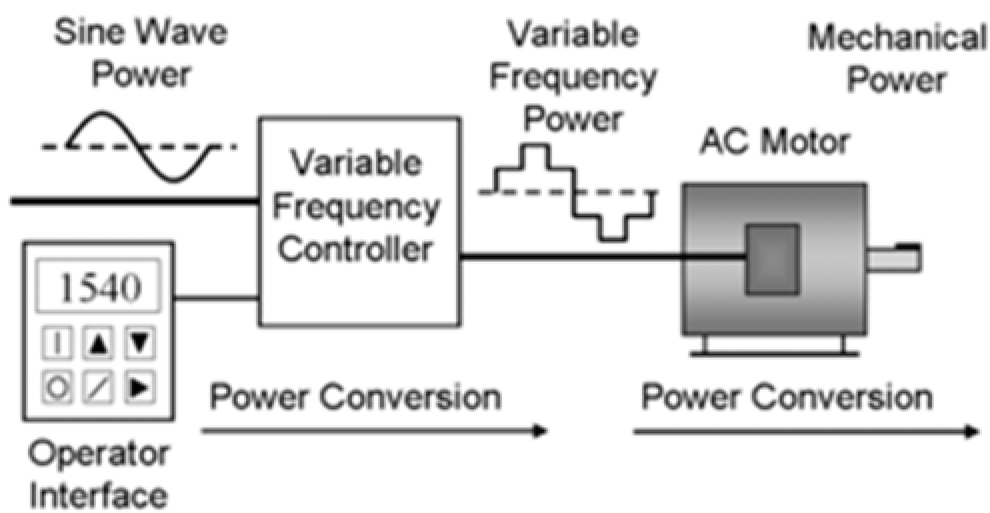
- VFDs are used in applications ranging from small appliances to the largest of mine mill drives and compressors.

- However, about a third of the world's electrical energy is consumed by electric motors in fixed-speed centrifugal pump, fan and compressor applications and VFDs' global market penetration for all applications is still relatively small.

- This highlights especially significant energy efficiency improvement opportunities for retrofitted and new VFD installations.

- Over the last four decades, power electronics technology has reduced VFD cost and size and improved performance through advances in semiconductor switching devices, drive topologies, simulation and control techniques, and control hardware and software.

- VFDs are available in a number of different low and medium voltage AC-AC and DC-AC topologies.



AC Motor

- The AC electric motor used in a VFD system is usually a three-phase induction motor.
- Some types of single-phase motors can be used, but three-phase motors are usually preferred.
- Various types of synchronous motors offer advantages in some situations, but three phase induction motors are suitable for most purposes and are generally the most economical choice.

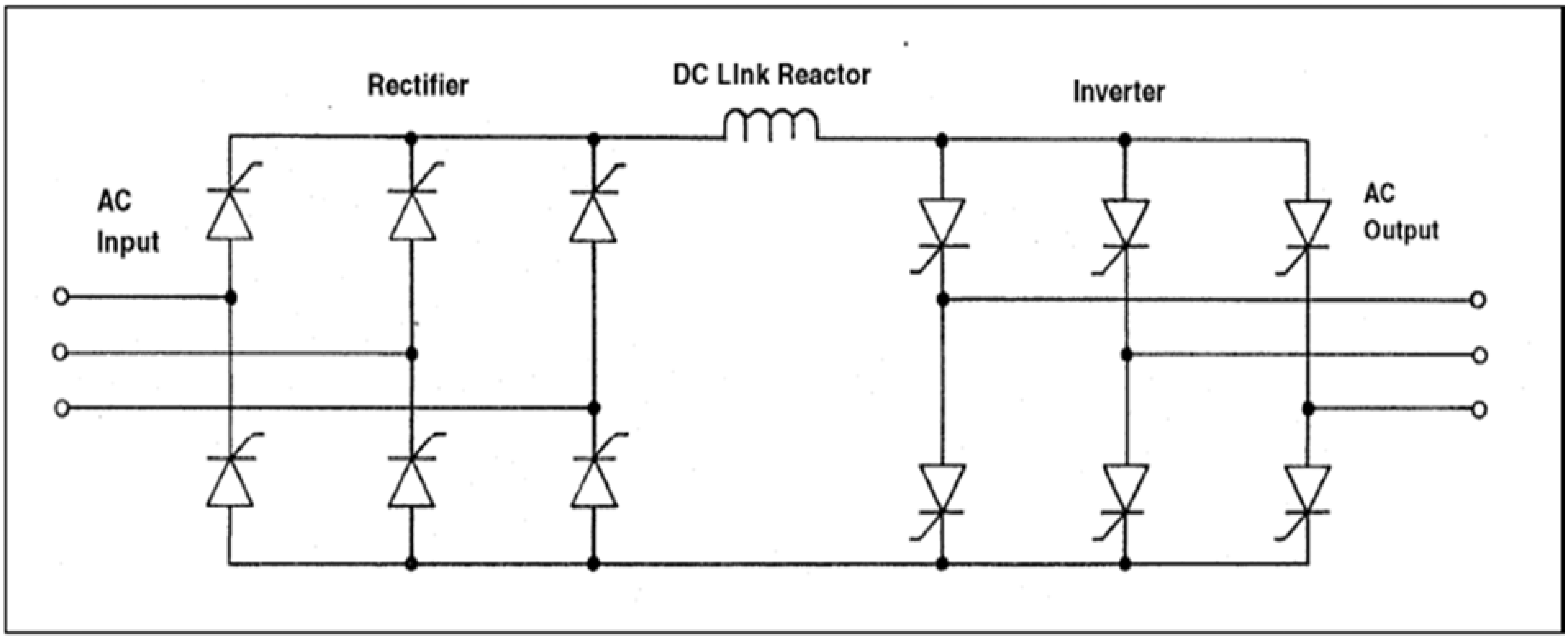
AC Motor

- Motors that are designed for fixed-speed operation are often used.

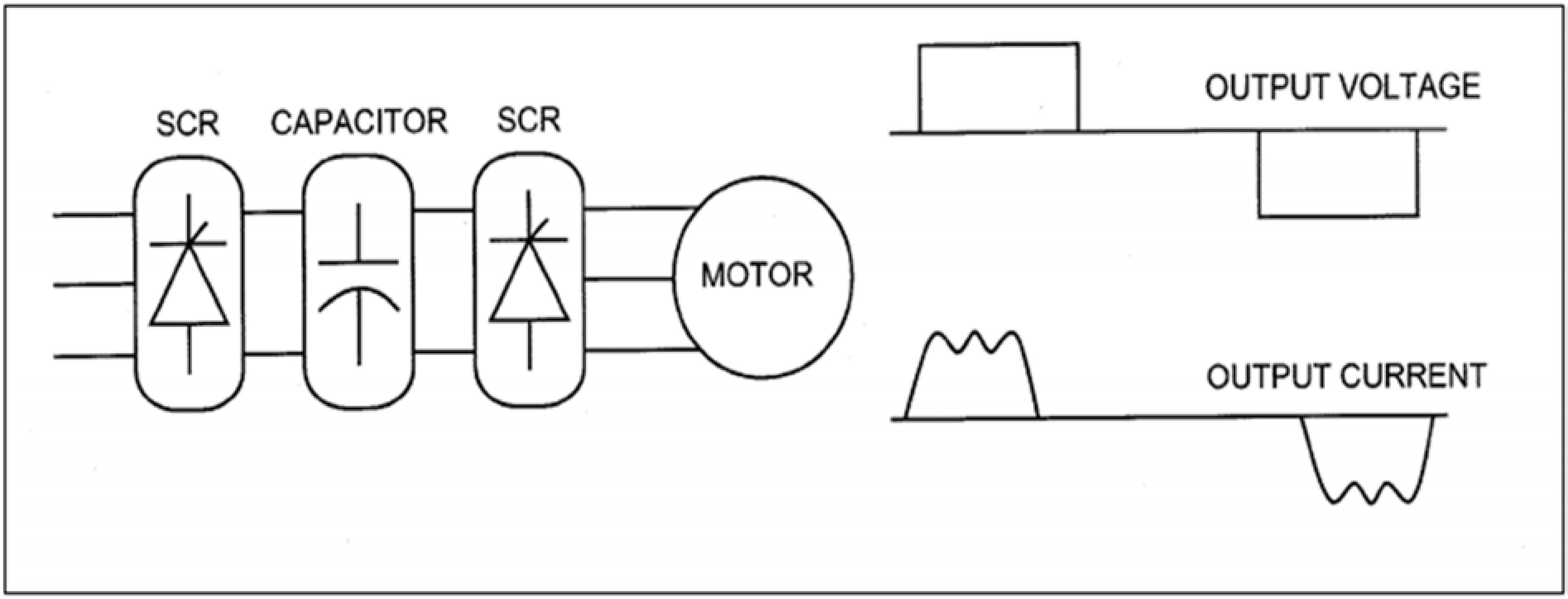
- Elevated voltage stresses imposed on induction motors that are supplied by VFDs

- require that such motors be designed for definite-purpose inverter-fed duty in accordance to such requirements as Part 31 of NEMA Standard MG-1.

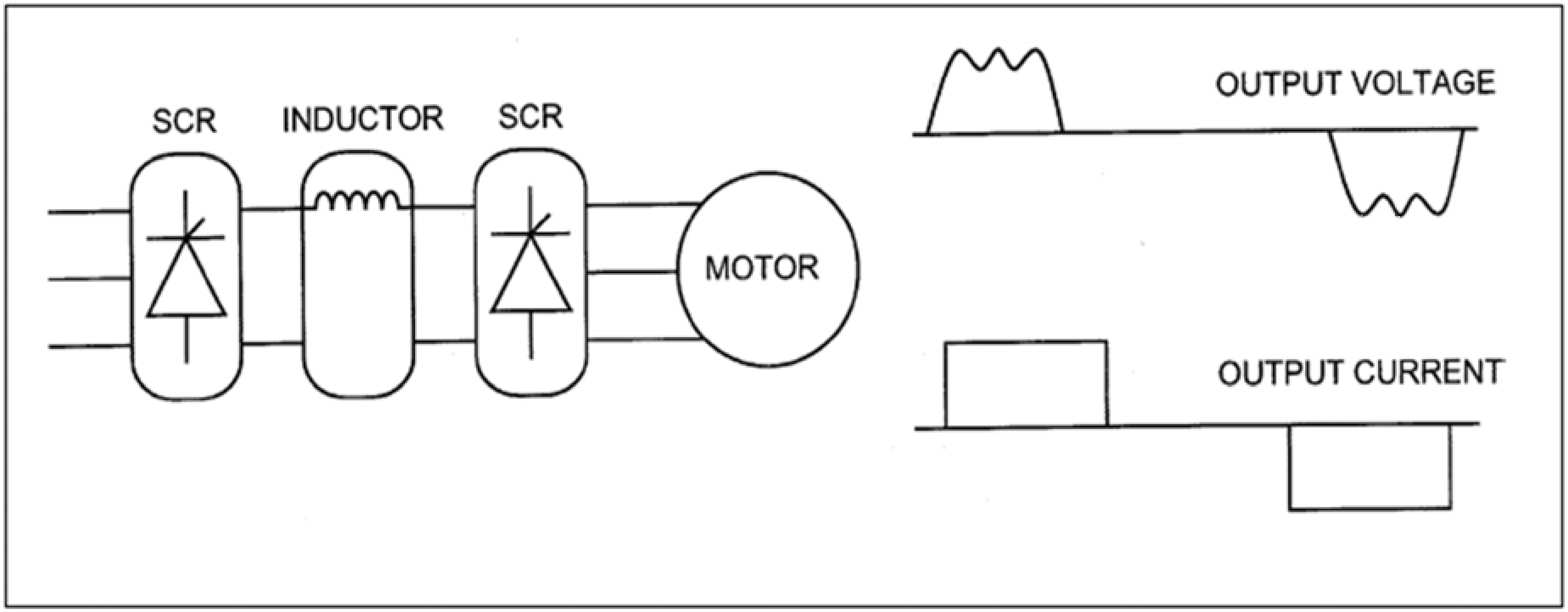
Typical Six-Pulse ASD Configuration



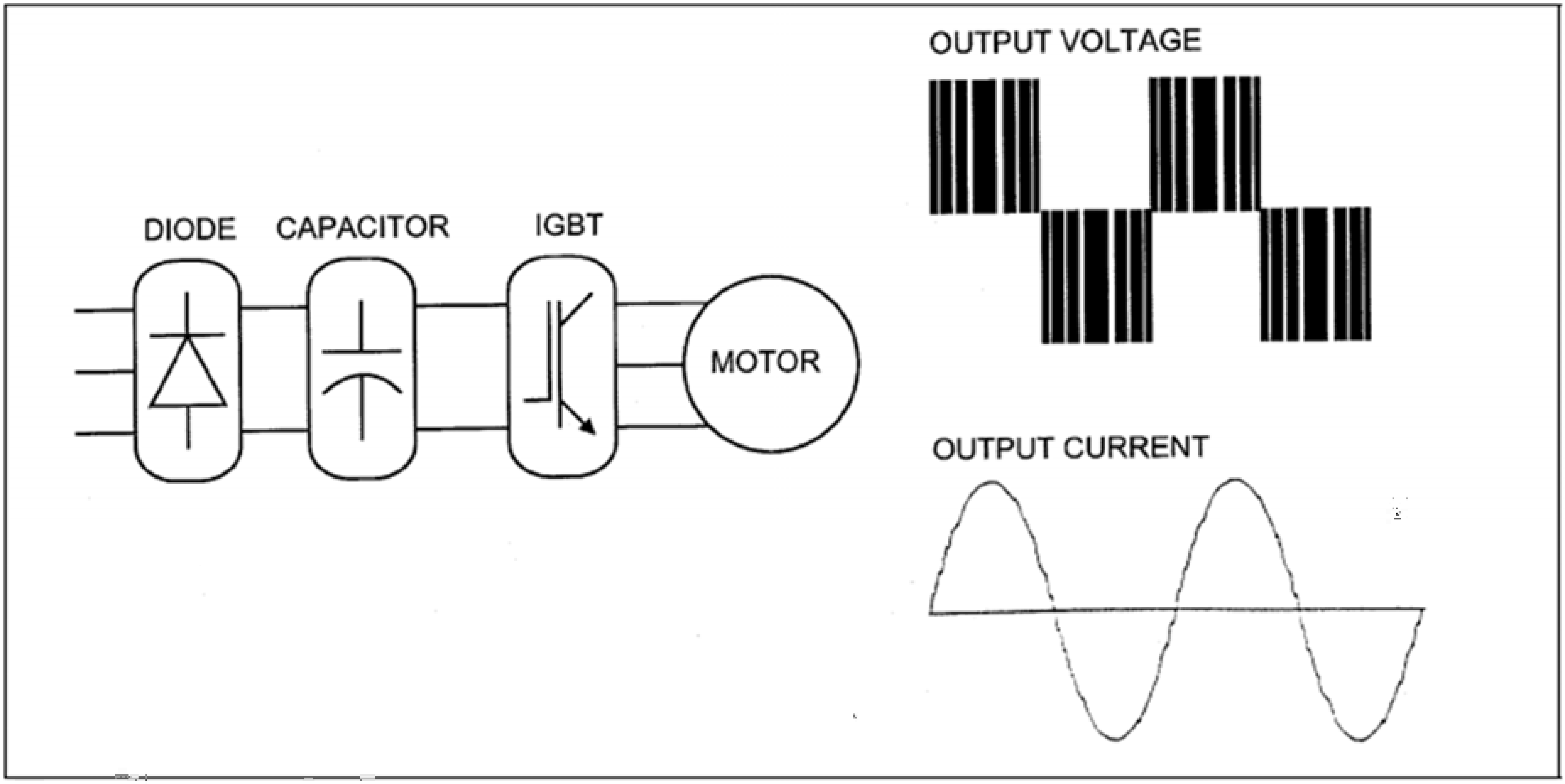
Variable Voltage Inverter Drive



Current Source Inverter Drive

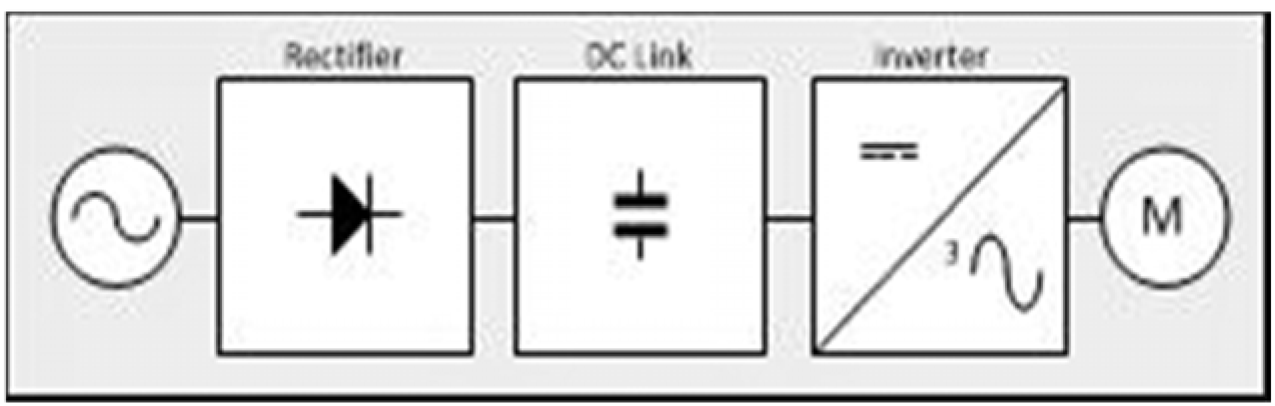


Pulse Width Modulated Drive



Controller (the VFD)

- The variable frequency drive controller is a solid state power electronics conversion system consisting of three distinct sub-systems:
  - a rectifier bridge converter,
  - a direct current (DC) link,
  - and an inverter.



Controller (the VFD)

- Voltage-source inverter (VSI) drives are by far the most common type of drives.
- Most drives are AC-AC drives in that they convert AC line input to AC inverter output.
- However, in some applications such as common DC bus or solar applications, drives are configured as DC-AC drives.

Controller (the VFD)

- The most basic rectifier converter for the VSI drive is configured as a three-phase, six-pulse, full-wave diode bridge.
-
- In a VSI drive, the DC link consists of a capacitor which smooths out the converter's DC output ripple and provides a stiff input to the inverter.

- This filtered DC voltage is converted to quasi-sinusoidal AC voltage output using the inverter's active switching elements.

6 pulse rectifier front end

- Diodes or thyristors are usually grouped in 3-phase bridge rectifiers
- Each 3-phase bridge is a 6-pulse converter
- A 6-pulse converter has a distinct harmonic current signature
- A 6-pulse converter has at least 30% harmonic current distortion

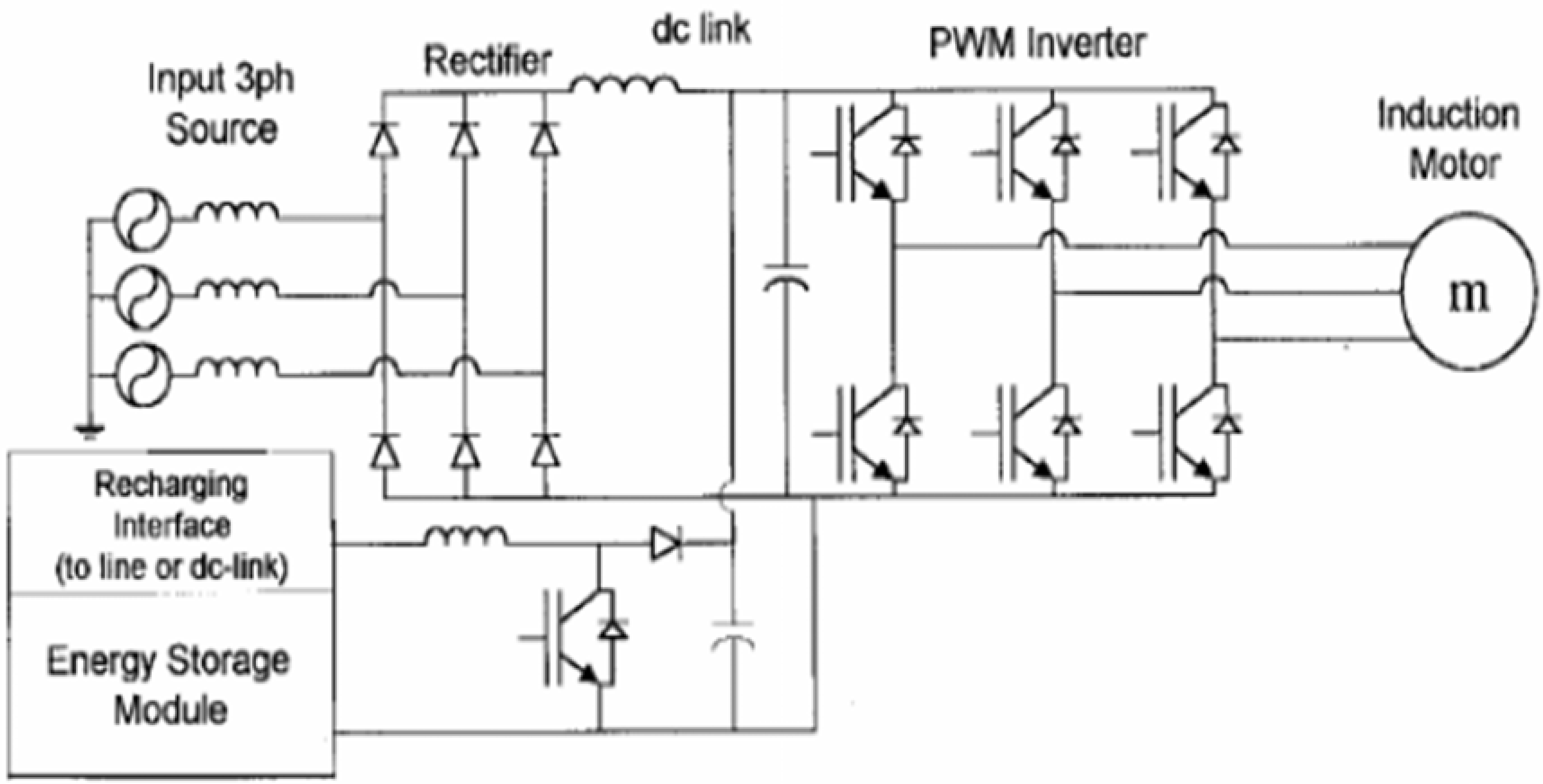
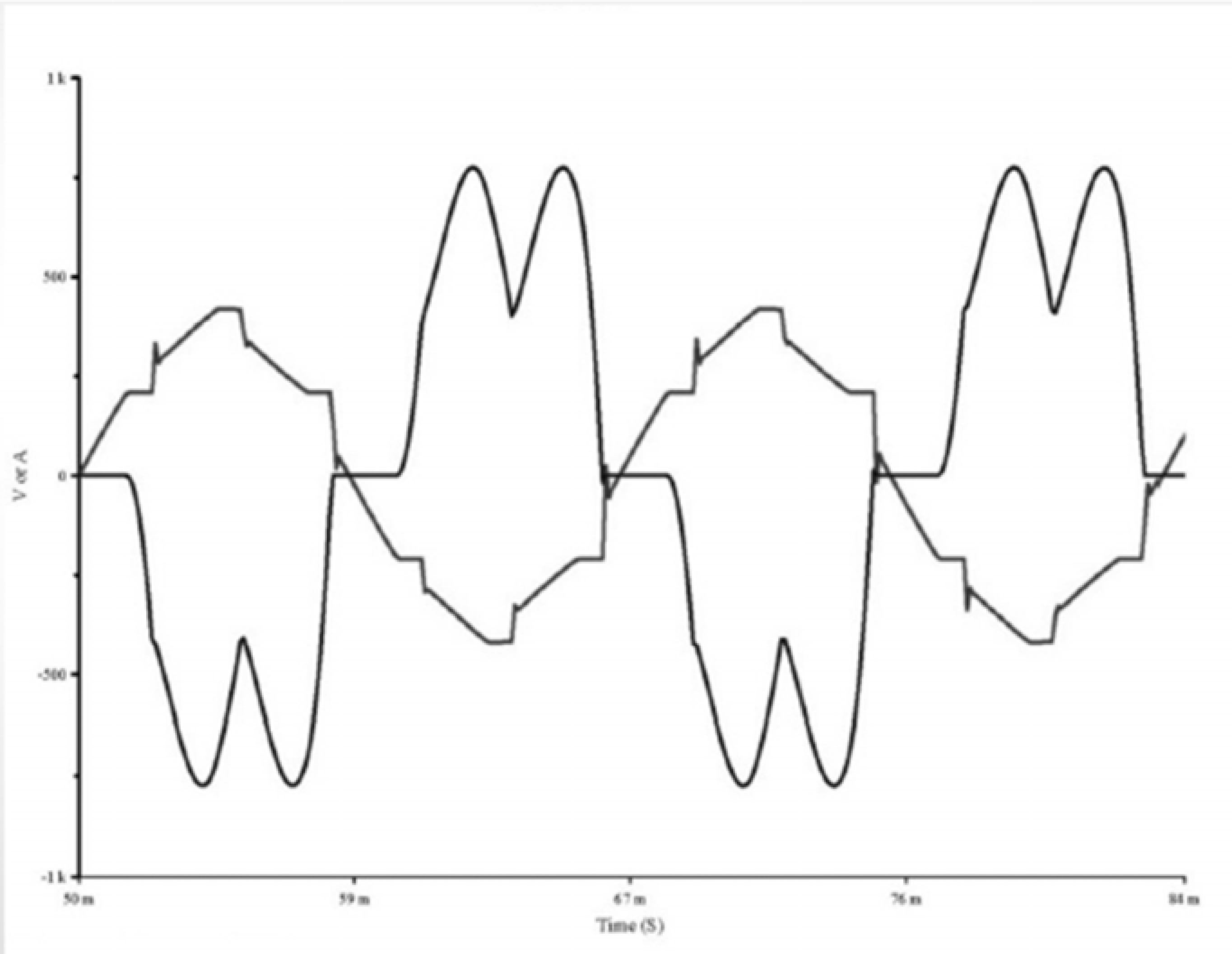


Figure 2. 2 General schematic diagram for energy storage device to increase the ride-through capability of ASD.

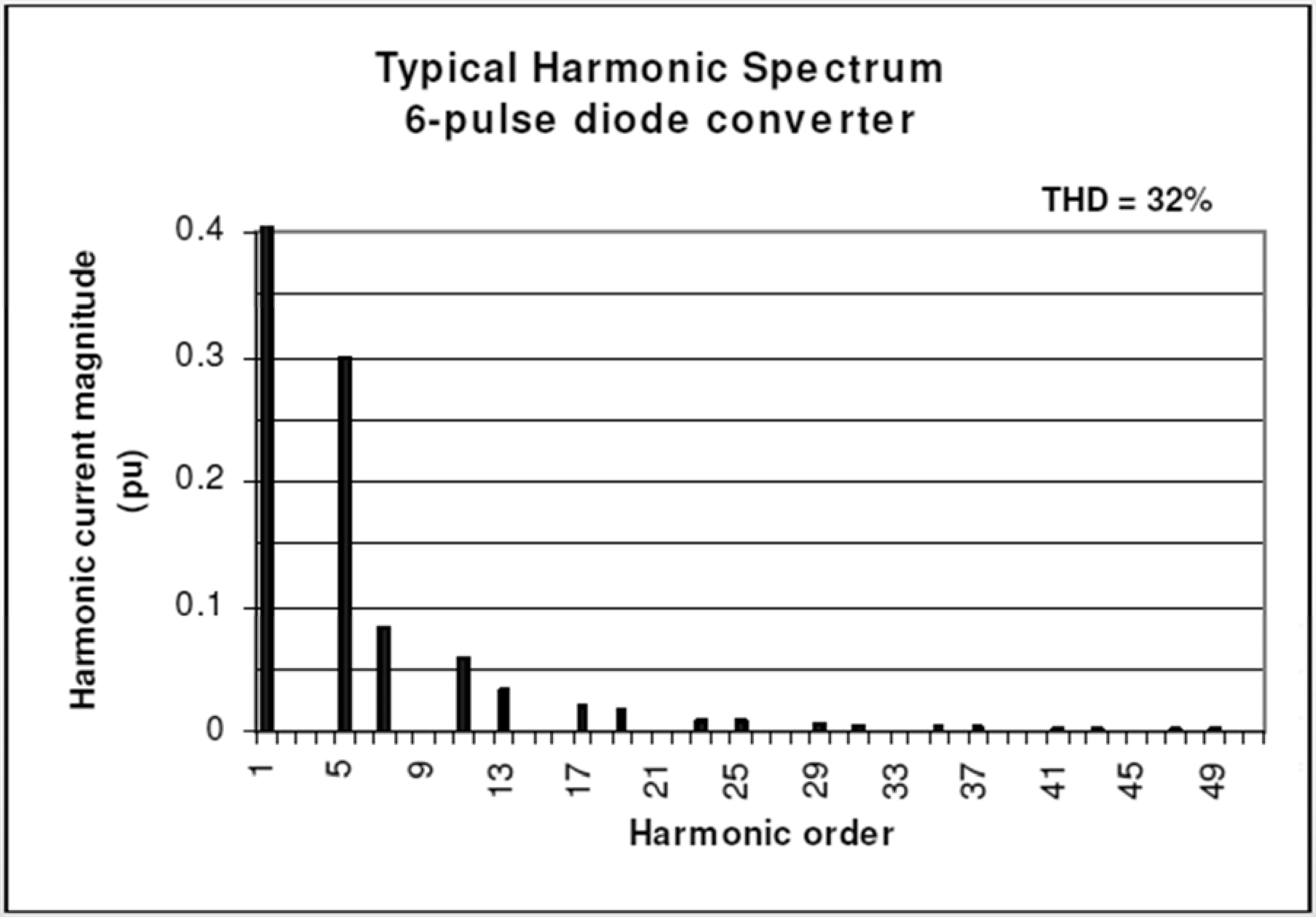
6 pulse waveform seen by utility



Blue: Current

Red: Voltage

Note: Current inverted to separate waveforms


Typical Harmonic Spectrum
6-pulse diode converter
THD = 32%
Harmonic current magnitude (pu)
0.4
0.3
0.2
0.1
0
1
5
9
13
17
21
25
29
33
37
41
45
49
Harmonic order

Controller (the VFD)

- VSI drives provide higher power factor and lower harmonic distortion than phase-controlled current-source inverter (CSI) and load-commutated inverter (LCI) drives.
- The drive controller can also be configured as a phase converter having single-phase converter input and three-phase inverter output.

Controller (the VFD)

- Controller advances have exploited dramatic increases in the voltage and current ratings and switching frequency of solid state power devices over the past six decades.
- Introduced in 1983, the insulated-gate bipolar transistor (IGBT) has in the past two decades come to dominate VFDs as an inverter switching device.

Controller (the VFD)

- In variable-torque applications suited for Volts per Hertz (V/Hz) drive control,

- AC motor characteristics require that the voltage magnitude of the inverter's output to the motor be adjusted to match the required load torque in a linear V/Hz relationship.

Controller (the VFD)

- For example, for 460 volt, 60 Hz motors this linear V/Hz relationship is 460/60 = 7.67 V/Hz.

- While suitable in wide ranging applications, V/Hz control is sub-optimal in high performance applications involving
  – low speed or demanding,
  – dynamic speed regulation,
  – positioning and reversing load requirements.

Controller (the VFD)

- Some V/Hz control drives can also operate in quadratic V/Hz mode or can even be programmed to suit special multi-point V/Hz paths.

Controller (the VFD)

- The two other drive control platforms,
- vector control and
- direct torque control (DTC),
- adjust the motor
  - voltage magnitude, angle from reference and frequency
  - such as to precisely control the motor's magnetic flux and mechanical torque.

Controller (the VFD)

- Although space vector pulse-width modulation (SVPWM) is becoming increasingly popular,
-
- sinusoidal PWM (SPWM) is the most straightforward method used to vary drives' motor voltage (or current) and frequency.

- With SPWM control, quasi-sinusoidal, variable-pulse-width output is constructed from intersections of a saw-toothed carrier frequency signal with a modulating sinusoidal signal which is variable in operating frequency as well as in voltage (or current).

Controller (the VFD)

- Operation of the motors above rated nameplate speed (base speed) is possible, but is limited to conditions that do not require more power than the nameplate rating of the motor.

- This is sometimes called "field weakening" and, for AC motors, means operating at less than rated V/Hz and above rated nameplate speed.

Controller (the VFD)

- Permanent magnet synchronous motors have quite limited field weakening speed range due to the constant magnet flux linkage.

- Wound rotor synchronous motors and induction motors have much wider speed range.

Controller (the VFD)

- For example,
- a 100 hp, 460 V, 60 Hz, 1775 RPM (4 pole) induction motor

- supplied with 460 V, 75 Hz (6.134 V/Hz),
- 460V/75Hz = 6.134 V/Hz

- would be limited to 60/75 = 80% torque at 125% speed (2218.75 RPM) = 100% power.

Controller (the VFD)

- At higher speeds the induction motor torque has to be limited further due to the lowering of the breakaway torque of the motor.

- Thus rated power can be typically produced only up to 130...150% of the rated nameplate speed.

Controller (the VFD)

- Wound rotor synchronous motors can be run at even higher speeds.
- In rolling mill drives often 200...300% of the base speed is used.
- The mechanical strength of the rotor limits the maximum speed of the motor.

Controller (the VFD)

- An embedded microprocessor governs the overall operation of the VFD controller.
- Basic programming of the microprocessor is provided as user inaccessible firmware.
- User programming of display, variable and function block parameters is provided to control, protect and monitor the VFD, motor and driven equipment.

Controller (the VFD)

- The basic drive controller can be configured to selectively include such optional power components and accessories as follows:

- Connected upstream of converter
  - circuit breaker or
  - Fuses
  - isolation contactor
  - EMC filter
  - line reactor
  - passive filter

Controller (the VFD)

- Connected to DC link
  - braking chopper
  - braking resistor

- Connected downstream of inverter
  - output reactor
  - sine wave filter
  - dV/dt filter.

Operator interface

- The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed.
- Additional operator control functions might include reversing, and switching between manual speed adjustment and automatic control from an external process control signal.

Operator interface

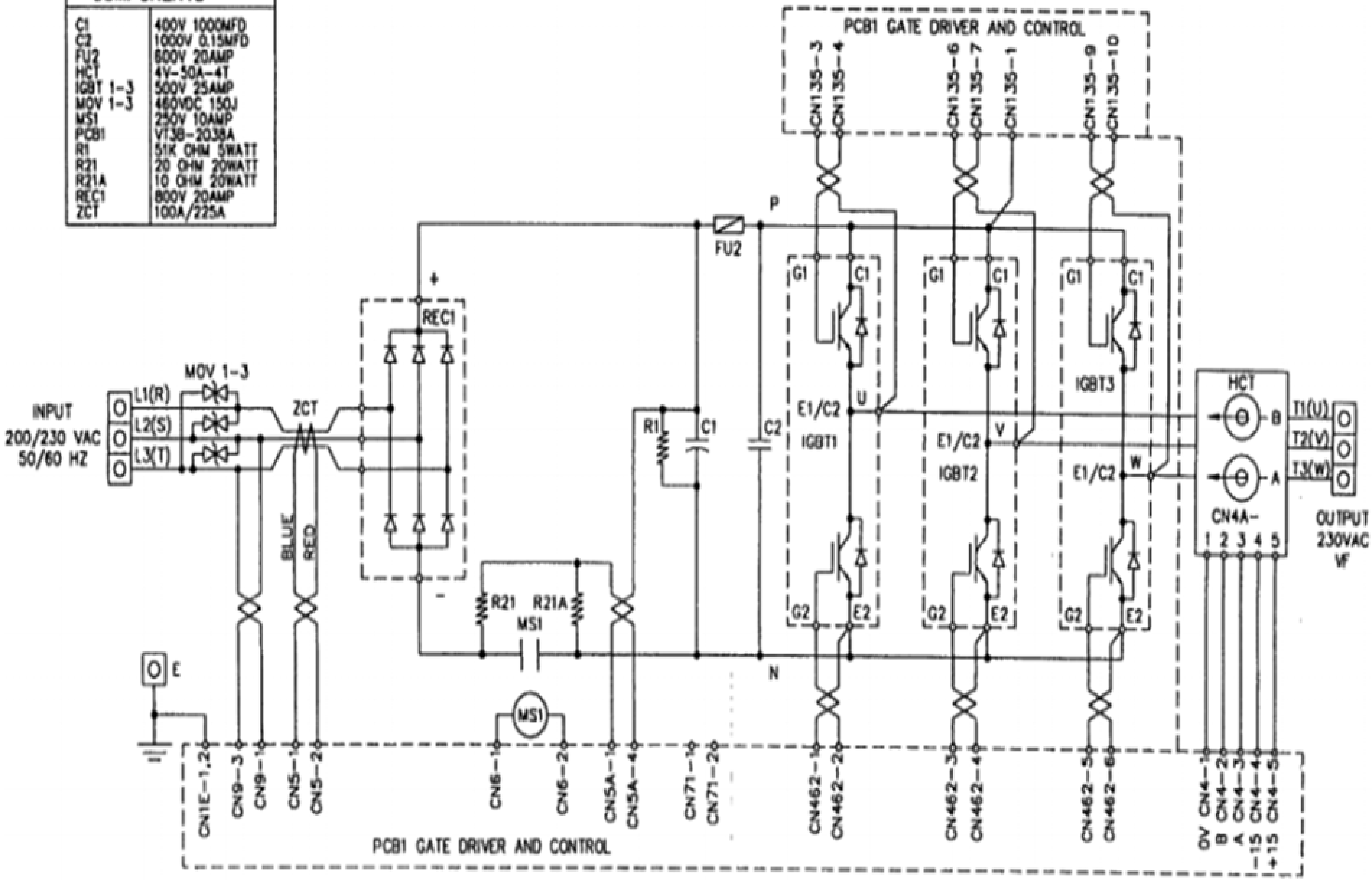
- The operator interface often includes an alphanumeric display and/or indication lights and meters to provide information about the operation of the drive.
- An operator interface keypad and display unit is often provided on the front of the VFD controller as shown in the photograph above.
- The keypad display can often be cable-connected and mounted a short distance from the VFD controller.

Operator interface

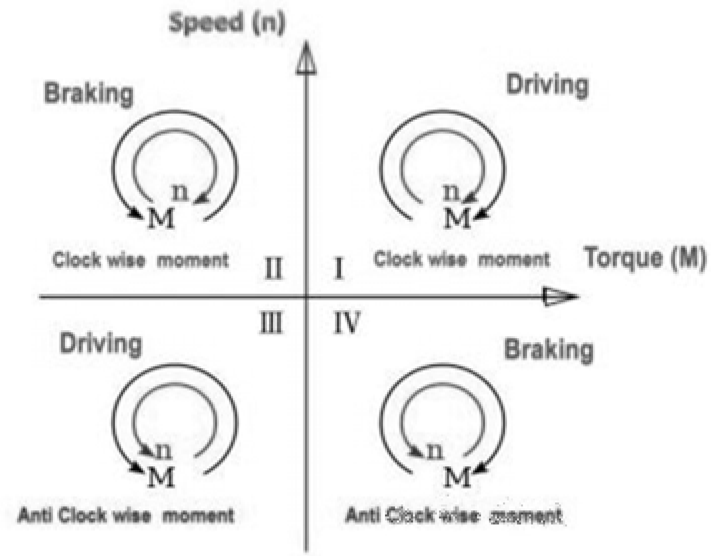
- Most are also provided with input_and output (I/O) terminals for connecting pushbuttons, switches and other operator interface devices or control signals.

- A serial communications port is also often available to allow the VFD to be configured, adjusted, monitored and controlled using a computer

COMPONENTS	
C1	400V 1000MFD
C2	1000V 0.15MFD
FU2	600V 20AMP
HCT	4V-50A-4T
IGBT 1-3	500V 25AMP
MOV 1-3	460VDC 150J
MS1	250V 10AMP
PCB1	VT3B-2038A
R1	51K OHM 5WATT
R21	20 OHM 20WATT
R21A	10 OHM 20WATT
REC1	800V 20AMP
ZCT	100A/225A



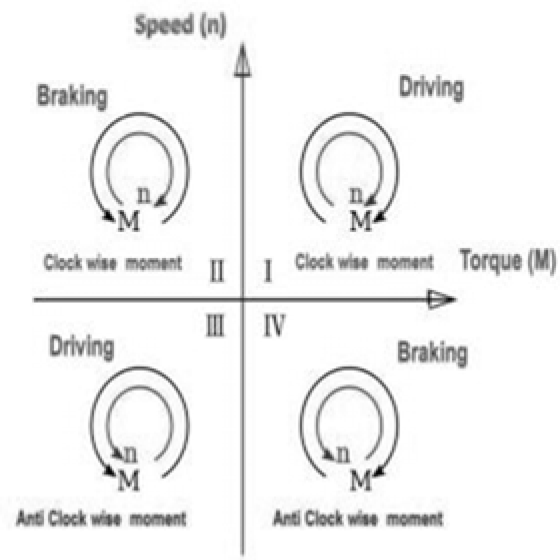
Drive operation



- Drive applications can be categorized as single-quadrant, two-quadrant or four-quadrant; the chart's four quadrants are defined as follows:
- Quadrant I - ***Driving or motoring***, *forward* accelerating quadrant with positive speed and torque
- Quadrant II - ***Generating or braking***, forward braking-decelerating quadrant with positive speed and negative torque
- Quadrant III - ***Driving or motoring***, *reverse* accelerating quadrant with negative speed and torque
- Quadrant IV - **Generating or braking**, *reverse* braking-decelerating quadrant with negative speed and positive torque.

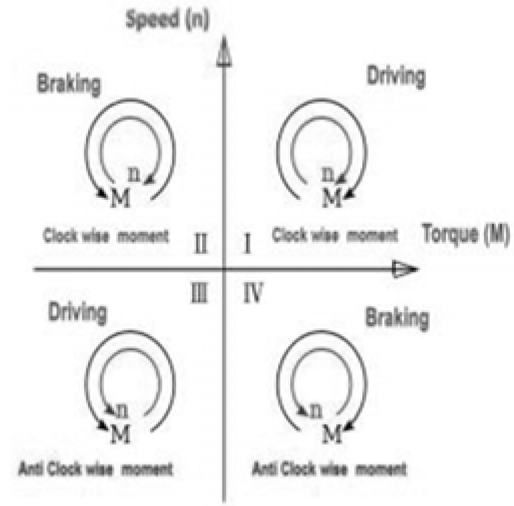
Drive operation

- Most applications involve single-quadrant loads operating in quadrant I, such as in variable-torque (e.g. centrifugal pumps or fans) and certain constant-torque (e.g. extruders) loads.



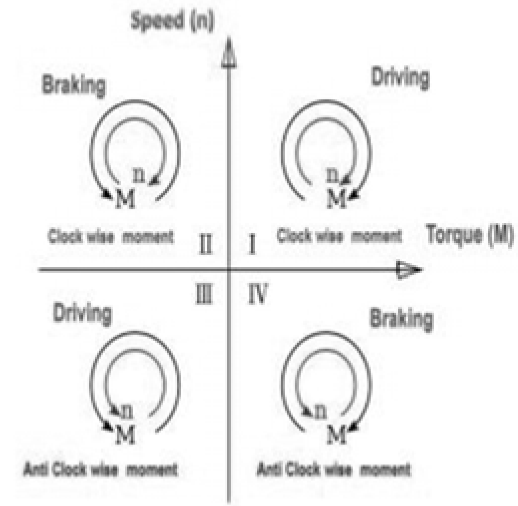
Drive operation

- Certain applications involve two-quadrant loads operating in quadrant I and II where the speed is positive but the torque changes polarity as in case of a fa decelerating faster than natural mechanical losses.
- Some sources define two-quadrant drives as loads operating in quadrants I and III where the speed and torque is same (positive or negative) polarity in both directions.



Drive operation

- Certain high-performance applications involve four-quadrant loads (Quadrants I to IV) where the speed and torque can be in any direction such as in hoists, elevators and hilly conveyors.
- Regeneration can only occur in the drive's DC link bus when inverter voltage is smaller in magnitude than the motor back-EMF and inverter voltage and back-EMF are the same polarity.



Drive operation

- In starting a motor, a VFD initially applies a low frequency and voltage, thus avoiding high inrush current associated with direct on line starting.

- After the start of the VFD, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load.

- This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low speed range.

Drive operation

- A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed.

- However, motor cooling deteriorates and can result in overheating as speed decreases such that prolonged low speed motor operation with significant torque is not usually possible without separately-motorized fan ventilation.

Drive operation

- With a VFD, the stopping sequence is just the opposite as the starting sequence.

- The frequency and voltage applied to the motor are ramped down at a controlled rate.

- When the frequency approaches zero, the motor is shut off.

Drive operation

- A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast.

- Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy.

- With a four-quadrant rectifier (active-front-end), the VFD is able to brake the load by applying a reverse torque and injecting the energy back to the AC line.

Energy savings

- Many fixed-speed motor load applications that are supplied direct from AC line power can save energy when they are operated at variable-speed, by means of VFD.

- Such energy cost savings are especially pronounced in variable-torque centrifugal fan and pump applications, where the loads' torque and power vary with the square and cube, respectively, of the speed.

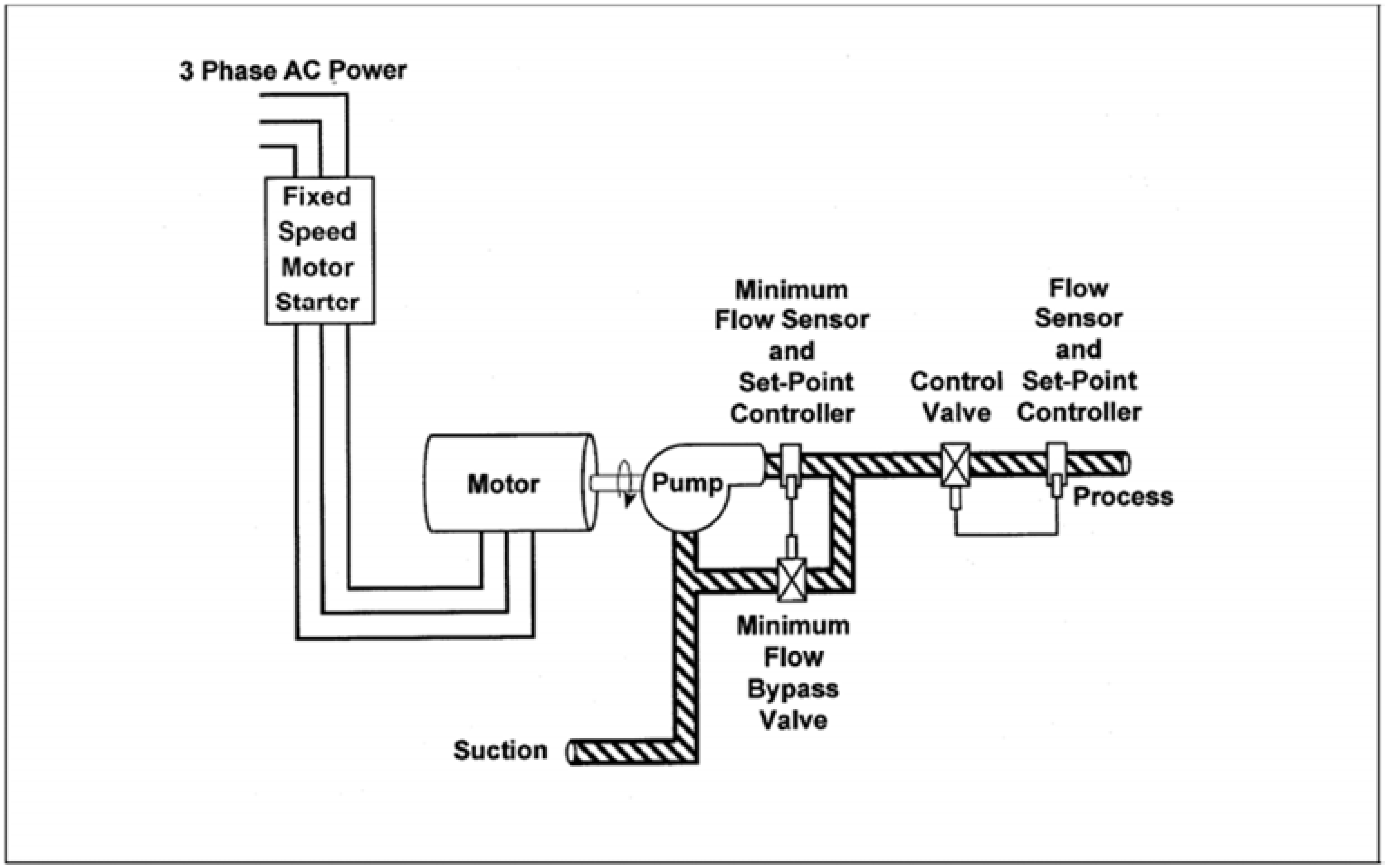
Energy savings

- This change gives a large power reduction compared to fixed-speed operation for a relatively small reduction in speed.

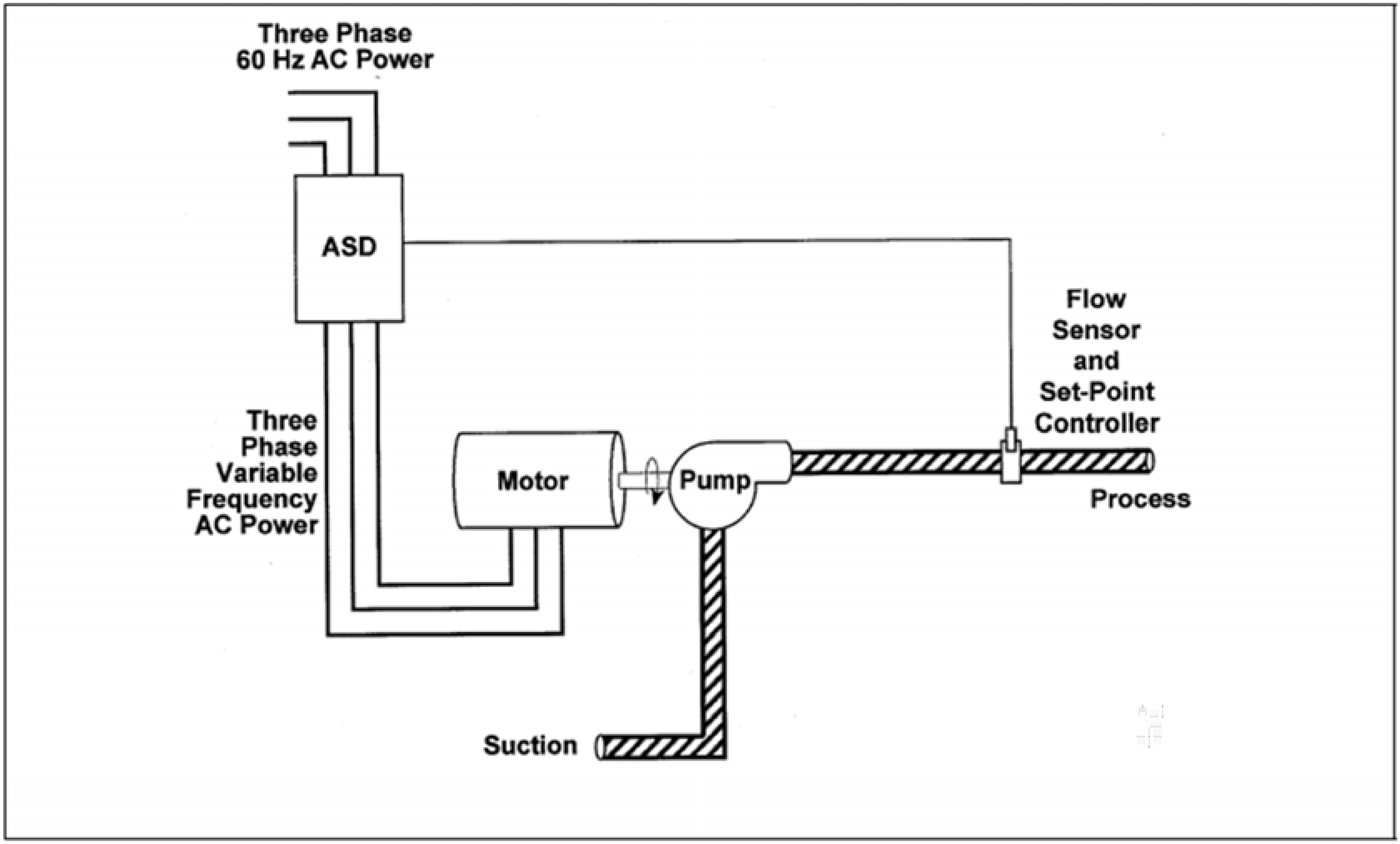
- For example, at 63% speed a motor load consumes only 25% of its full speed power.

- This is in accordance with affinity laws that define the relationship between various centrifugal load variables.

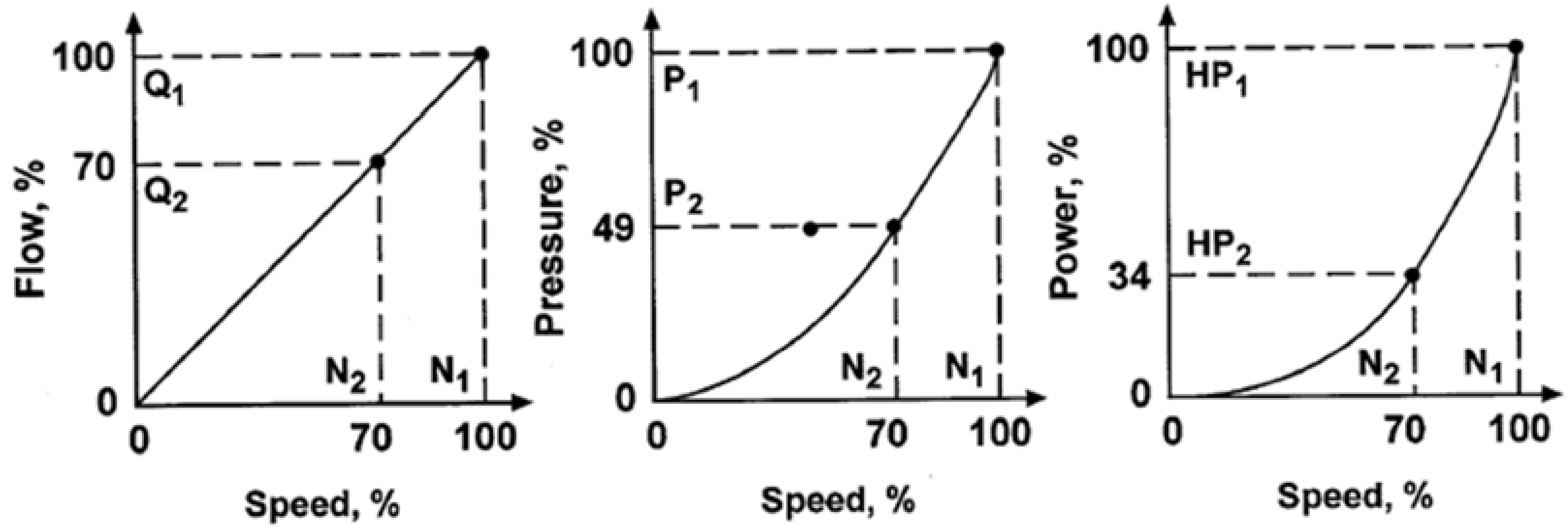
Simplified Fixed Speed Pump System Using Control Valves



Typical ASD Controlled Pump System



Affinity Laws for Centrifugal Equipment



$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}$$

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^2$$

$$\frac{HP_2}{HP_1} = \left(\frac{N_2}{N_1}\right)^2$$

N = Speed
Q = Flow
P = Pressure
HP = Horsepower

- In practice, this degree of power reduction does not occur because the system static head and losses require the motor to operate at a speed greater than 60 percent to provide 60 percent flow.

Energy savings

- In the United States, an estimated 60-65% of electrical energy is used to supply motors, 75% of which are variable torque fan, pump and compressor loads.

- Eighteen percent of the energy used in the 40 million motors in the U.S. could be saved by efficient energy improvement technologies such as VFDs.

Energy savings

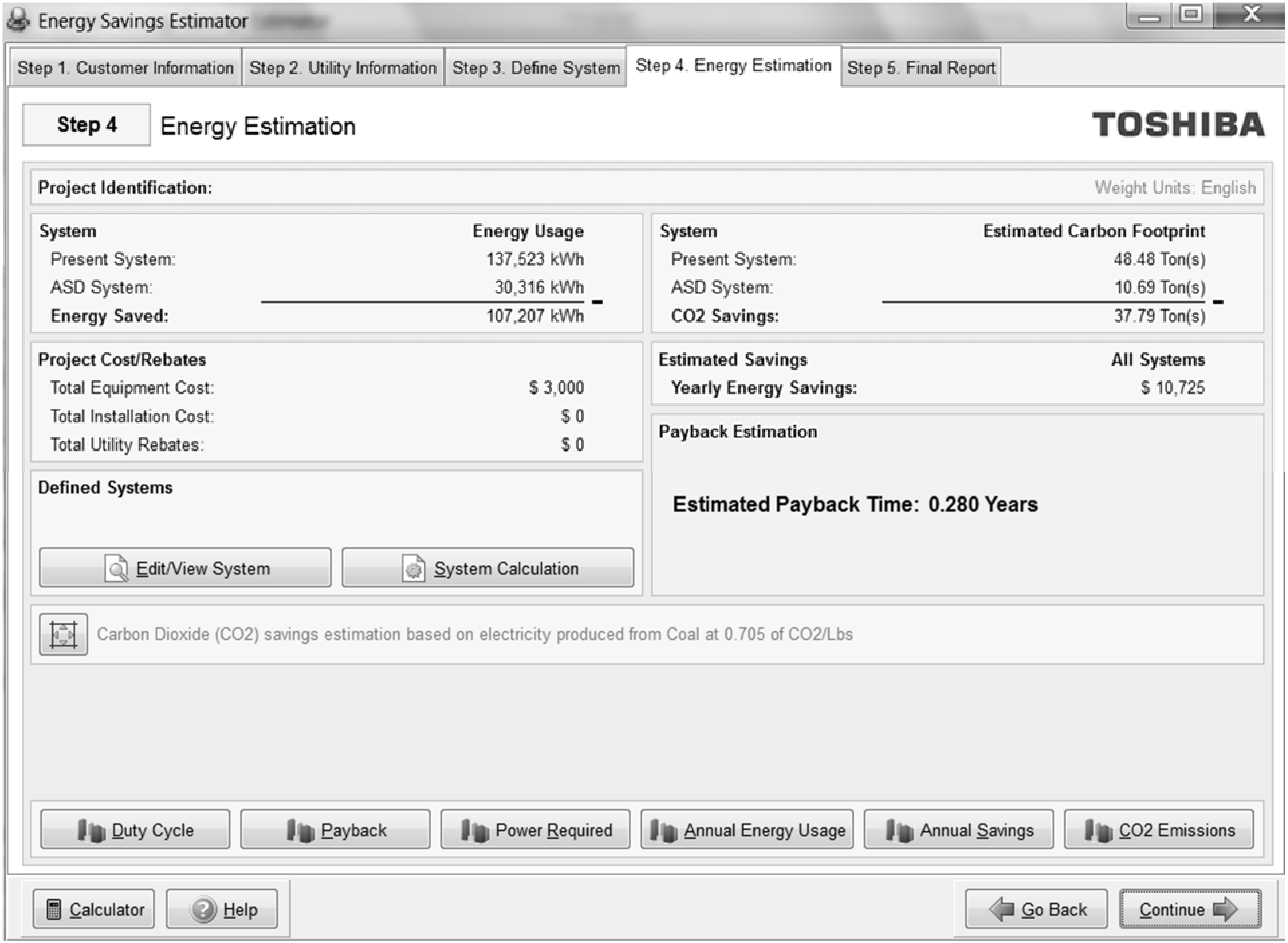
- Only about 3% of the total installed base of AC motors are provided with AC drives.
- However, it is estimated that drive technology is adopted in as many as 30-40% of all newly installed motors.

Energy savings

- An energy consumption breakdown of the global population of AC motor installations is as shown in the following table:

	Small	General Purpose - Medium-Size	Large
Power	10W to 750W	750W to 375 kW	375 kW to 100MW
Phase, voltage	1-ph., <240V	3-ph., 200V to 1kV	3-ph., 1kV to 20kV
% total motor energy	9%	68%	23%
Total stock	2 billion	230 million	0.6 million

Energy Savings Estimator
Step 1. Customer Information
Step 2. Utility Information
Step 3. Define System
Step 4. Energy Estimation
Step 5. Final Report
Step 3
System Information
TOSHIBA
System Data
Name:
Type: Fan
Flow Control: None (Across-the-Line)
Motor Data
Efficiency: 95.0 %
Power: 20.0 HP
Adjustable Speed Drive Data
Drive Cost: $ 3000
Install Cost: $ 0
Systems: 1
Q7
HVAC
TOSHIBA
Leading Innovation >>>
Duty Cycle
Alt. Flow Time
100 % 1 %
90 % 2 %
80 % 9 %
70 % 17 %
60 % 24 %
50 % 17 %
40 % 13 %
30 % 11 %
20 % 6 %
10 % 0 %
+
100%
Duty Cycle
Time (%)
0 2 4 6 8 10 12 14 16 18 20 22 24
Flow (%)
0 10 20 30 40 50 60 70 80 90 100
Restore
Graph
Hours of Operation
1 Hours per Day: 24 Hours
2 Days per Week: 7 Days
Weeks per Year: 52 Weeks
Incentive
Utility Incentive: 0.0 $/HP
One-time
Yearly
Calculator
Help
Go Back
Continue


Energy Savings Estimator
Step 1. Customer Information
Step 2. Utility Information
Step 3. Define System
Step 4. Energy Estimation
Step 5. Final Report
Step 4
Energy Estimation
TOSHIBA
Project Identification:
Weight Units: English
System
Energy Usage
Present System: 137,523 kWh
ASD System: 30,316 kWh
Energy Saved: 107,207 kWh
System
Estimated Carbon Footprint
Present System: 48.48 Ton(s)
ASD System: 10.69 Ton(s)
CO2 Savings: 37.79 Ton(s)
Project Cost/Rebates
Total Equipment Cost: $ 3,000
Total Installation Cost: $ 0
Total Utility Rebates: $ 0
Estimated Savings
All Systems
Yearly Energy Savings: $ 10,725
Payback Estimation
Estimated Payback Time: 0.280 Years
Defined Systems
Edit/View System
System Calculation
Carbon Dioxide (CO2) savings estimation based on electricity produced from Coal at 0.705 of CO2/Lbs
Duty Cycle
Payback
Power Required
Annual Energy Usage
Annual Savings
CO2 Emissions
Calculator
Help
Go Back
Continue

Control performance

- AC drives are used to bring about process and quality improvements in industrial and commercial applications‘
  - Acceleration
  - Flow
  - Monitoring
  - Pressure
  - Speed
  - Temperature
  - Tension and
  - Torque.

Control performance

- Fixed-speed operated loads subject the motor to a high starting torque and to current surges that are up to eight times the full-load current.

- AC drives instead gradually ramp the motor up to operating speed to lessen mechanical and electrical stress, reducing maintenance and repair costs, and extending the life of the motor and the driven equipment.

Control performance

- Variable speed drives can also run a motor in specialized patterns to further minimize mechanical and electrical stress.

- For example, an S-curve pattern can be applied to a conveyor application for smoother deceleration and acceleration control, which reduces the backlash that can occur when a conveyor is accelerating or decelerating.

Control performance

- Performance factors tending to favor use of DC, over AC, drives include such requirements as
  - continuous operation at low speed
  - four-quadrant operation with regeneration
  - frequent acceleration and deceleration routines
  - and need for motor to be protected for hazardous area.

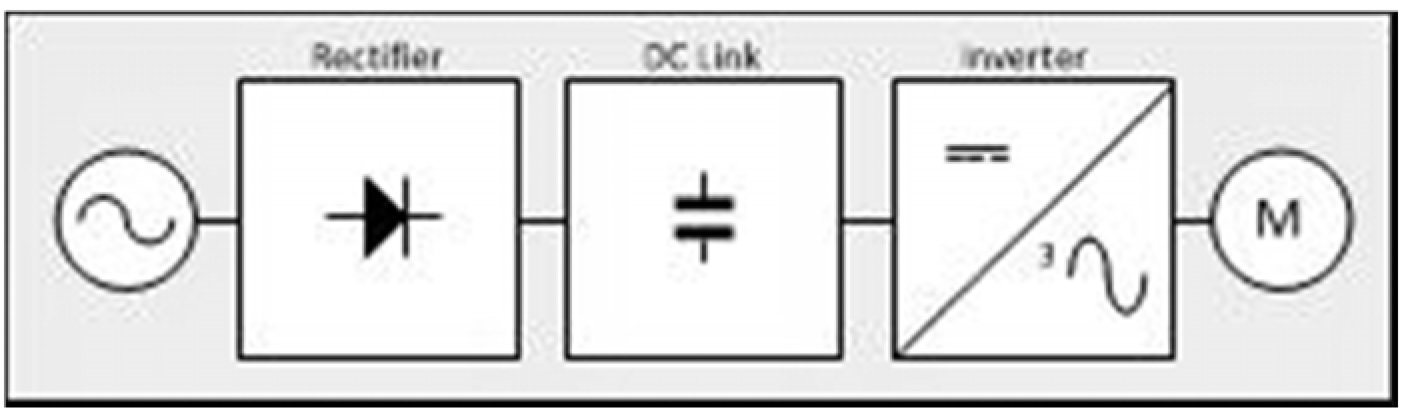
Control performance

- The following table compares AC and DC drives according to certain key parameters:

Drive type	DC	AC VFD	AC VFD	AC VFD	AC VFD
Control platform	Brush type DC	V/Hz control	Vector control	Vector control	Vector control
Control criteria	Closed-loop	Open-loop	Open-loop	Closed-loop	Open-loop w. HFI^
Motor	DC	IM	IM	IM	Interior PM
Typical speed regulation (%)	0.01	1	0.5	0.01	0.02
Typical speed range at constant torque (%)	0-100	10-100	3-100	0-100	0-100
Min. speed at 100% torque (% of base)	Standstill	8%	2%	Standstill	Standstill (200%)
Multiple-motor operation recommended	No	Yes	No	No	No
Fault protection (Fused only or inherent to drive)	Fused only	Inherent	Inherent	Inherent	Inherent
Maintenance	(Brushes)	Low	Low	Low	Low
Feedback device	Tachometer or encoder	N/A	N/A	Encoder	N/A

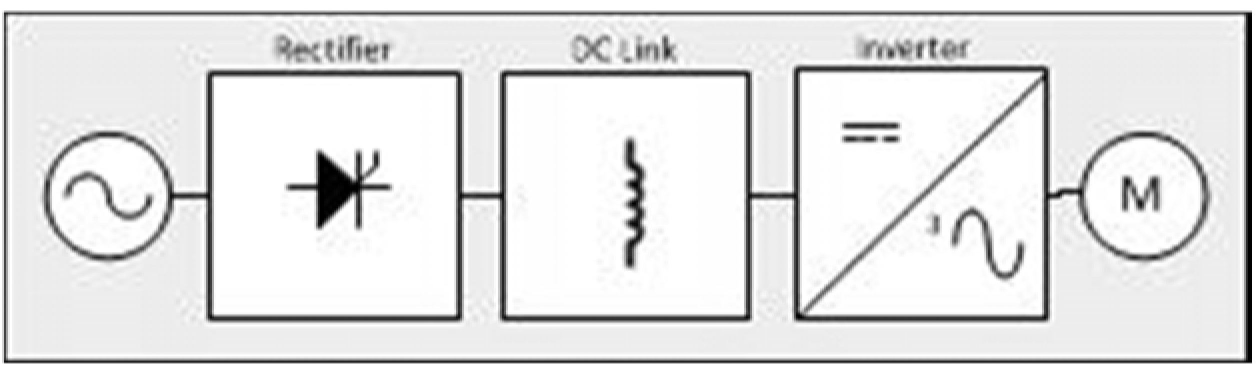
VFD types and ratings

- **Voltage-source inverter (VSI) drive topologies**: In a VSI drive, the DC output of the diode-bridge converter stores energy in the capacitor bus to supply stiff voltage input to the inverter. The vast majority of drives are VSI type with PWM voltage output.



VFD types and ratings

- **Current-source inverter (CSI) drive topologies**: In a CSI drive, the DC output of the SCR-bridge converter stores energy in series-reactor connection to supply stiff current input to the inverter. CSI drives can be operated with either PWM or six-step waveform output.

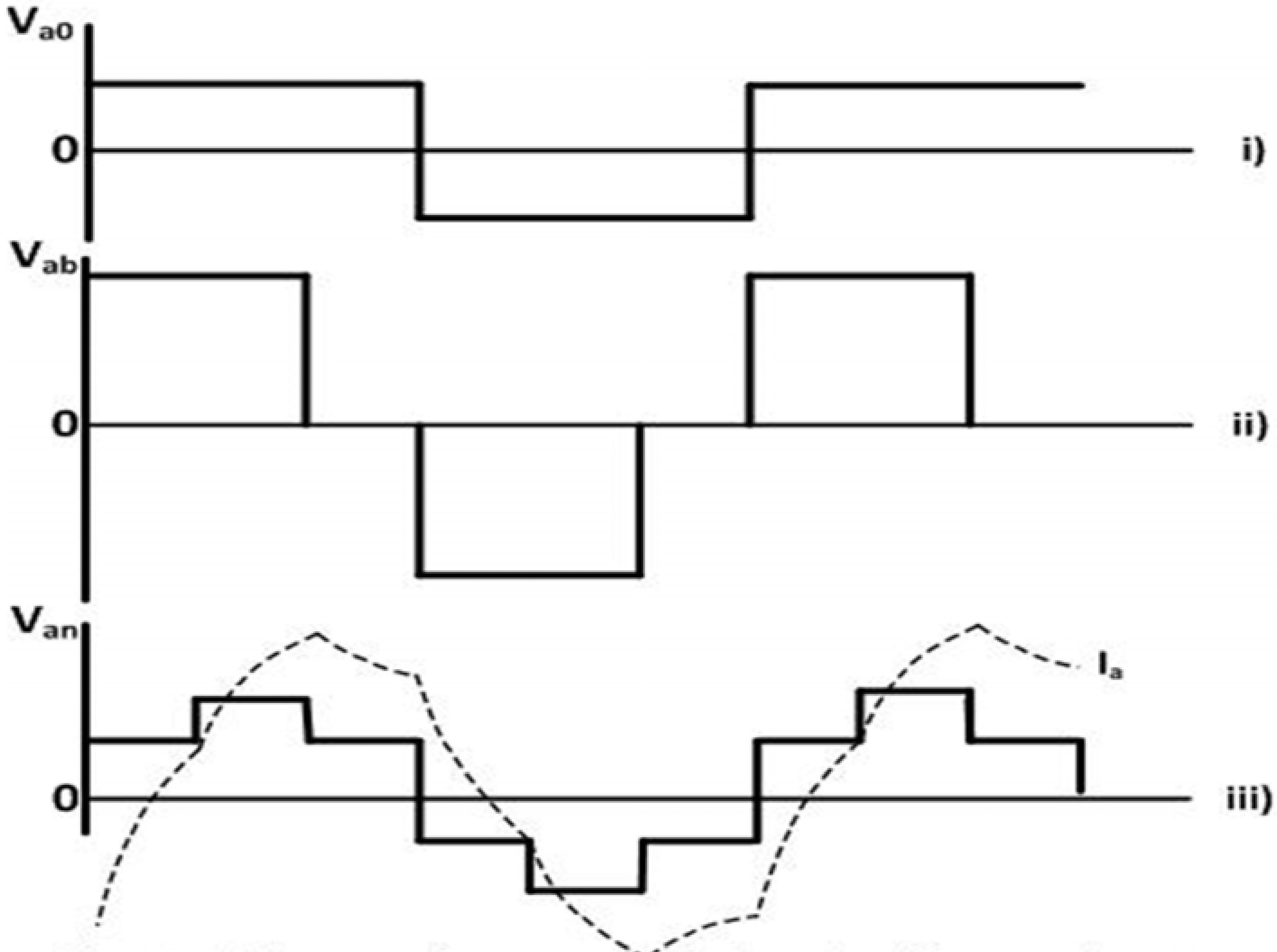


VFD types and ratings

- **Six-step inverter drive topologies**: Now largely obsolete, six-step drives can be either VSI or CSI type and are also referred to as
  - variable-voltage inverter drives
  - pulse-amplitude_modulation (PAM) drives
  - Square-wave drives or D.C. chopper inverter drives.

In a six-step drive, the DC output of the SCR-bridge converter is smoothed via capacitor bus and series-reactor connection to supply via Darlington
Pair or IGBT inverter quasi-sinusoidal, six-step voltage or current input to an induction motor

VFD types and ratings



Six-step drive waveforms per VSI phase leg: i) across inverter bridge, ii) line-to-line, and iii) line-to-neutral

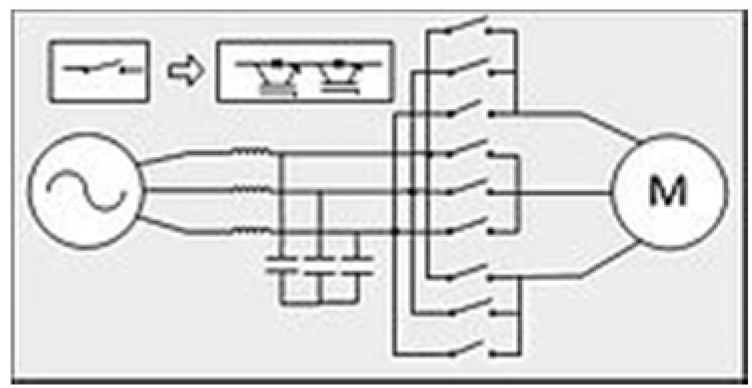
VFD types and ratings

- **Cycloconverter or matrix converter (MC) topologies** (see image): Cycloconverter and MCs are AC-AC *converters* that have no intermediate DC link for energy storage.

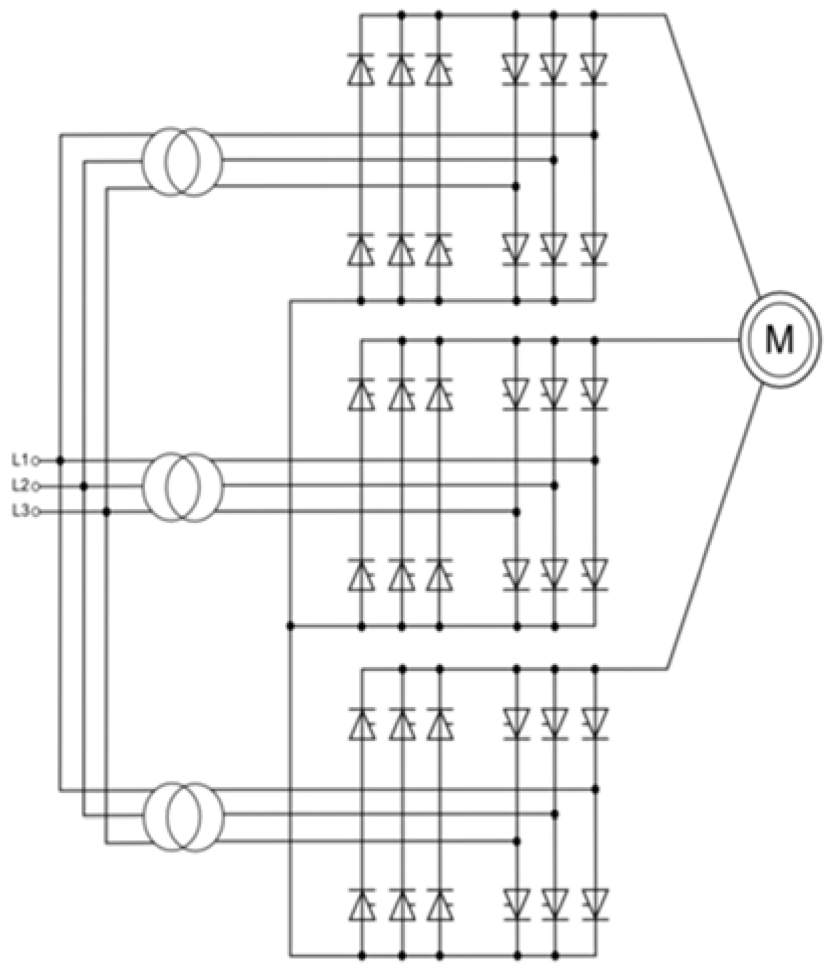
- A cycloconverter operates as a three-phase current source via three anti-parallel connected SCR-bridges in six-pulse configuration,

- each cycloconverter phase acting selectively to convert fixed line frequency AC voltage to an alternating voltage at a variable load frequency.

- MC drives are IGBT-based.

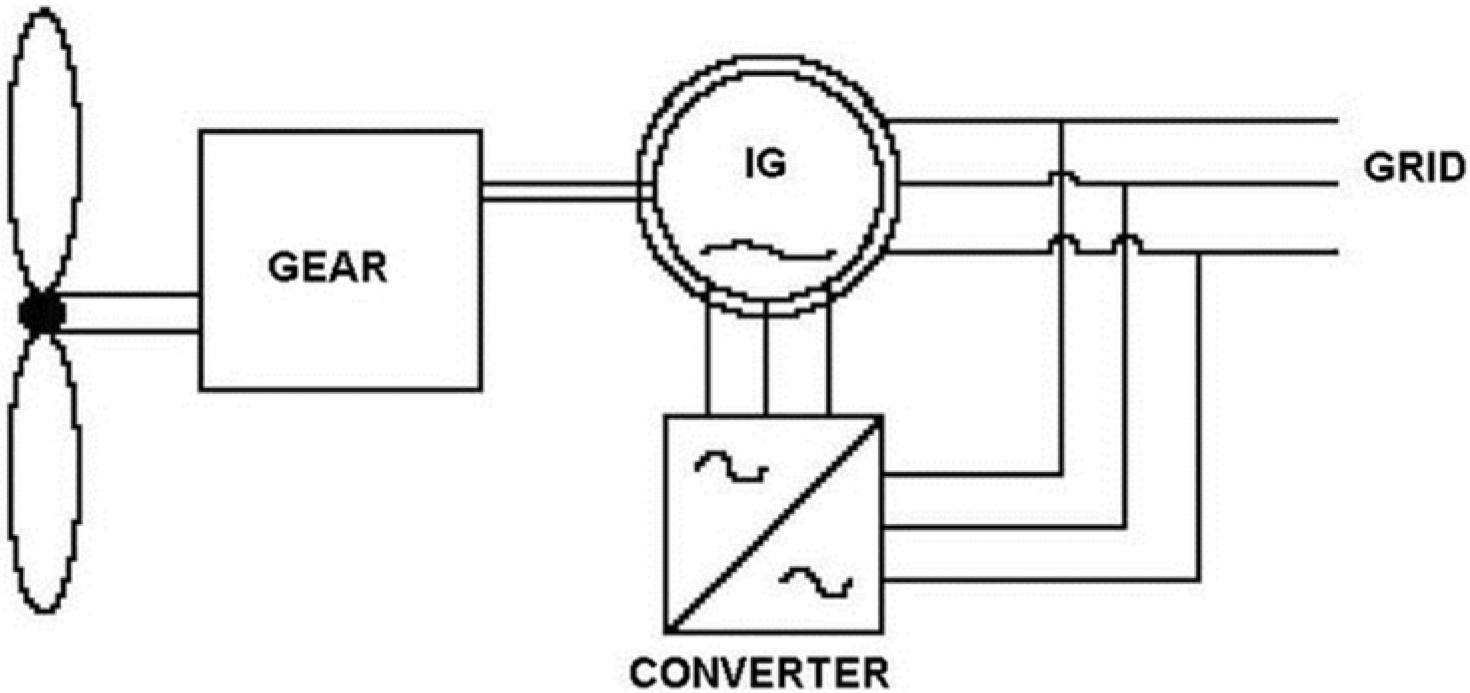


Cycloconverter



VFD types and ratings

- **Doubly fed slip recovery system topologies**: A doubly fed slip recovery system feeds rectified slip power to a smoothing reactor to supply power to the AC supply network via an inverter, the speed of the motor being controlled by adjusting the DC current.



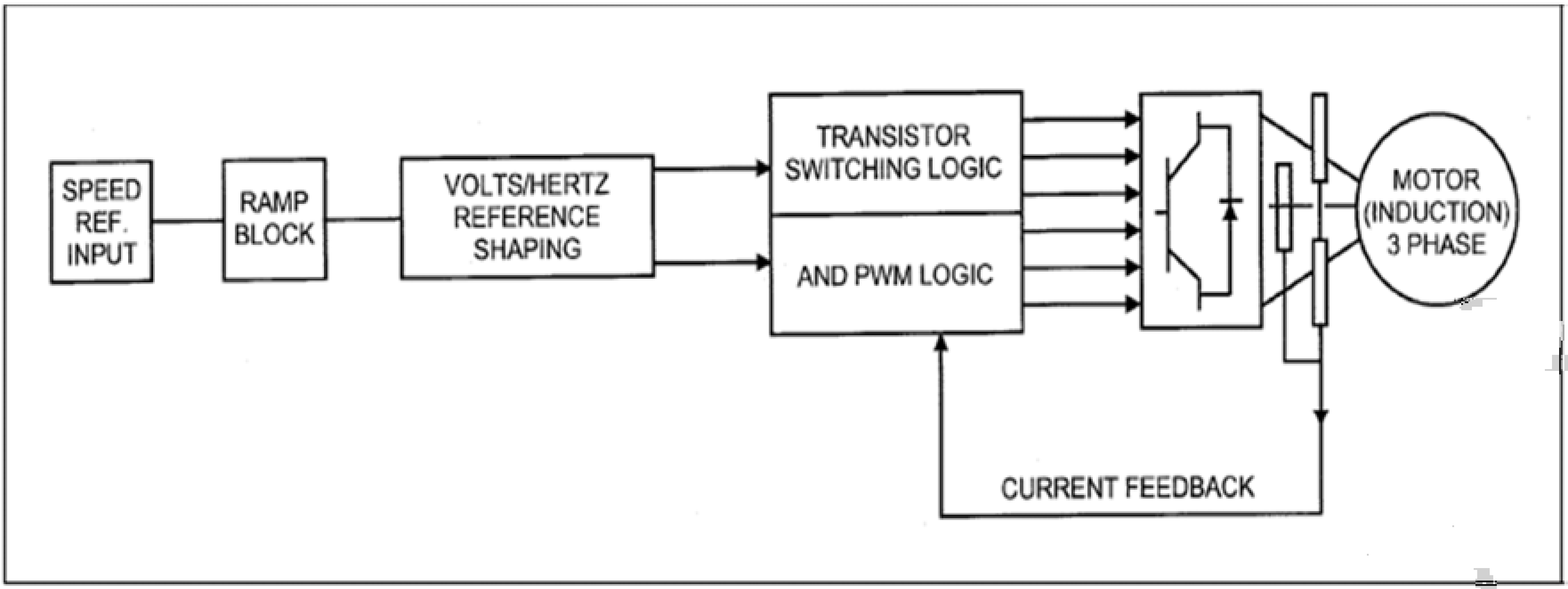
PRINCIPLE OF DFIG CONNECTED TO A WIND TURBINE

Doubly fed slip recovery system

Control platforms

- Most drives use one or more of the following control platforms:
  - PWM V/Hz scalar control
  - PWM field-oriented control (FOC) or vector control
  - Direct torque control (DTC).

Typical Volts/Hertz Control Block Diagram



Load torque and power characteristics

- Variable frequency drives are also categorized by the following load torque and power characteristics:
  - Variable torque, such as in centrifugal fan, pump and blower applications
  - Constant torque, such as in conveyor and displacement pump applications
  - Constant power, such as in machine tool and traction applications.

Available power ratings

- VFDs are available with voltage and current ratings covering a wide range of single-phase and multi-phase AC motors.

- Low voltage (LV) drives are designed to operate at output voltages equal to or less than 690 V.

- While motor-application LV drives are available in ratings of up to the order of 5 or 6 MW, economic considerations typically favor medium voltage (MV) drives with much lower power ratings.

Available power ratings

- Different MV drive topologies are configured in accordance with the voltage/current-combination ratings used in different drive controllers' switching devices such that any given voltage rating is greater than or equal to one to the following standard nominal motor voltage ratings:

- generally either
  - 2.3/4.16 kV (60 Hz) or
  - 3.3/6.6 kV (50 Hz),

- with one thyristor manufacturer rated for up to 12 kV switching.

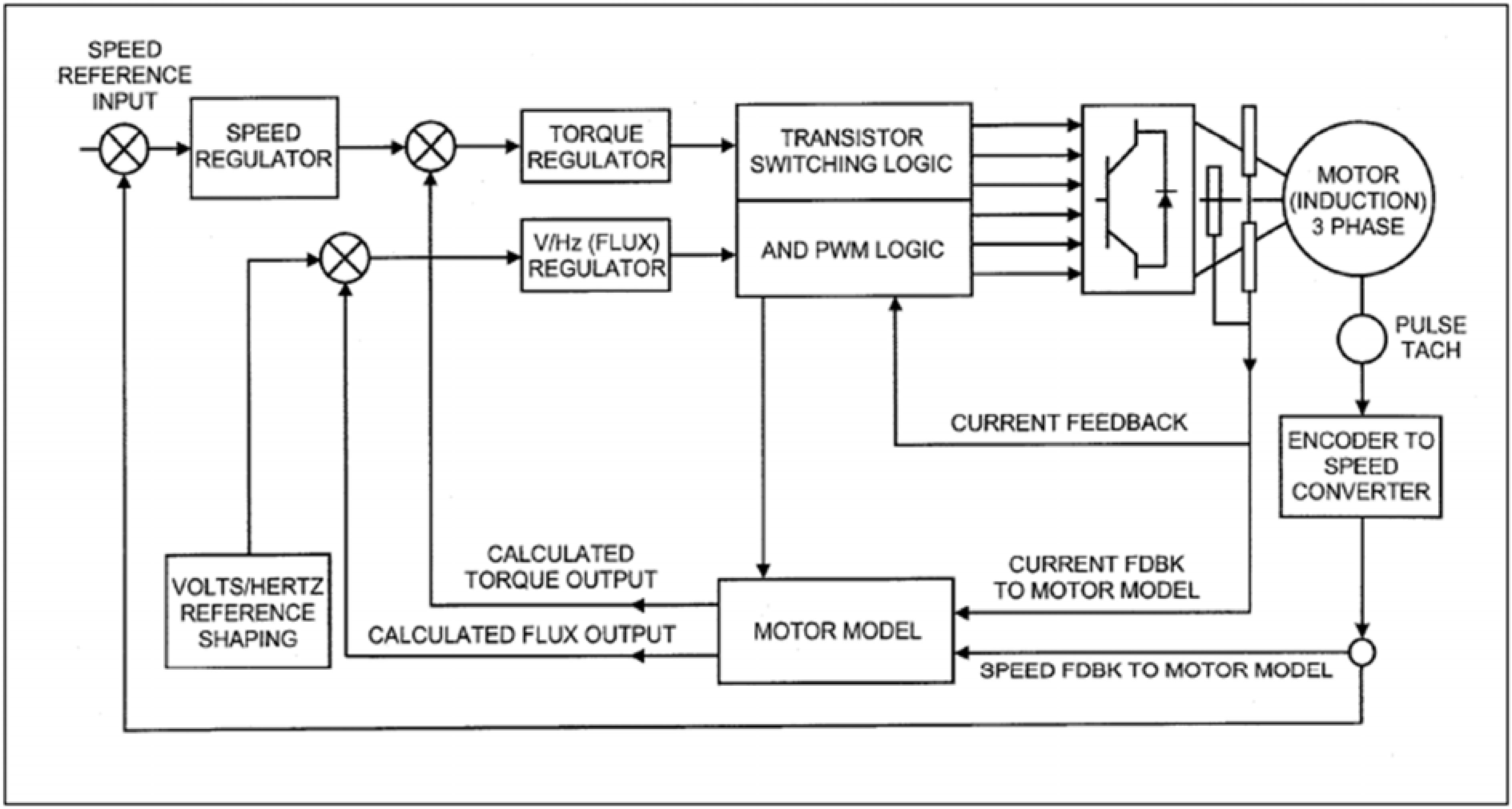
Available power ratings

- In some applications a step up transformer is placed between a LV drive and a MV motor load.
- MV drives are typically rated for motor applications greater than between about 375 kW (500 hp) and 750 kW (1000 hp).
- MV drives have historically required considerably more application design effort than required for LV drive applications.
- The power rating of MV drives can reach 100 MW, a range of different drive topologies being involved for different rating, performance, power quality and reliability requirements.

Typical Drive Voltage and HP Ratings

Drive Voltage	HP Range
460 and 575	up to 650
460 and 575 with Input & Output Transformers	600 - 2,500
2,400	650 - 5,000
4,160	650 - 20,000
6,900	10,000 - 30,000
13,800	25,000 - 50,000+

Flux Vector Control Scheme Block Diagram



Understanding Power Concepts

Part 3

- ***Motors***
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (*VFD* and **Harmonics**)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

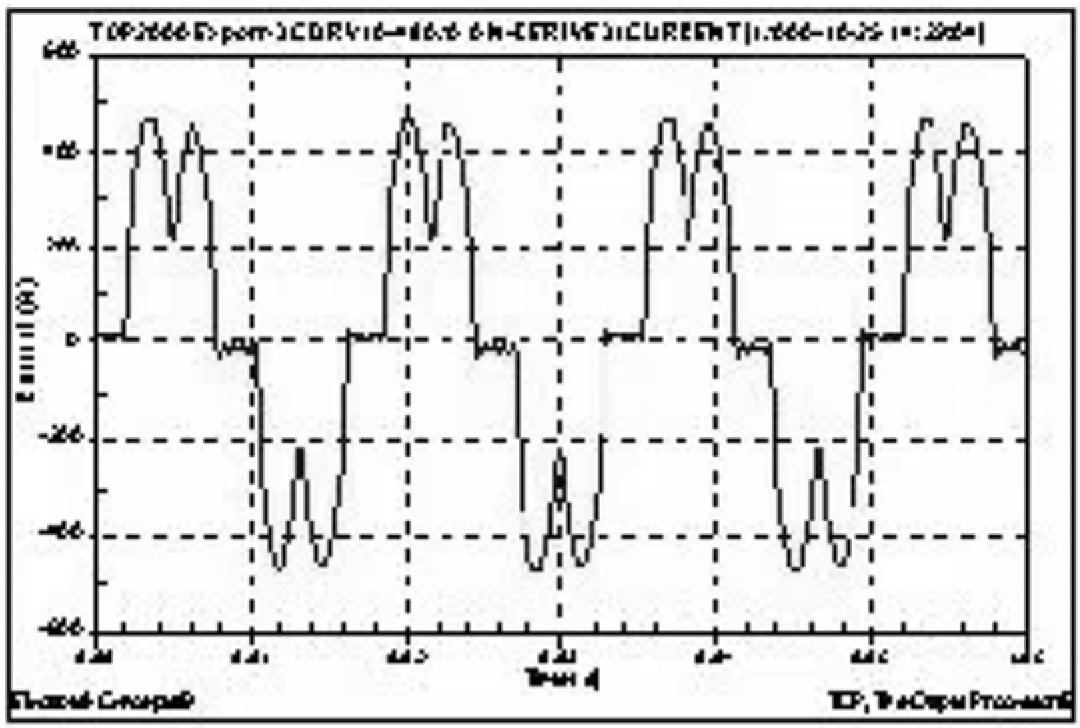
Application considerations

- It is very common practice for power companies or their customers to impose harmonic distortion limits based On IEC or IEEE standards.

- For example, IEEE Standard 519 limits at the customer's connection point call for the maximum individual frequency voltage harmonic to be no more than 3% of the fundamental and call for the voltage total harmonic distortion (THD) to be no more than 5% for a general AC power supply system.

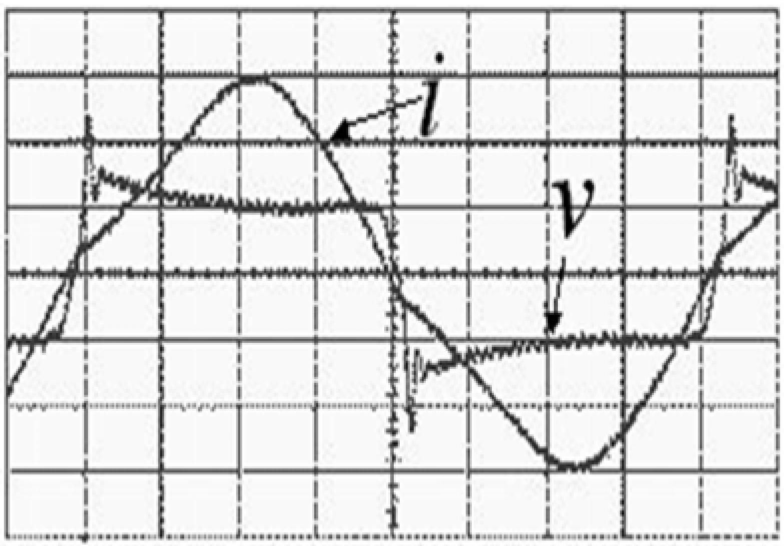
Harmonic

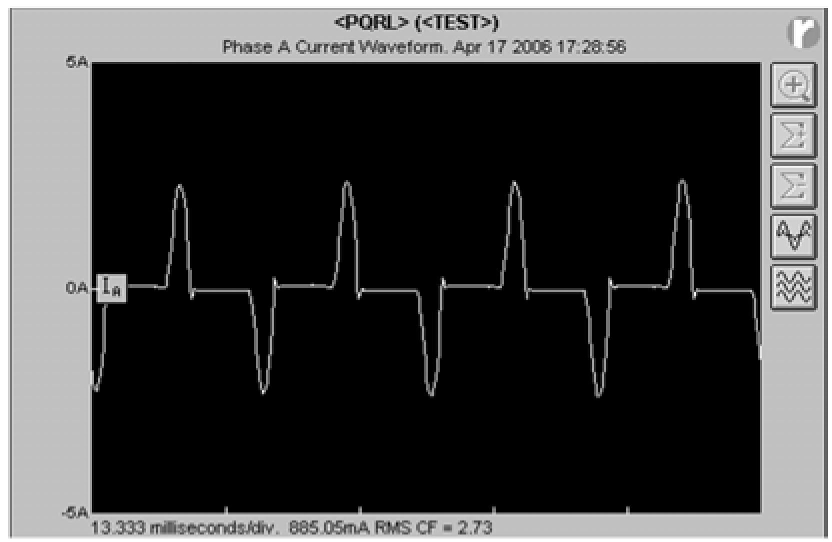
- Steady state distortion of the waveform
- Periodic and continuous in nature.



Harmonic Sources（nonlinear loads）

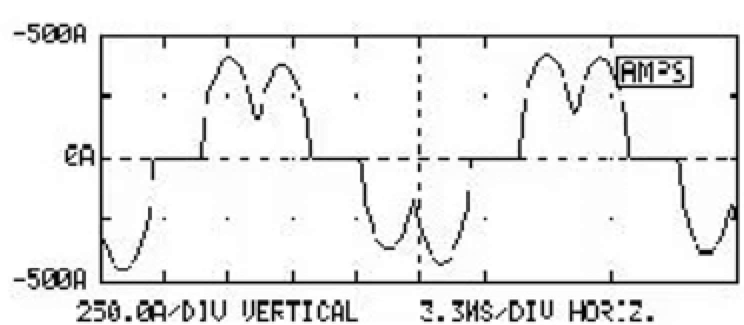
– Single-phase loads: fluorescent lights, personal computers
– Three-phase loads: arc furnaces, ac/dc converters

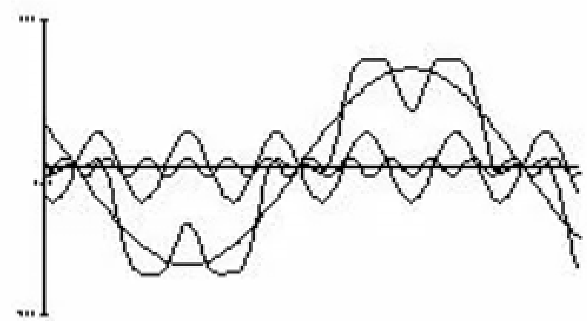




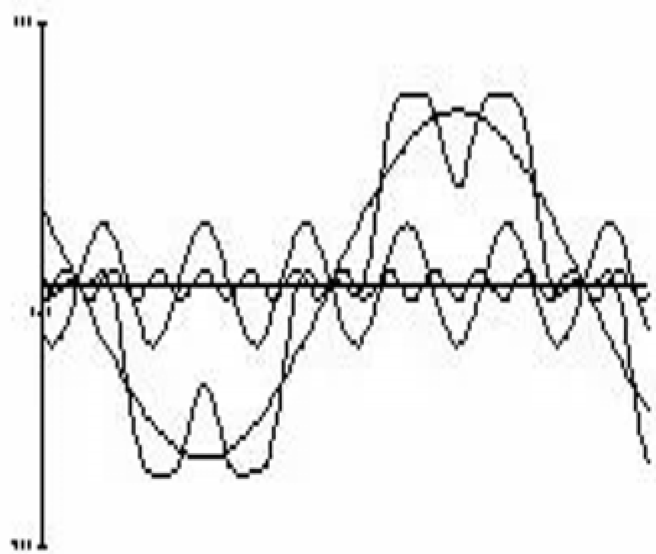
Basic Harmonic Principles

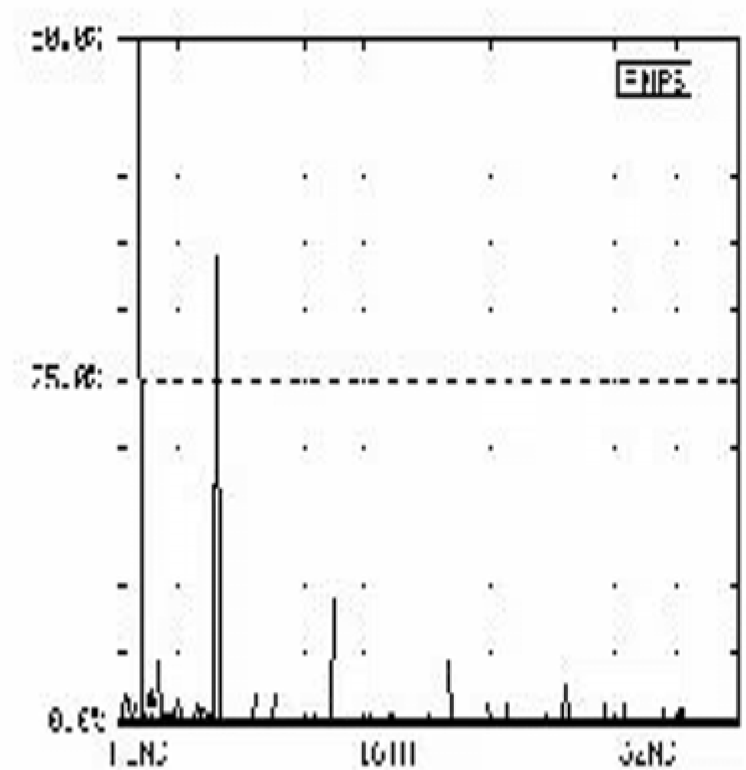
- Harmonics are persistent distortions in a wave shape.
- They represent integers multiples of the fundamental frequencies.





Harmonic Spectrum Analysis

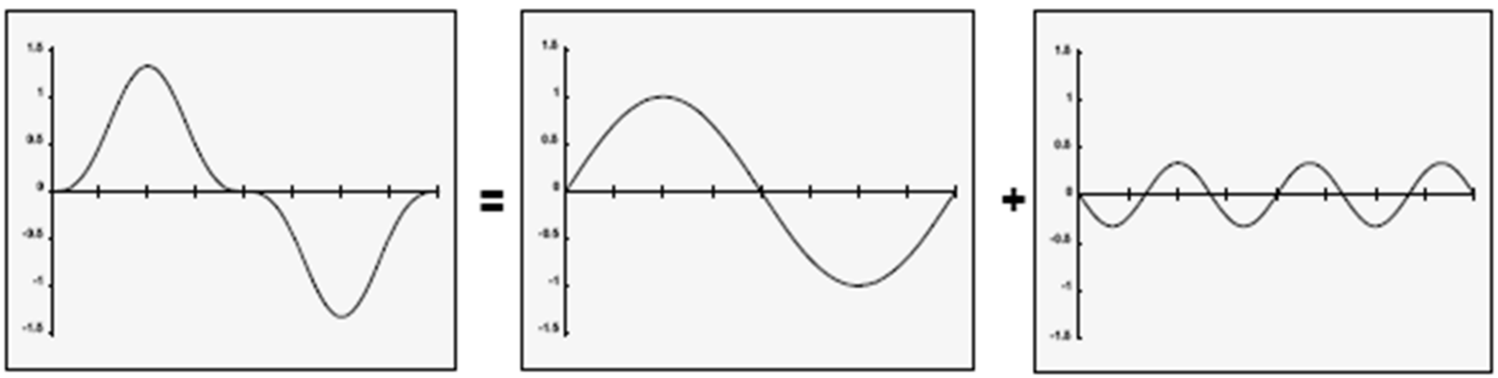




All periodic signals of frequency "f" can be represented in the form of a composite sum:

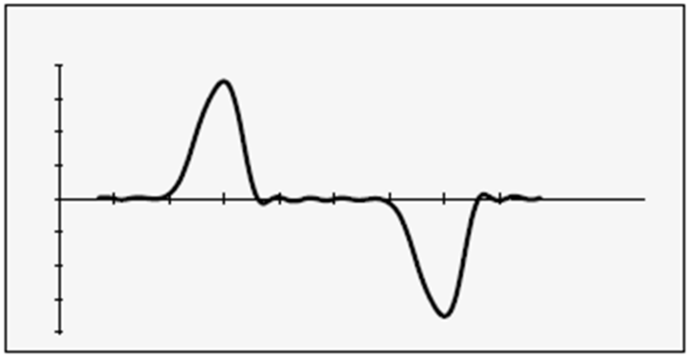
1. of a sinusoidal term at frequency "f": the FUNDAMENTAL (H_1).
2. of sinusoidal terms of which frequencies are integer multiples of fundamental H_1: the HARMONICS (H_n).
3. of a possible continuous component (DC component)

$$y(t) = h_1(t) + h_3(t)$$

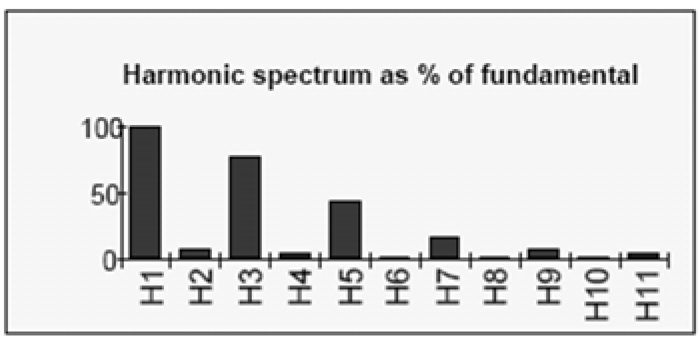


y (t) h1 (t) h3 (t)

Harmonics :Order and Spectrum



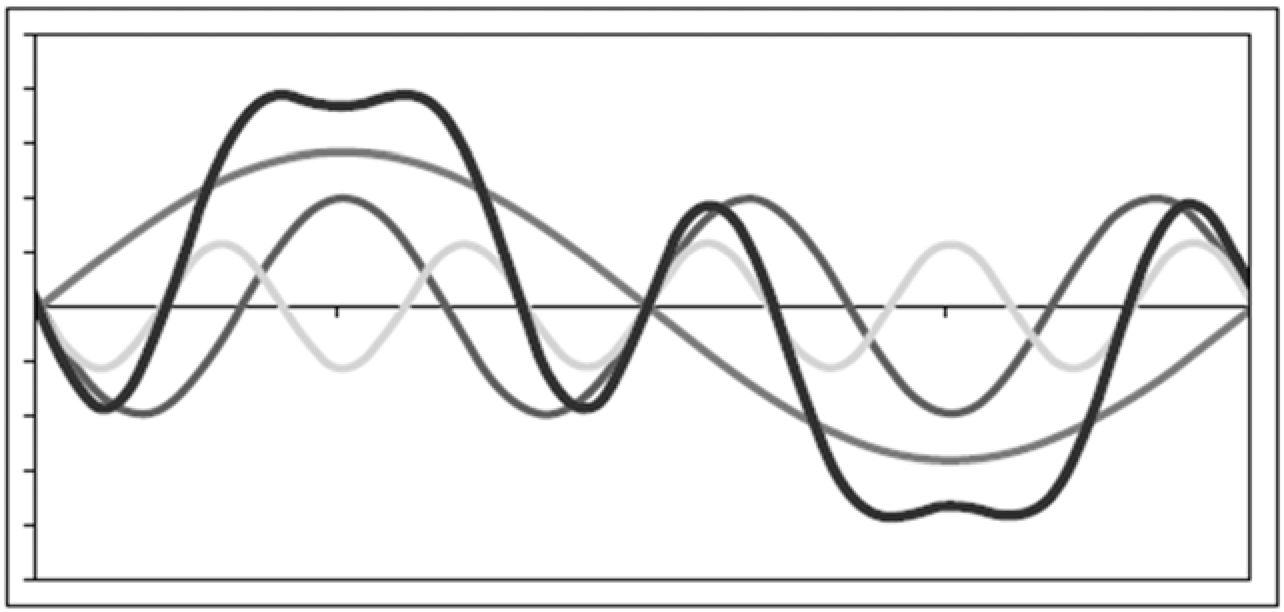
Order:
The order of the harmonic is the value of the integer which determines its frequency.
Example: harmonic of order 5, frequency = 250 Hz
(when fundamental f is 50 Hz)



Spectrum:
The spectrum of a signal is the graph representing amplitudes of the harmonics as a function of their frequency.

To summarize: the harmonics are nothing less than the components of a distorted waveform and their use allows us to analyze any periodic non-sinusoidal waveform through different sinusoidal waveform components.

Figure below shows a graphical representation of this concept.



Non-sinusoidal waveform

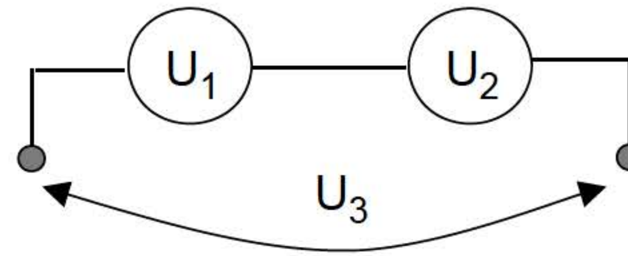
First harmonic (fundamental)

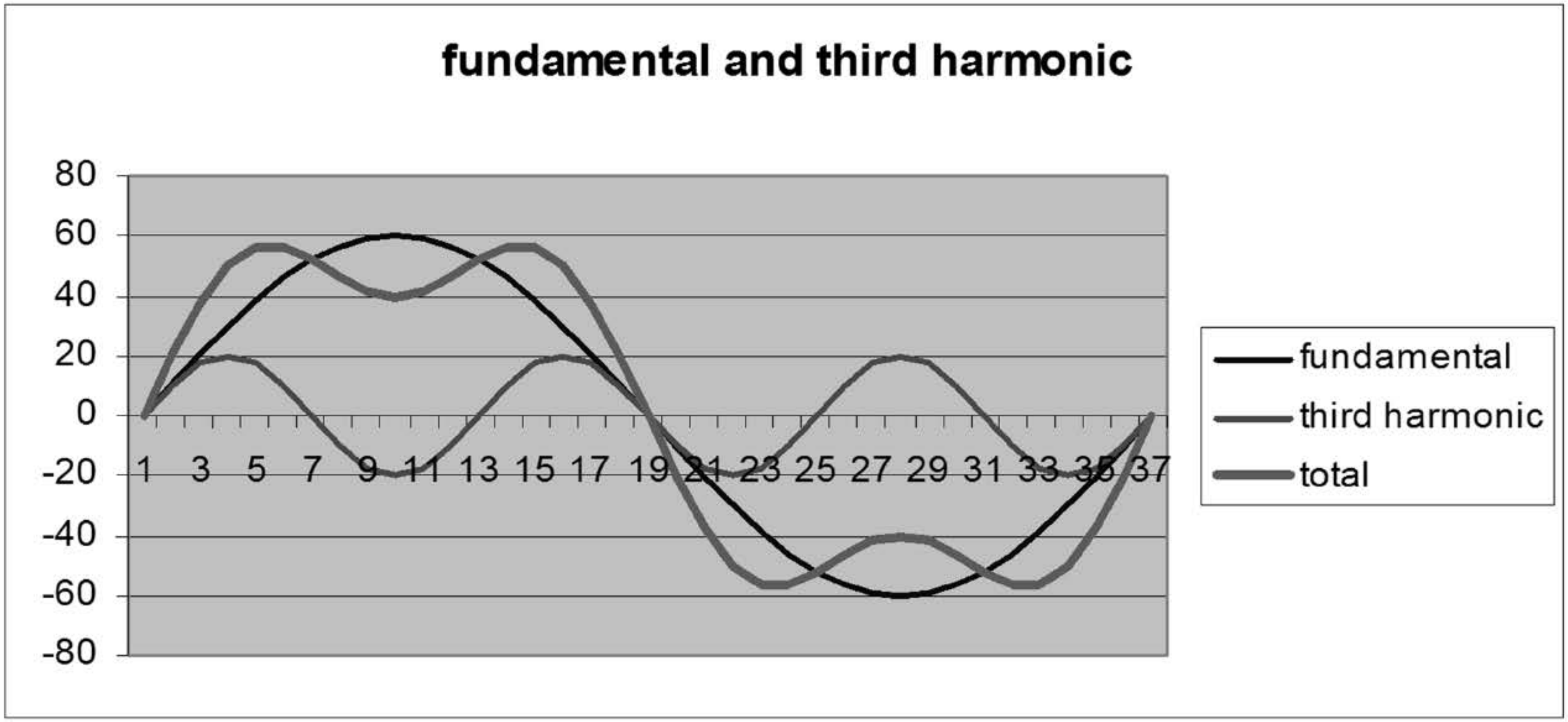
Third harmonic

Fifth harmonic

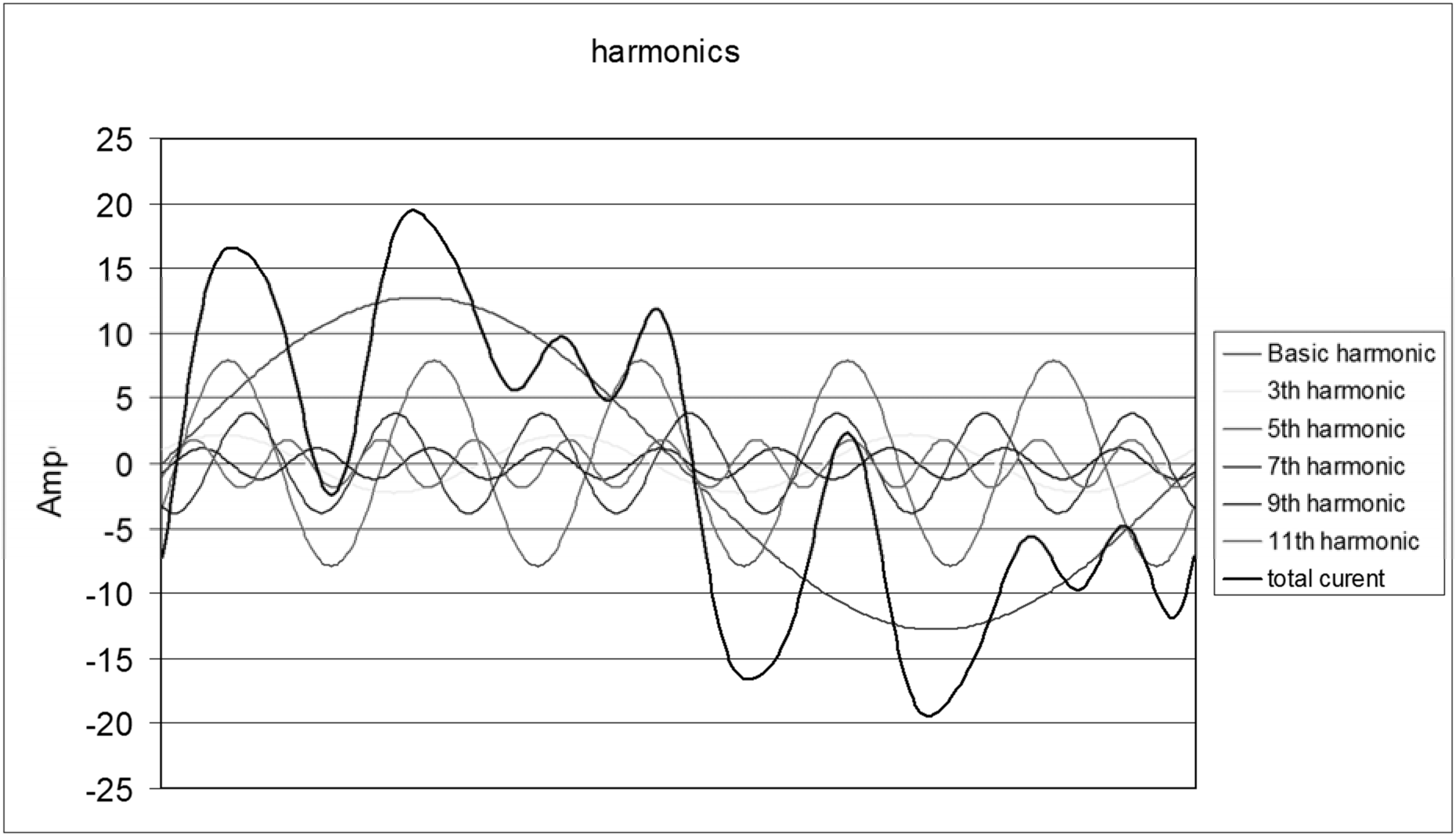
Two sinusoidal sources connected in series

U_{1max} = 60 V @ 50 Hz
U_{2max} = 20 V @ 150 Hz





EXAMPLE OF HARMONICS

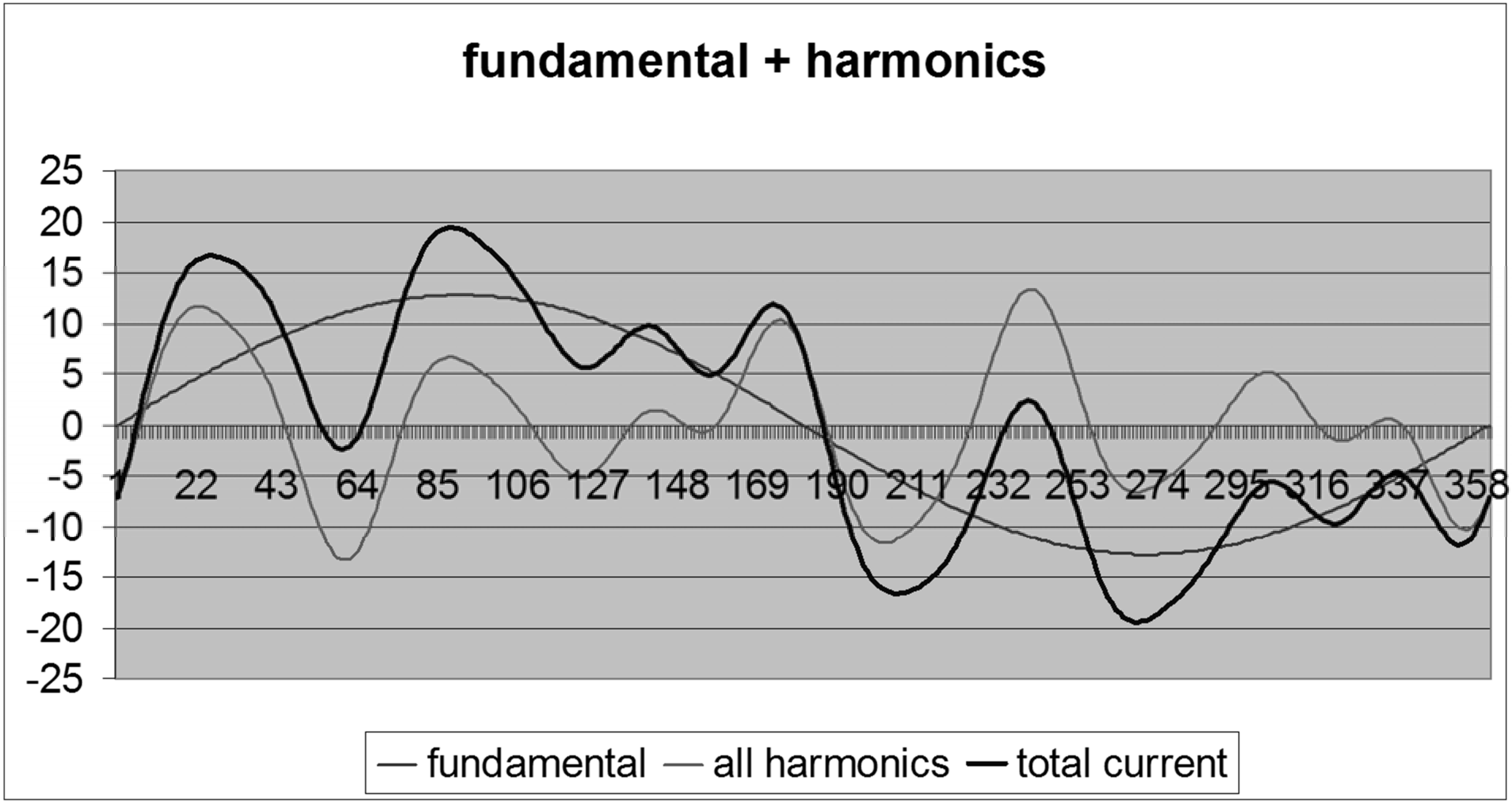


HARMONICS IN POWER SYSTEM

A harmonic is any voltage or current whose frequencies are integral multiples of f. For example a set of sine waves whose frequencies are 50, 150, 250, 450 Hz is said to possess the following components:

Fundamental frequency 50 Hz (the lowest frequency)
Third harmonic: 150 Hz (3 x 50 Hz)
Fifth harmonic: 250 Hz (5 x 50 Hz)
Ninth harmonic: 450 Hz (9 x 50 Hz)

The distortion of a voltage or current can be traced to the harmonics it contains. This distortion can be produced by magnetic saturation in the core of transformers or by the switching of thyristors or IGBTs in electronics drive.


fundamental + harmonics
25
20
15
10
5
0
-5
-10
-15
-20
-25
1
22
43
64
85
106
127
148
169
190
211
232
253
274
295
316
337
358
fundamental
all harmonics
total current

Sources of Harmonics

There are many sources of power system harmonics. Some examples of harmonic producing devices are:

Transformers:
Third harmonic currents are present in the magnetizing current (a small portion of the transformer full load current). If the transformer saturates (due to over-voltage), the harmonic distortion level of the current increases substantially.

Fluorescent Lamps:
These devices produce a predominantly third order harmonic current on the order of 20% to 30% of the fundamental current. Electronic ballasts have slightly different characteristics but exhibit similar levels of harmonics.

Pulse-Width Modulated Converters:
These devices use an external controller for switching the input transistors allowing the current waveform to be shaped more desirably. However, these converters are limited in power and typically used in applications less than a few hundred kilowatts.

Switched Mode Power Supplies:

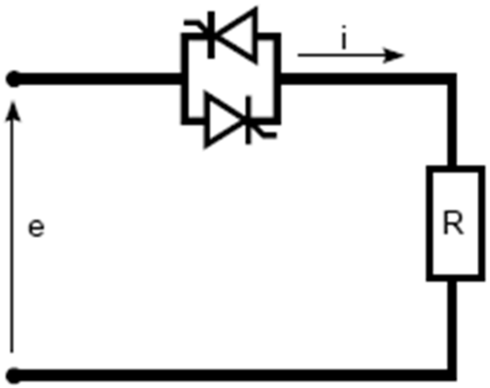
Typically found in single-phase electronic devices such as computers and other business and consumer electronics, these devices use a switching regulator to precisely control the DC voltage.

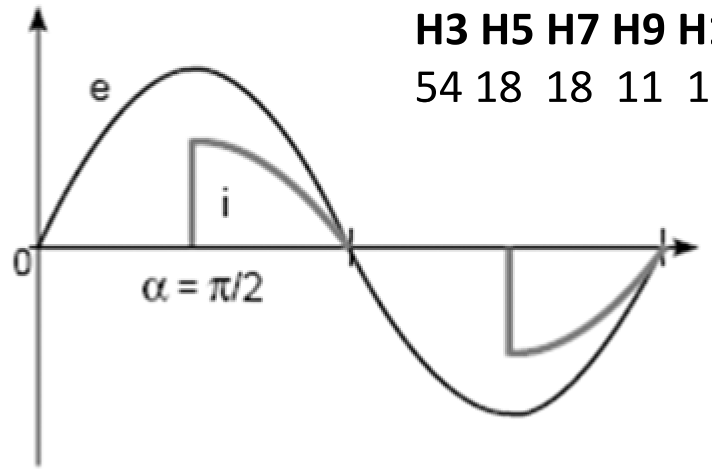
The input of these power supplies normally consists of a full-wave bridge rectifier and a DC filter capacitor which produces an alternating pulse current waveform rich in third harmonic.

Though they are not used in large power applications, the cumulative effects of many devices may create concerns, particularly for 400/230 Volt Y systems.

Wave shape of current absorbed by some non-linear loads.

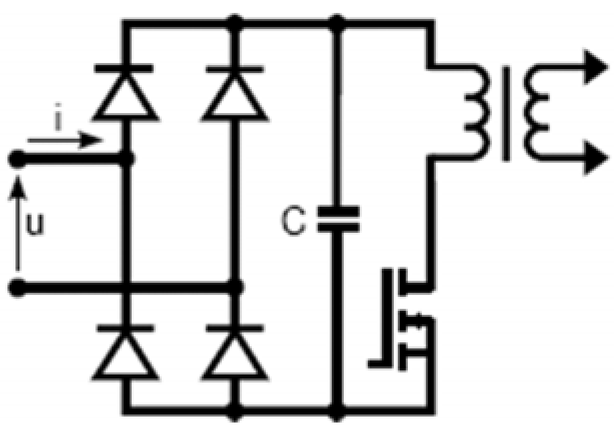
Light dimmer or heating regulator

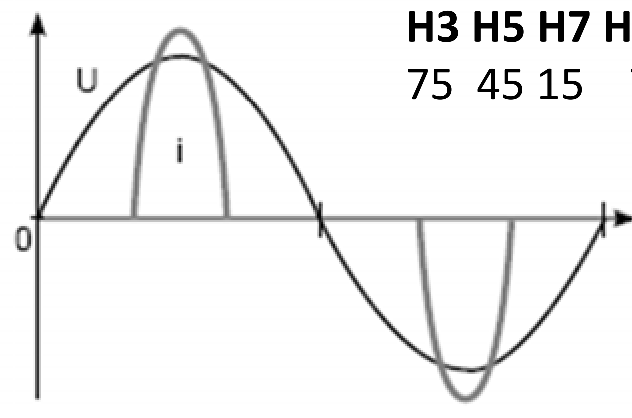




H3	H5	H7	H9	H11	H13	H15	H17	H19
54	18	18	11	11	8	8	6	6

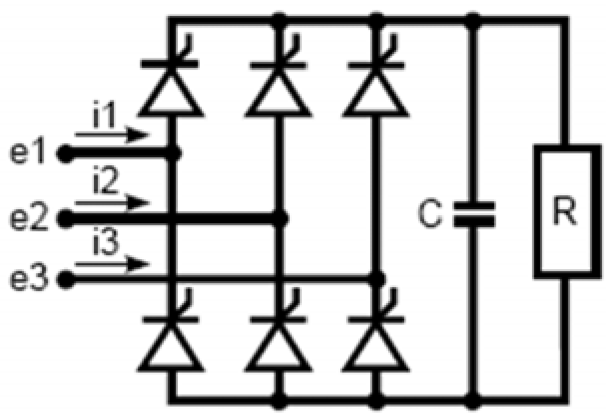
Switch mode power supply rectifier

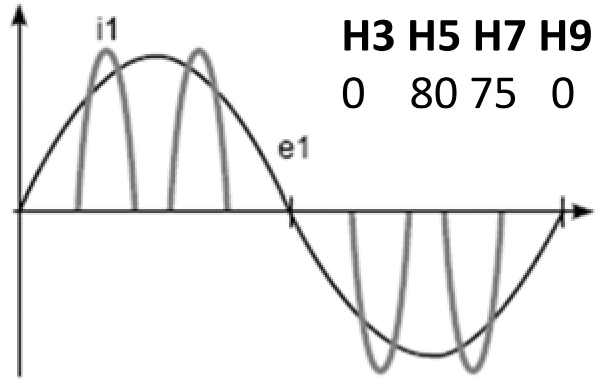




H3	H5	H7	H9	H11	H13	H15	H17	H19
75	45	15	7	6	3	3	3	2

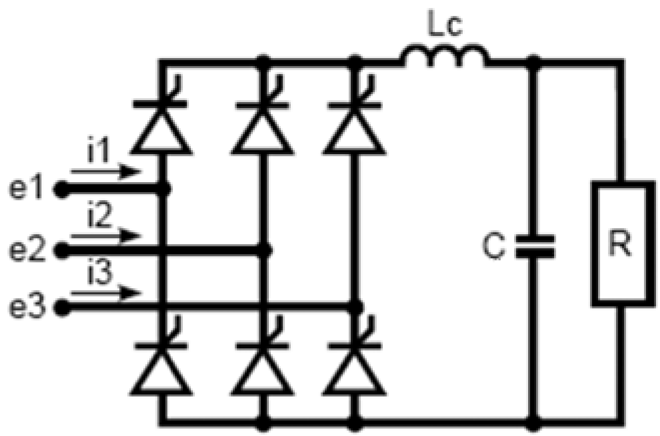
Three-phase rectifier with front end capacitor

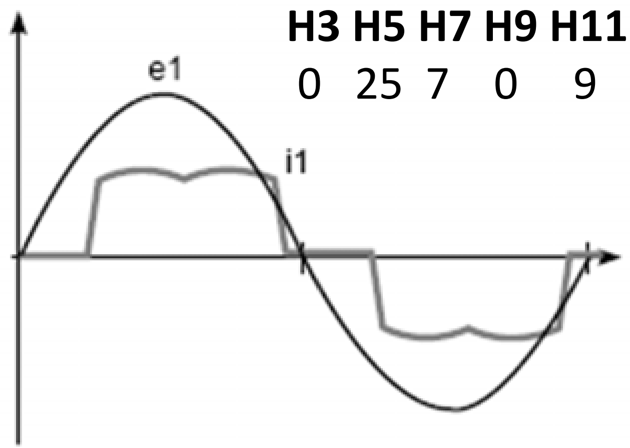




H3	H5	H7	H9	H11	H13	H15	H17	H19
0	80	75	0	40	35	0	10	5

Three-phase rectifier with DC filtering reactor





H3	H5	H7	H9	H11	H13	H15	H17	H19
0	25	7	0	9	4	0	5	3

Harmonic currents in three phase systems

Neutral conductor

Harmonics get more complicated in three phase applications.

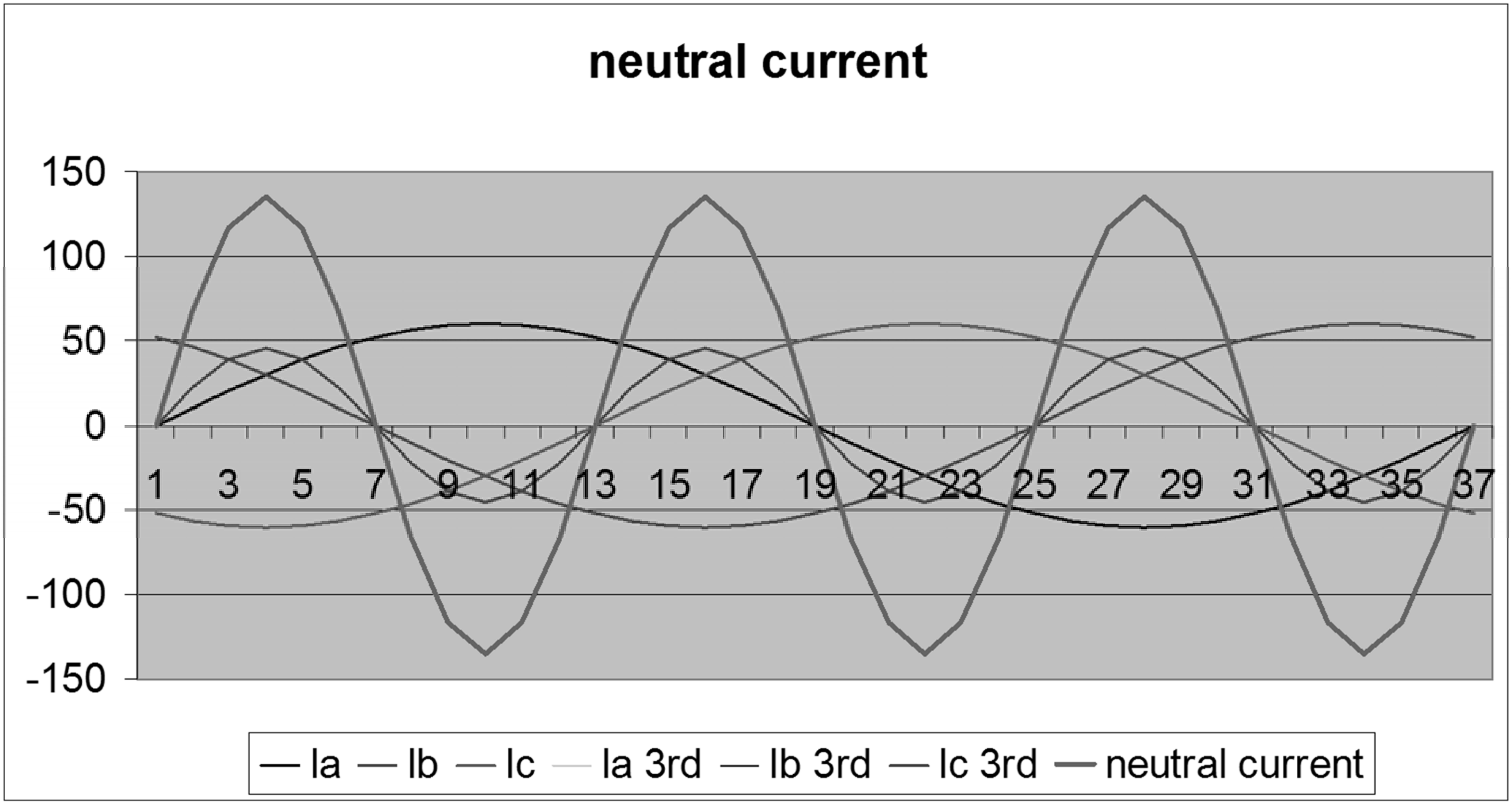
Here not only do we have to deal with phase conductors, but also the neutral conductor, triplen (odd multiples of 3 i.e. 3rd, 9th, 15th etc,) harmonics, and sequence harmonics.

The triplen harmonics are the major cause of heat because they add together in the neutral conductor.

The magnitude of the harmonic current produced by the triplens can approach twice the phase current.

This causes the neutral conductor to overheat because neutral conductors were historically designed with the same ampacity as the phase conductors.

For example, a 3rd harmonic of 75%, the current flowing in the neutral is 2.25 times the fundamental. The current in each phase is only SQR $(1+ 0.75^2)$ = 1.25 times the fundamental.



Induction motor

A situation that produces abnormal amounts of heat in motors is the combination of positive and negative sequenced harmonics.

The positive sequenced harmonics are the fundamental, 7th, 13th, 19th, etc. They tend to apply an additional forward force in the direction of the motor rotation.

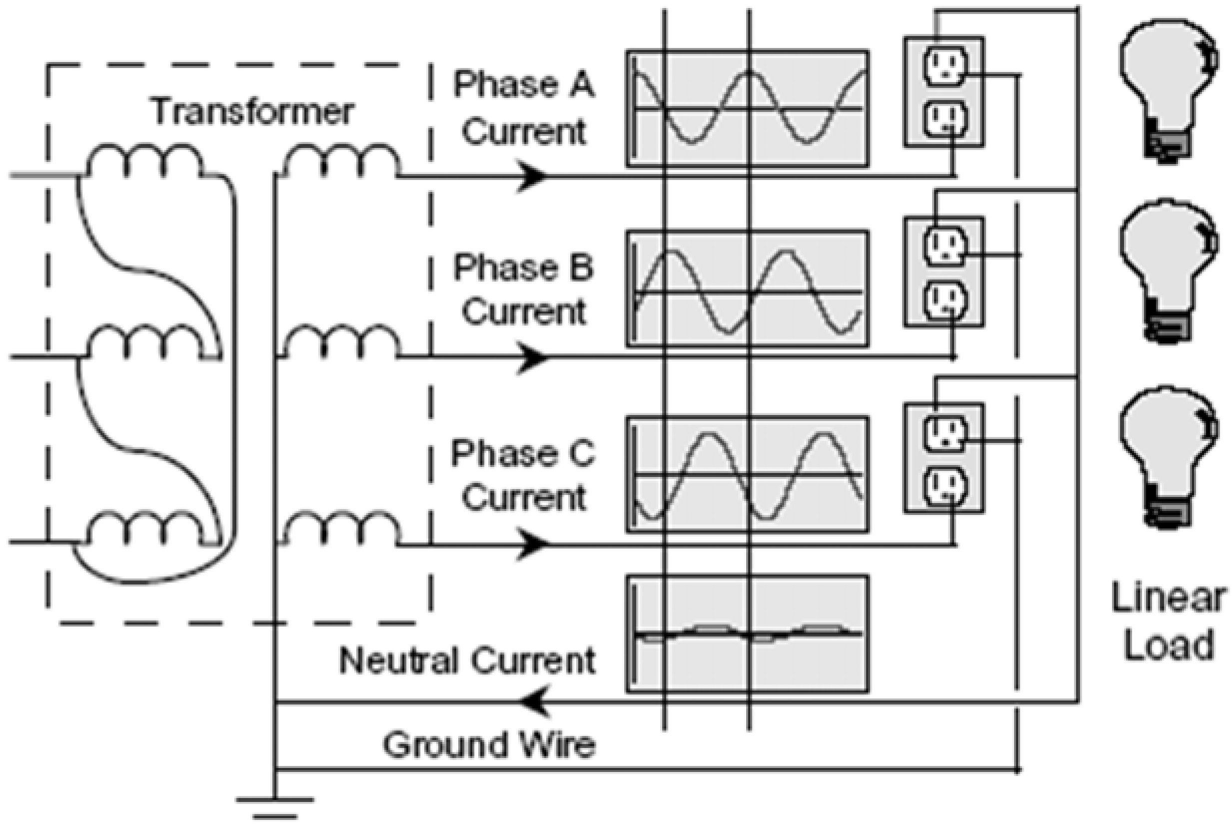
The negative sequenced harmonics are the 5th, 11th, 17th, etc. They present a force that opposes the motor rotation and tries to make the motor rotate in the opposite direction.

The force of these harmonics acting upon each other creates heat which leads to premature failure.

Harmonic voltage distortion causes increased eddy current losses in the motors, in the same way as seen for transformers.

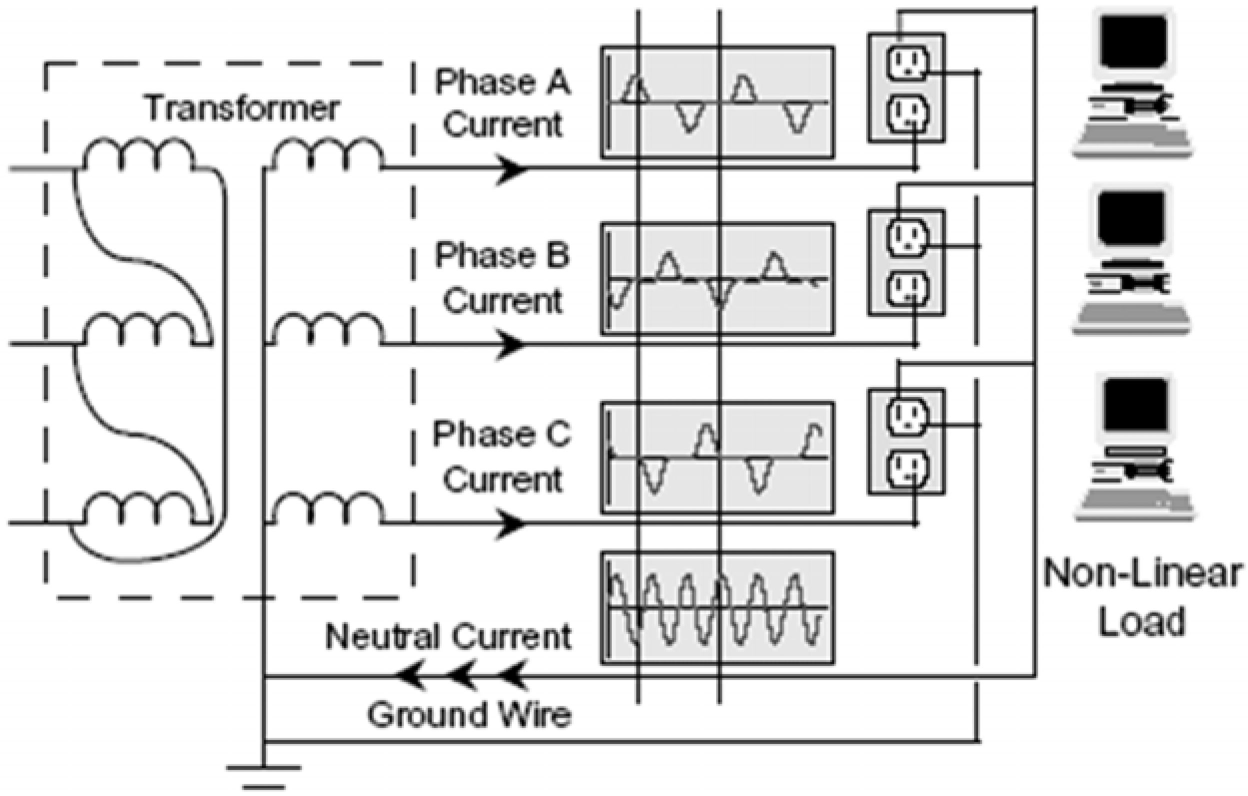
Harmonic Currents add in the Neutral

The 120° phase shift between linear load currents will result in their balanced portions instantaneously canceling in the neutral.



With linear loads, the neutral can be the same size as the phase conductors because the neutral current cannot be larger than the largest phase current, even when the load is completely unbalanced.

When the load is non-linear however, the current pulse on one phase will not have a pulse on either of the other phases for which to cancel. The pulses are additive which often leads to heavier current on the neutral conductor than on any phase conductor. The frequency of this neutral current is primarily 150 Hz (3rd harmonic).



With non-linear loads, the neutral current generally exceeds the largest phase current, even when the loads are in perfect RMS current balance.

Harmful Effects on Receivers

Cables:
Overheating of cables
Additional losses due to skin effect
Increase in dielectric losses of insulation

Induction motors:
Increase in core (stator) and Joule losses
Pulsating torques causing efficiency reduction, abnormal vibration, rotor overheating

General Solutions

Limit injected harmonic currents:
Install limitation induction coils for speed drives
Install specific rectifiers called active front end

Install anti-harmonics induction coils

Install filters to trap harmonics:
Passive filters
Active filters
Hybrid filters

Oversize equipment

Passive harmonic filters

Passive or ‘trap’ filters employ ‘passive’ elements (capacitors and inductors) to ‘trap’ or absorb harmonics.

Passive filters are generally configured to remove only one or two specific harmonics.

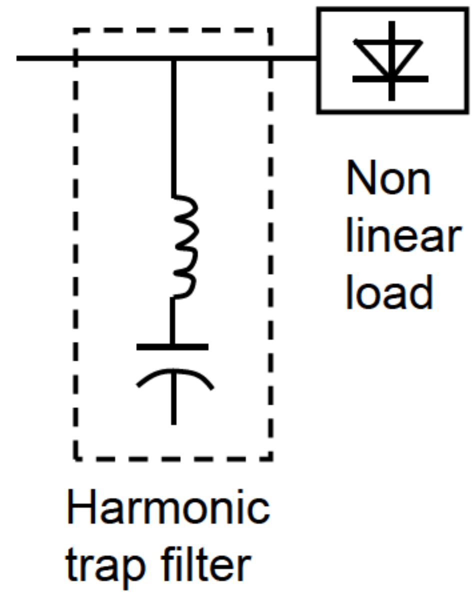
Passive filters are generally regarded as unsuitable for filtering 3rd harmonics.

For this reason, they are best suited for applications in which 3rd harmonics are not an issue, power factor correction is required, and specific harmonics such as 5th or 7th are creating the problem.

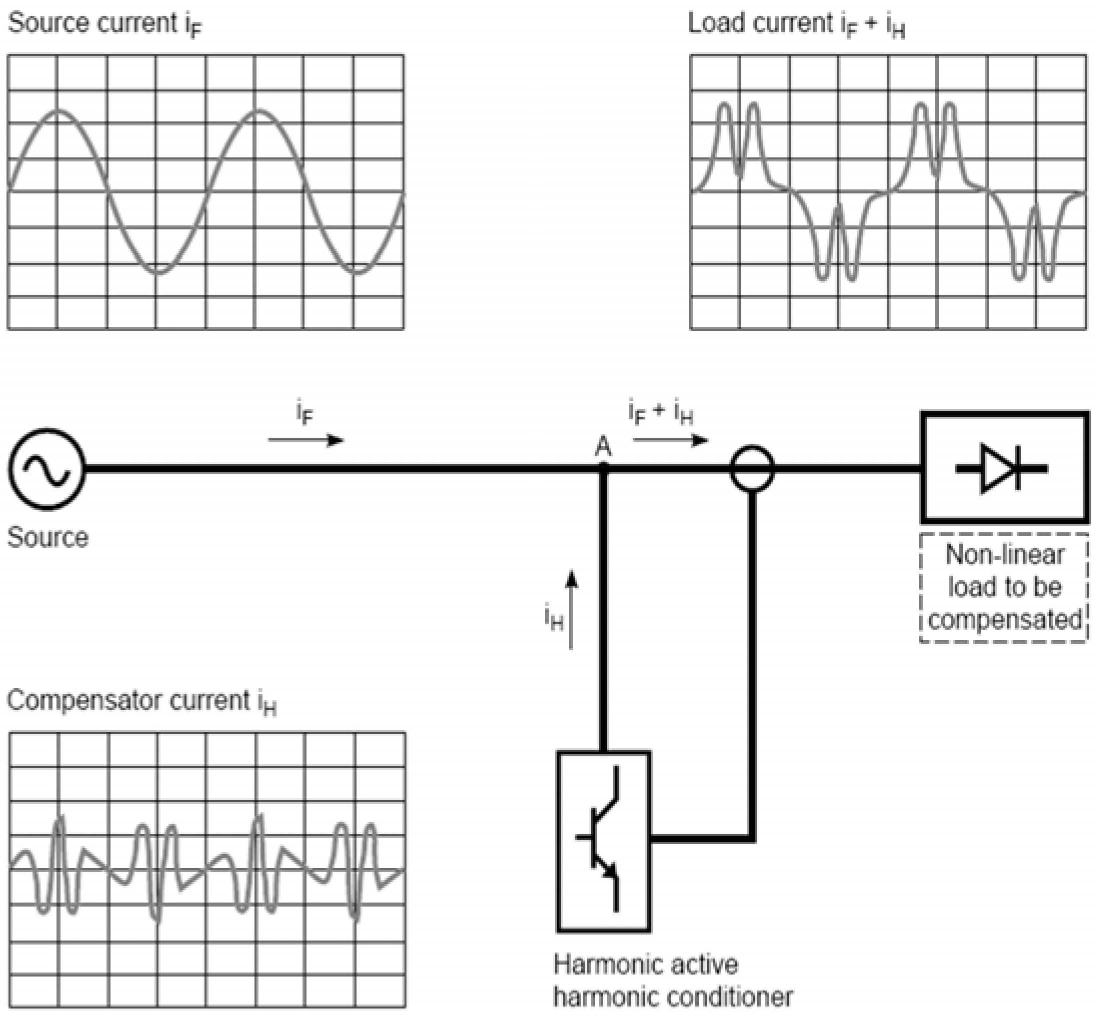
Passive filters are ideal for systems that have a high percentage of 6 pulse drives and other linear loads.

However, the filters may need to be retuned for changes in the power system.

Filters can be designed for several nonlinear loads or for an individual load,



Principle of compensation of harmonic components by "shunt-type" active harmonic conditioner



The device should be able to inject **at any time** a current where each harmonic current has the same amplitude as that of the current in the load and is in opposition of phases, then Kirchoff's law at point A guarantees that the current supplied by the source is purely sinusoidal

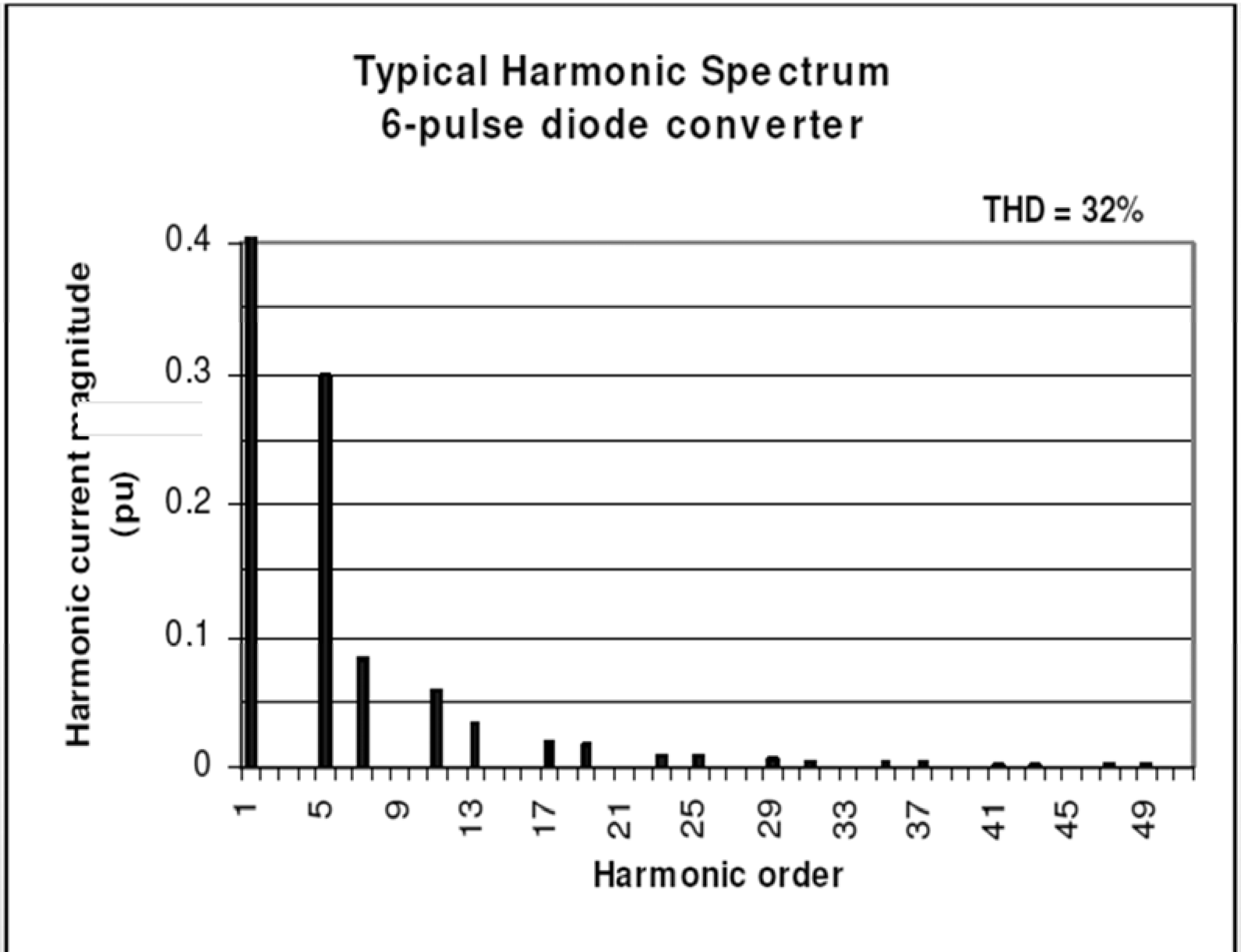
Isolation Transformers:

An isolation transformer provides several advantages.

First and foremost, it provides impedance to the drive, which reduces current distortion.

It obviously resolves voltage mismatch between the supply and the load.

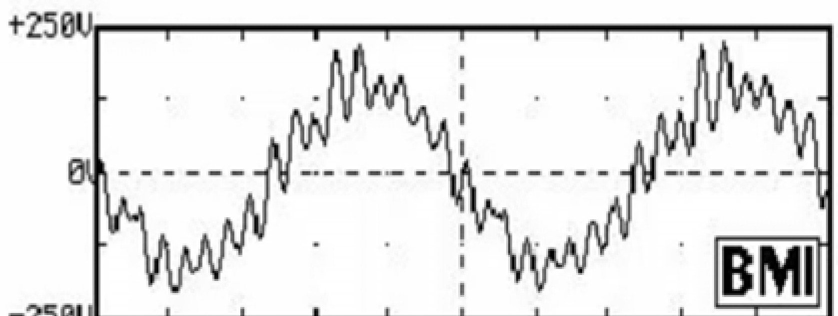
If the secondary is grounded, it isolates ground faults and reduces common mode noise.



Typical Harmonic Spectrum
6-pulse diode converter
THD = 32%
Harmonic current magnitude (pu)
0.4
0.3
0.2
0.1
0
1
5
9
13
17
21
25
29
33
37
41
45
49
Harmonic order

Harmonics Resonance

Characteristic Harmonics		
6 pulse	12 pulse	18 pulse
	11	17
5	13	19
7	23	35
	25	53
11	35	55
13	37	
17		
19		



125.0V/DIV VERTICAL 3.3MS/DIV HORIZ.
PHASE A SNAPSHOT

TE COPIER Sep 16 1991 (Mon)

PHASE A VOLTAGE SPECTRUM 9:58:25 AM

Fundamental volts: 113.6 Vrms

Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	0	2nd	0.4%	105
3rd	0.5%	-168	4th	0.2%	54
5th	6.9%	73	6th	0.1%	-43
7th	5.1%	0	8th	0.2%	117
9th	0.8%	16	10th	0.2%	179
11th	8.9%	-156	12th	0.2%	-147
13th	10.4%	121	14th	0.4%	-59
15th	3.4%	135	16th	2.0%	-140
17th	24.1%	-176	18th		
19th	4.1%	98	20th	0.2%	-114
21st	0.6%	77	22nd	0.2%	-135
23rd	0.9%	-56	24th	0.2%	146
25th			26th		
27th	0.1%	-39	28th	0.2%	-109
29th	0.4%	-106	30th	0.1%	48
31st	0.6%	147	32nd	0.1%	21
33rd	0.4%	159	34th	0.1%	-59
35th	0.5%	11	36th		
37th	0.6%	-78	38th	0.2%	-20
39th	0.4%	-89	40th		
41st	1.0%	150	42nd	0.1%	100
43rd	0.7%	68	44th	0.2%	-29
45th	0.4%	31	46th		
47th	0.9%	-84	48th		
49th	0.7%	-167	50th	0.1%	86
ODD	29.6%		EVEN	2.2%	

THD: 29.7%

Sources of Harmonics

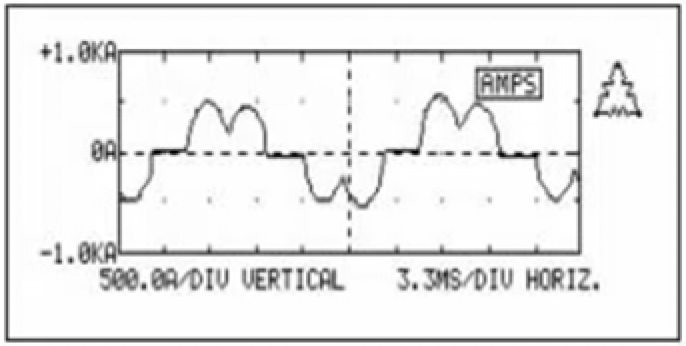
- Saturable devices transformers and nonlinear reactors

- Arcing devices arc furnaces, welders, and florescent lighting

- Power electronic equipment adjustable speed motor drives, dc motor drives and electronic power supplies

			6 Pulse Rectifier Voltage Harmonic			
6 Pulse Rectifier Current Harmon			Z50=	0.3267	line-neutral VA	3810.624
Harmonic#	%	Amps	Ohms	Volts	VTHD	
5	20	0.56	1.6335	0.91455	0.024	
7	14.2	0.40	2.2869	0.909062	0.023856	
11	9.09	0.25	3.5937	0.914458	0.0239976	
13	7.69	0.22	4.2471	0.914275	0.0239928	
17	5.88	0.16	5.5539	0.914184	0.0239904	
19	5.26	0.15	6.2073	0.914001	0.0239856	
23	4.36	0.12	7.5141	0.91711	0.0240672	
25	4	0.11	8.1675	0.91455	0.024	
29	3.45	0.10	9.4743	0.915007	0.024012	
31	3.23	0.09	10.1277	0.915739	0.0240312	
35	2.86	0.08	11.4345	0.915464	0.024024	
37	2.7	0.08	12.0879	0.913635	0.023976	
TDD=	29.8	%				

DC Motor Drive Current



VOLTAGE & CURRENT SNAPSHOT 11:21:10 AM

VOLTAGE	458.9 Vrms	
Phase A-B:	459.3 Vrms,	0° (ref)
Phase B-C:	461.0 Vrms,	120°
Phase C-A:	456.5 Vrms,	-121°
Imbalance:	0.4%	
CURRENT	945.6 A rms	
Phase A	339.5 A rms,	-75°
Phase B	347.8 A rms,	40°
Phase C	258.3 A rms,	157°
Imbalance:	9.4%	

PHASE A CURRENT SPECTRUM 11:23:42 AM

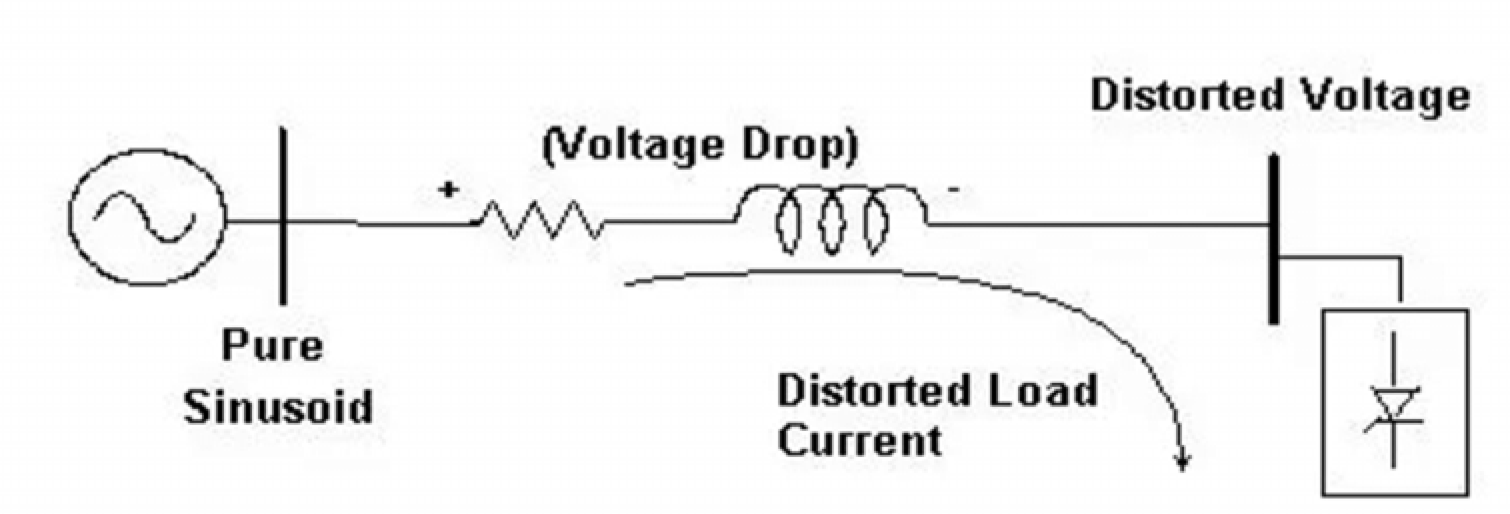
Fundamental amps: 319.6 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-75°	2nd	4.0%	-54°
3rd	1.2%	28°	4th	1.5%	154°
5th	33.6%	156°	6th		
7th	1.6%	29°	8th	1.7%	-170°
9th	0.4%	-91°	10th	0.3%	35°
11th	0.7%	40°	12th		
13th	1.2%	54°	14th	1.0%	[illegible]
15th	0.3%	148°	16th	0.2%	51°
17th	4.5%	-57°	18th		
19th	1.3%	-46°	20th	1.1%	-13°
21st	0.3%	34°	22nd	0.3%	-31°
23rd	2.0%	-100°	24th		
25th	1.2%	149°	26th	0.9%	123°
27th	0.3%	-75°	28th	0.3%	-123°
29th	2.0%	90°	30th		
31st	1.0%	107°	32nd	0.3%	133°
33rd	0.0%	170°	34th	0.1%	117°
35th	1.4%	-17°	36th		
37th	1.0%	2°	38th	0.3%	23°
39th	0.3%	63°	40th	0.3%	31°
41st	1.1%	-123°	42nd		
43rd	0.9%	-104°	44th	0.3%	-75°
45th	0.0%	-47°	46th	0.0%	-70°
47th	1.0%	128°	48th	0.2%	132°
49th	0.9%	152°	50th	0.7%	-179°
ODD	35.4%		EVEN	5.9%	
THD:	35.9%				

Why do we see such a high even THD%?

ODD 35.4% EVEN 5.9%
THD 35.9%

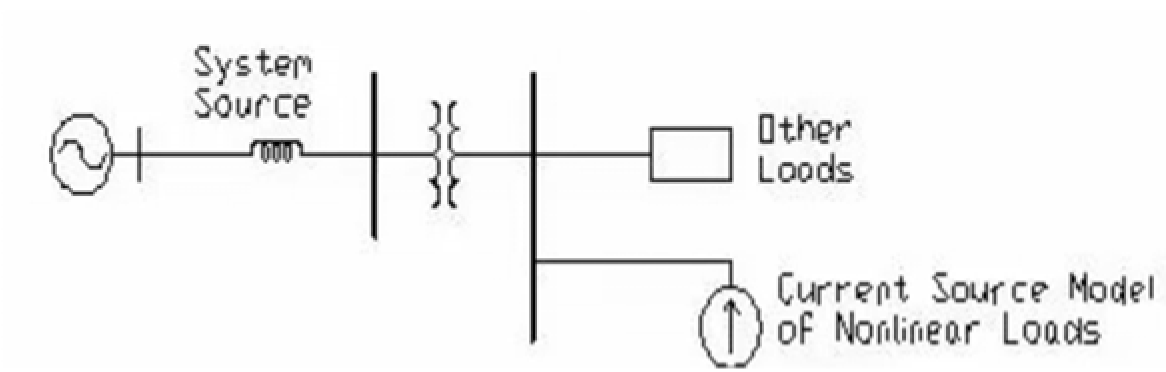
Current vs. Voltage Harmonics



- Harmonic currents flowing through the system impedance results in harmonic voltages at the load.

IEEE 519

- Harmonics generated by nonlinear device characteristics
- Most devices look like sources of harmonic currents
- Voltage distortion caused by system response characteristics



IEEE 519 Limits Harmonic Levels

- The customer is responsible for limiting harmonic currents injected onto the power system.

- The utility is responsible for maintaining quality of voltage waveform.

Harmonic Voltage Limits

- Utility Responsibility

Voltage Distortion Limits		
	Individual Voltage	Total Voltage
Bus Voltage at PCC	**Distortion (%)**	**Distortion THD (%)**
69 kV and Below	3.0	5.0
69.001kV through 161kV	1.5	2.5
161.001kV and above	1.0	1.5
NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.		

Harmonic Current Limits

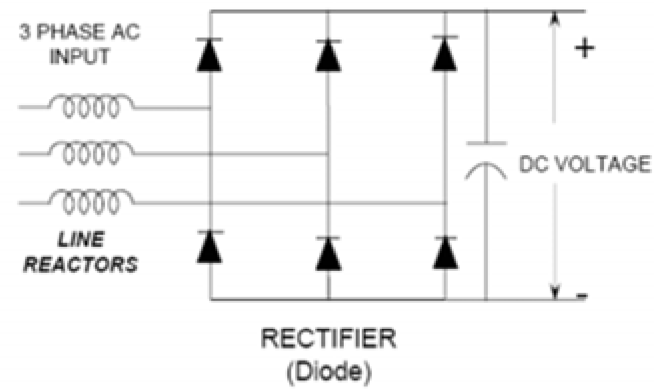
- Customer responsibility

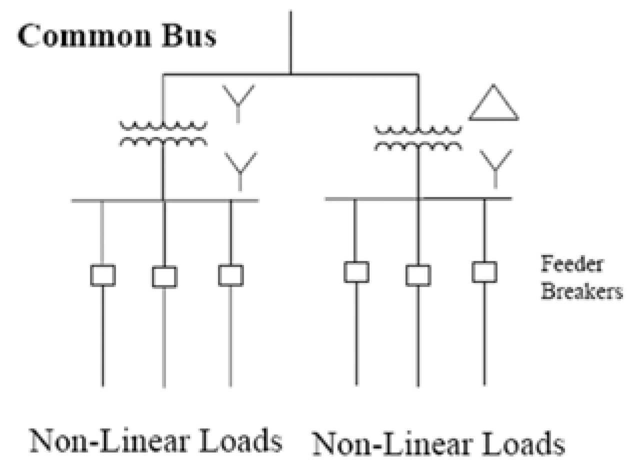
Current Distortion Limits for General Distribution Systems						
(120 V Through 69,000 V)						
Maximum Harmonic Current Distortion in Percent of IL						
Isc/IL	<11	11_h<17	17_h<23	23_h<35	35_h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonics limits above						
Current distortions that results in a dc offset, e.g., half-wave converters, are not allowed						
*All power generation equipment is limited to these values of current distortions,						
regardless of actual Isc/IL.						
where						
Isc = Maximum short-circuit current at PCC						
IL = Maximum demand load current (fundamental frequency components) at PCC.						

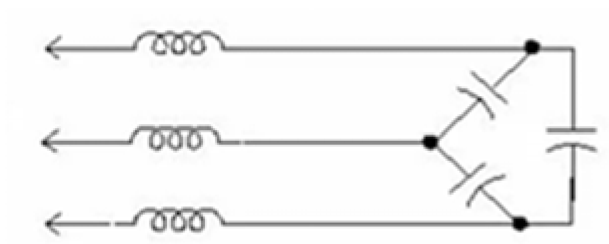
- Values shown are in percent of average maximum load current. SCR = short circuit ratio (utility short circuit current at point of common coupling divided by customers average maximum demand load current.

Mitigation Techniques

- Phase multiplication
- Line Reactor
- Phase shifting Transformers
- K-Factor Transformers
- De-Rating Transformers
- Filters







9.1 6-pulse rectifier without inductor

Manufacturing cost 100%
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	63%	54%	10%	6,1%	6,7%	4,8%

9.2 6-pulse rectifier with inductor

Manufacturing cost 120%. AC or DC choke added
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	30%	12%	8,9%	5,6%	4,4%	4,1%

9.3 12-pulse rectifier with polycon transformer

Manufacturing cost 200%
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	11%	5,8%	6,2%	4,7%	1,7%	1,4%

9.4 12-pulse with double wound transformer

Manufacturing cost 210%
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	3,6%	2,6%	7,5%	5,2%	1,2%	1,3%

9.5 24-pulse rectifier with 2 3-winding transformers

Manufacturing cost 250%
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	4,0%	2,7%	1,0%	0,7%	1,4%	1,4%

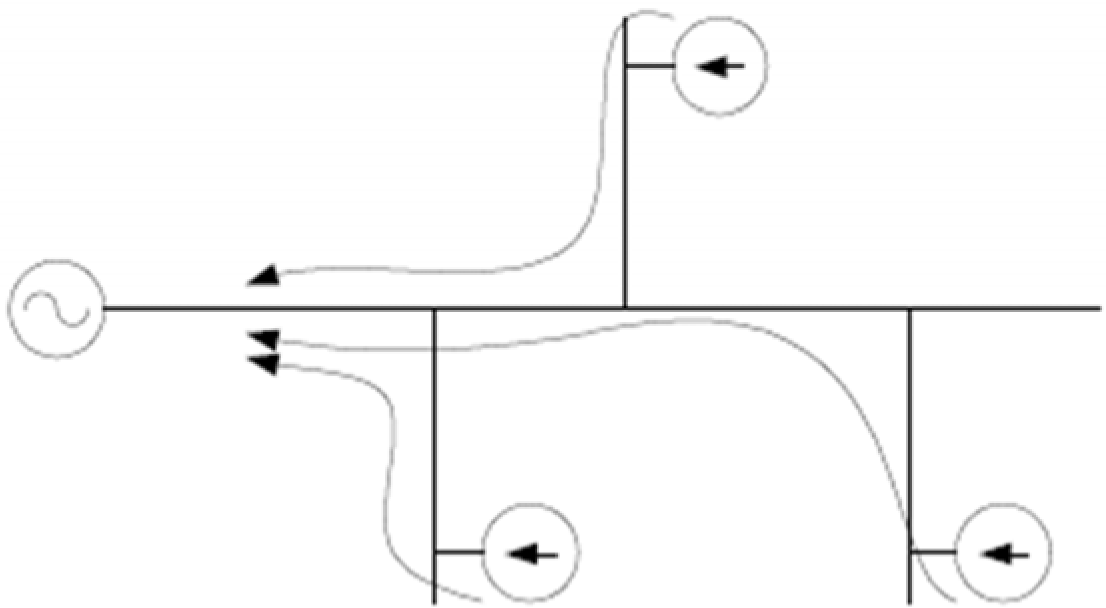
9.6 Active IGBT rectifier

Manufacturing cost 250%. Not significant if electrical braking is anyway needed.
Typical harmonic current components.

Fundamental	5th	7th	11th	13th	17th	19th
100%	2,6%	3,4%	3,0%	0,1%	2,1%	2,2%

Locating harmonic sources

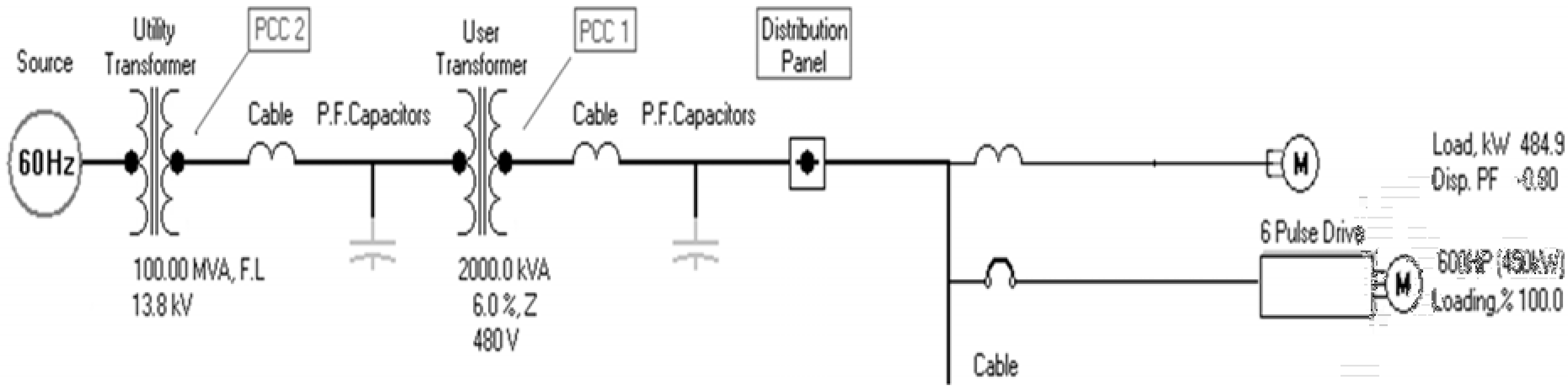
- Method described in the text:
  - Follow the current "downstream" to the load

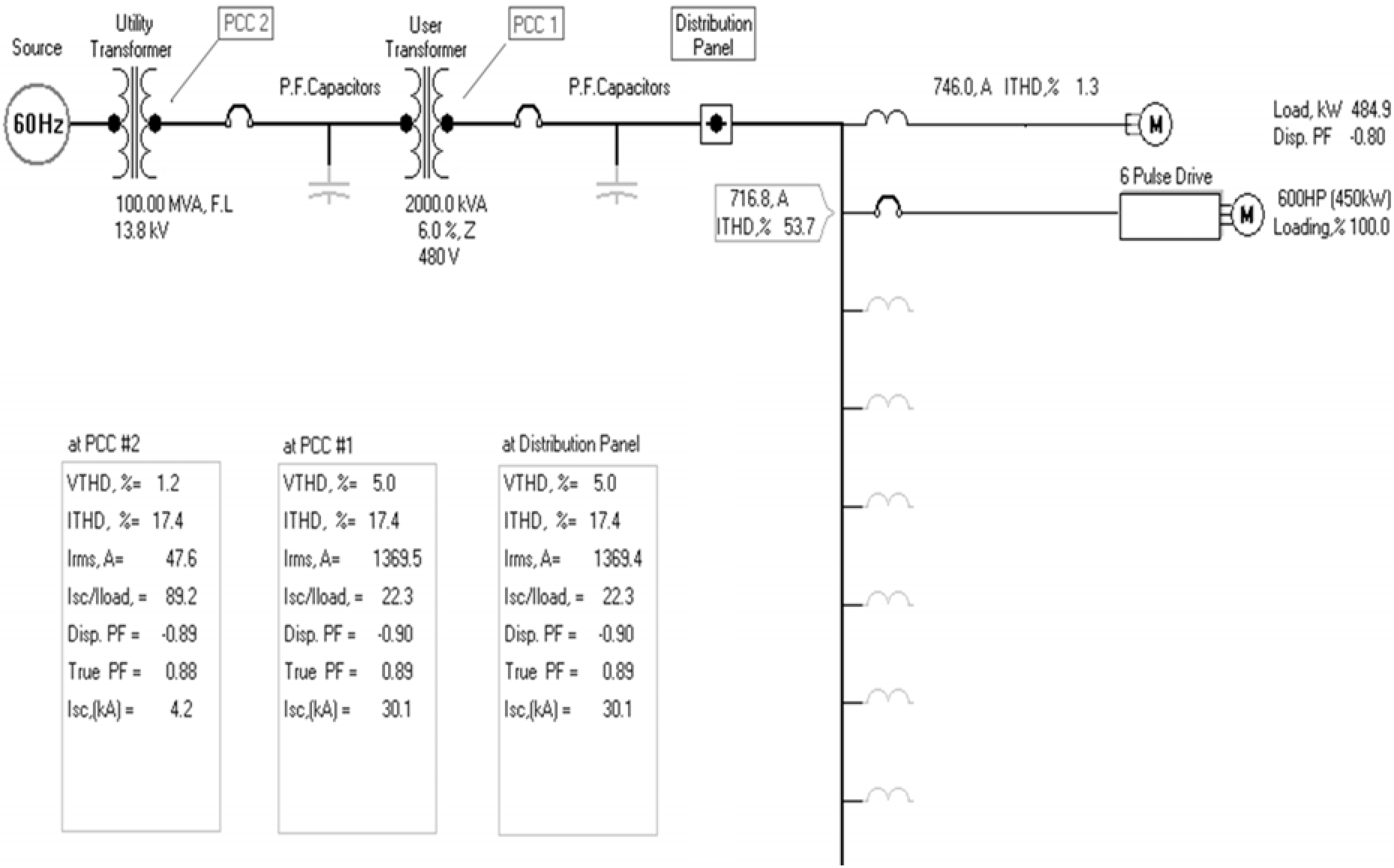


End-user harmonic control

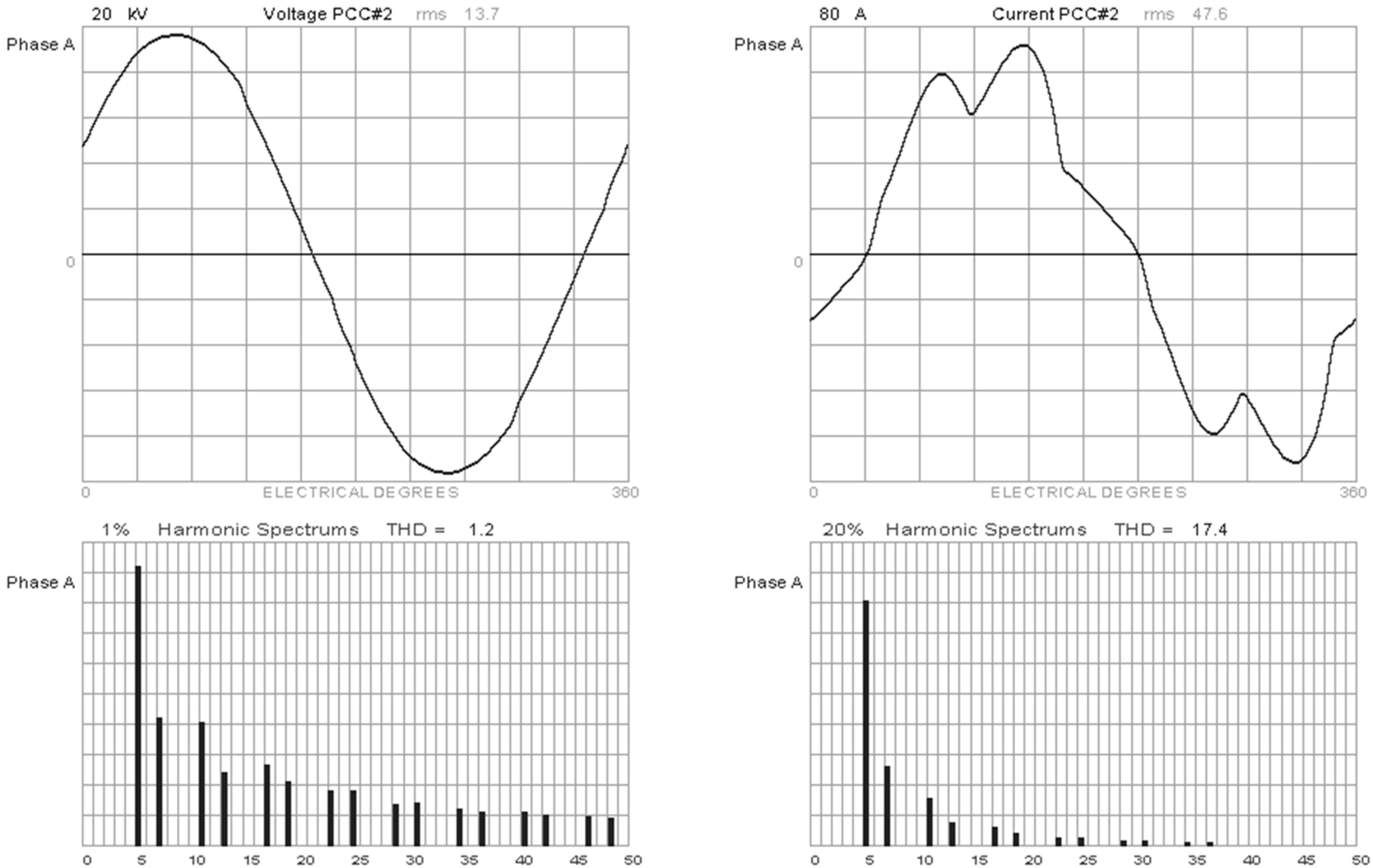
- Prevention is key
  - Know your sources
  - Check for resonance
  - Filter near the sources
  - Put PF correction capacitors near the loads that need them
  - Check wiring
    - Adequate size given true RMS current?

Do we have a harmonic problem?





Source
60Hz
Utility
Transformer
PCC 2
100.00 MVA, F.L
13.8 kV
P.F.Capacitors
User
Transformer
PCC 1
2000.0 kVA
6.0 %, Z
480 V
P.F.Capacitors
Distribution
Panel
746.0, A ITHD,% 1.3
M
Load, kW 484.9
Disp. PF -0.80
716.8, A
ITHD,% 53.7
6 Pulse Drive
M
600HP (450kW)
Loading,% 100.0
at PCC #2
VTHD, %= 1.2
ITHD, %= 17.4
Irms, A= 47.6
Isc/Iload, = 89.2
Disp. PF = -0.89
True PF = 0.88
Isc,(kA) = 4.2
at PCC #1
VTHD, %= 5.0
ITHD, %= 17.4
Irms, A= 1369.5
Isc/Iload, = 22.3
Disp. PF = -0.90
True PF = 0.89
Isc,(kA) = 30.1
at Distribution Panel
VTHD, %= 5.0
ITHD, %= 17.4
Irms, A= 1369.4
Isc/Iload, = 22.3
Disp. PF = -0.90
True PF = 0.89
Isc,(kA) = 30.1



20 kV
Voltage PCC#2
rms 13.7
Phase A
0
0
ELECTRICAL DEGREES
360
80 A
Current PCC#2
rms 47.6
Phase A
0
0
ELECTRICAL DEGREES
360
1%
Harmonic Spectrums
THD = 1.2
Phase A
0 5 10 15 20 25 30 35 40 45 50
20%
Harmonic Spectrums
THD = 17.4
Phase A
0 5 10 15 20 25 30 35 40 45 50

IEEE Std 519 Compliance Report

The following report describes the expected perfomance of a selected Variable Speed Drive(VSD) application under chosen conditions.
It includes a summary of the applications ability to meet IEEE Std 519 harmonic limits at the defined Point of Common Coupling (PCC) and has been prepared through the use of "SOLV" computer simulation software.
Calculations are approximate values. Actual performance may vary due to field conditions.

Project Name: **NEW**

Point of Coupling: **PCC #2**

Short-circuit ratio 89.2

Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	1.2	5.0	PASS
Max.Individual voltage harmonic	0.9 { 5}	3.0	PASS
Current Total Demand Distortion(Itdd)	17.4	12.0	FAIL
Max.Individual current harmonic <11	16.2 { 5}	10.0	FAIL
11 to 16	3.1 {11}	4.5	PASS
17 to 22	1.3 {17}	4.0	PASS
23 to 34	0.6 {23}	1.5	PASS
>35	0.2 {35}	0.7	PASS

Based on the information provided, this application will NOT meet IEEE Std 519 harmonic limits

Point of Coupling: **PCC #1**

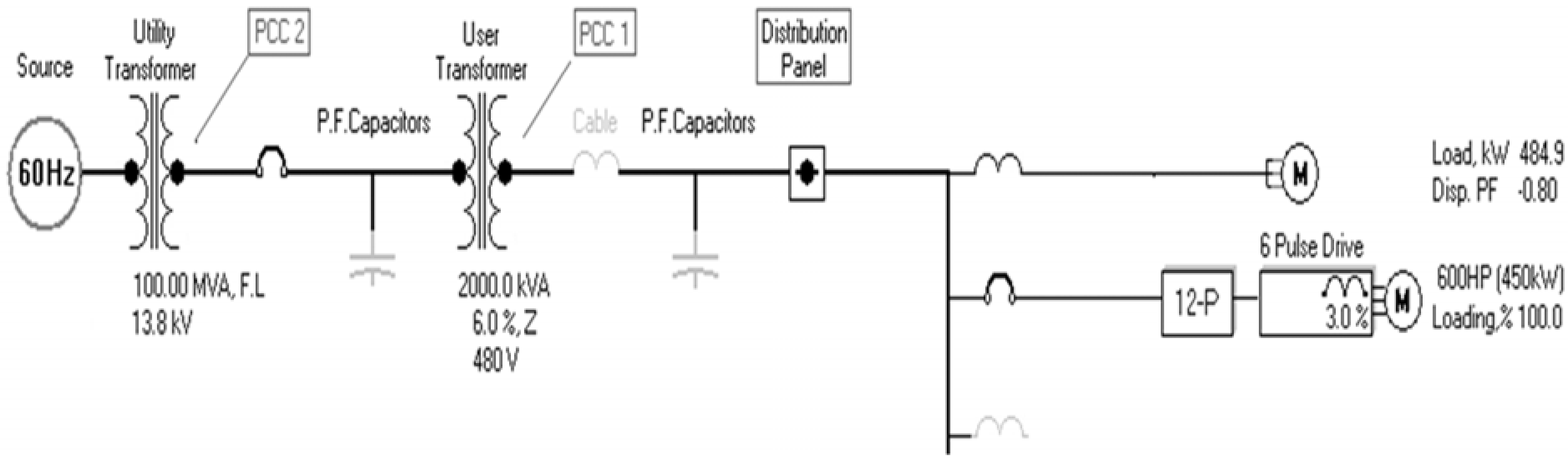
Short-circuit ratio 22.3

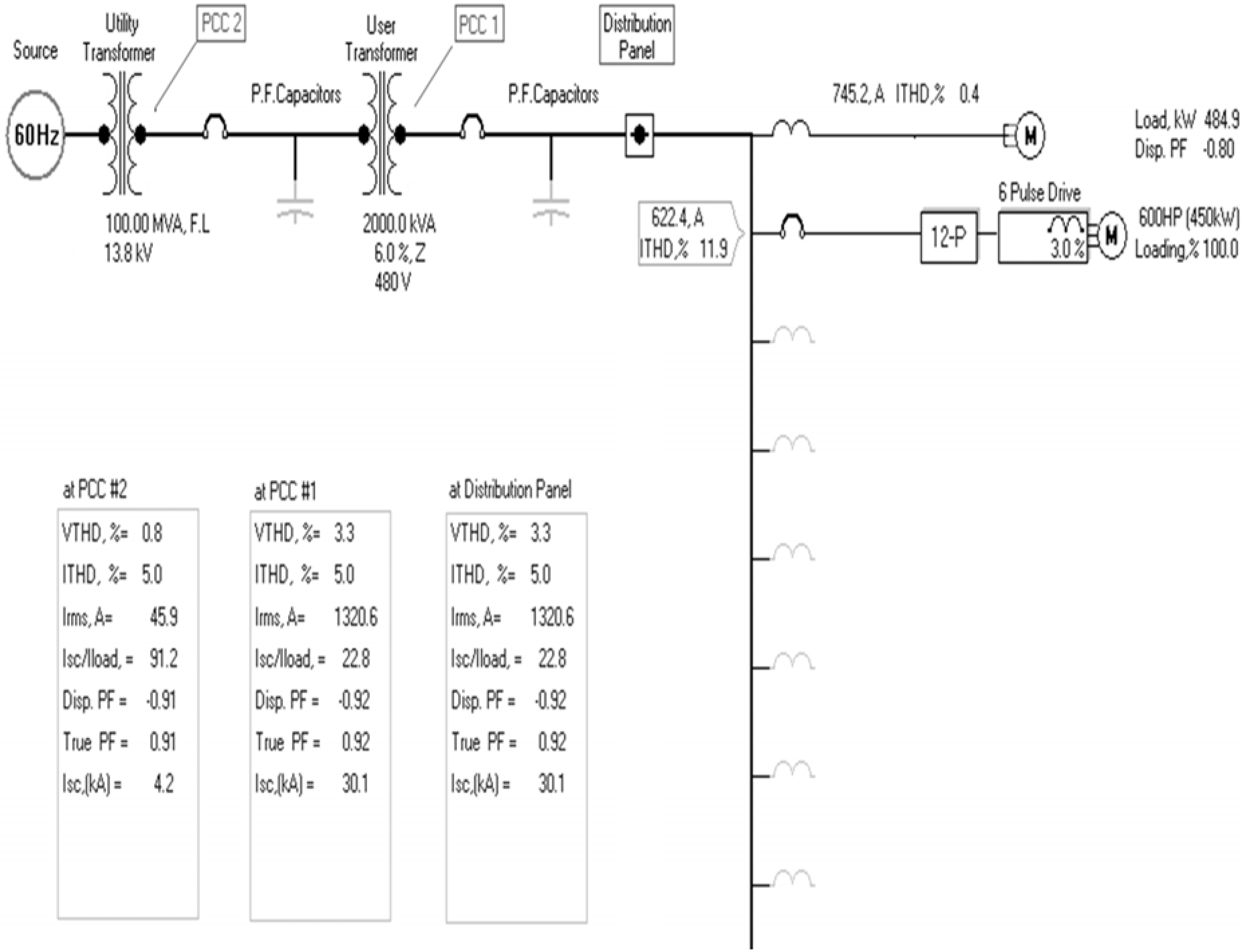
Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	5.0	5.0	FAIL
Max.Individual voltage harmonic	3.7 { 5}	3.0	FAIL
Current Total Demand Distortion(Itdd)	17.4	8.0	FAIL
Max.Individual current harmonic <11	16.2 { 5}	7.0	FAIL
11 to 16	3.1 {11}	3.5	PASS
17 to 22	1.3 {17}	2.5	PASS
23 to 34	0.6 {23}	1.0	PASS
>35	0.2 {35}	0.5	PASS

Based on the information provided, this application will NOT meet IEEE Std 519 harmonic limits

Changed the drive to a 12 pulse.





Source
60Hz
Utility Transformer
100.00 MVA, F.L
13.8 kV
PCC 2
P.F.Capacitors
User Transformer
2000.0 kVA
6.0 %, Z
480 V
PCC 1
P.F.Capacitors
Distribution Panel
745.2, A ITHD,% 0.4
Load, kW 484.9
Disp. PF -0.80
622.4, A
ITHD,% 11.9
12-P
6 Pulse Drive
3.0 %
600HP (450kW)
Loading,% 100.0
at PCC #2
VTHD, %= 0.8
ITHD, %= 5.0
Irms, A= 45.9
Isc/Iload, = 91.2
Disp. PF = -0.91
True PF = 0.91
Isc,(kA) = 4.2
at PCC #1
VTHD, %= 3.3
ITHD, %= 5.0
Irms, A= 1320.6
Isc/Iload, = 22.8
Disp. PF = -0.92
True PF = 0.92
Isc,(kA) = 30.1
at Distribution Panel
VTHD, %= 3.3
ITHD, %= 5.0
Irms, A= 1320.6
Isc/Iload, = 22.8
Disp. PF = -0.92
True PF = 0.92
Isc,(kA) = 30.1

IEEE Std 519 Compliance Report

The following report describes the expected perfomance of a selected Variable Speed Drive(VSD) application under chosen conditions.
It includes a summary of the applications ability to meet IEEE Std 519 harmonic limits at the defined Point of Common Coupling (PCC) and has been prepared through the use of "SOLV" computer simulation software.
Calculations are approximate values. Actual performance may vary due to field conditions.

Project Name: **NEW**

Point of Coupling: **PCC #2**

Short-circuit ratio 91.2

Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	0.8	5.0	PASS
Max.Individual voltage harmonic	0.5 {11}	3.0	PASS
Current Total Demand Distortion(Itdd)	5.0	12.0	PASS
Max.Individual current harmonic <11	0.1 { 5}	10.0	PASS
11 to 16	4.1 {11}	4.5	PASS
17 to 22	0.0 {19}	4.0	PASS
23 to 34	1.0 {23}	1.5	PASS
>35	0.3 {35}	0.7	PASS

Based on the information provided, this application will meet IEEE Std 519 harmonic limits

Point of Coupling: **PCC #1**

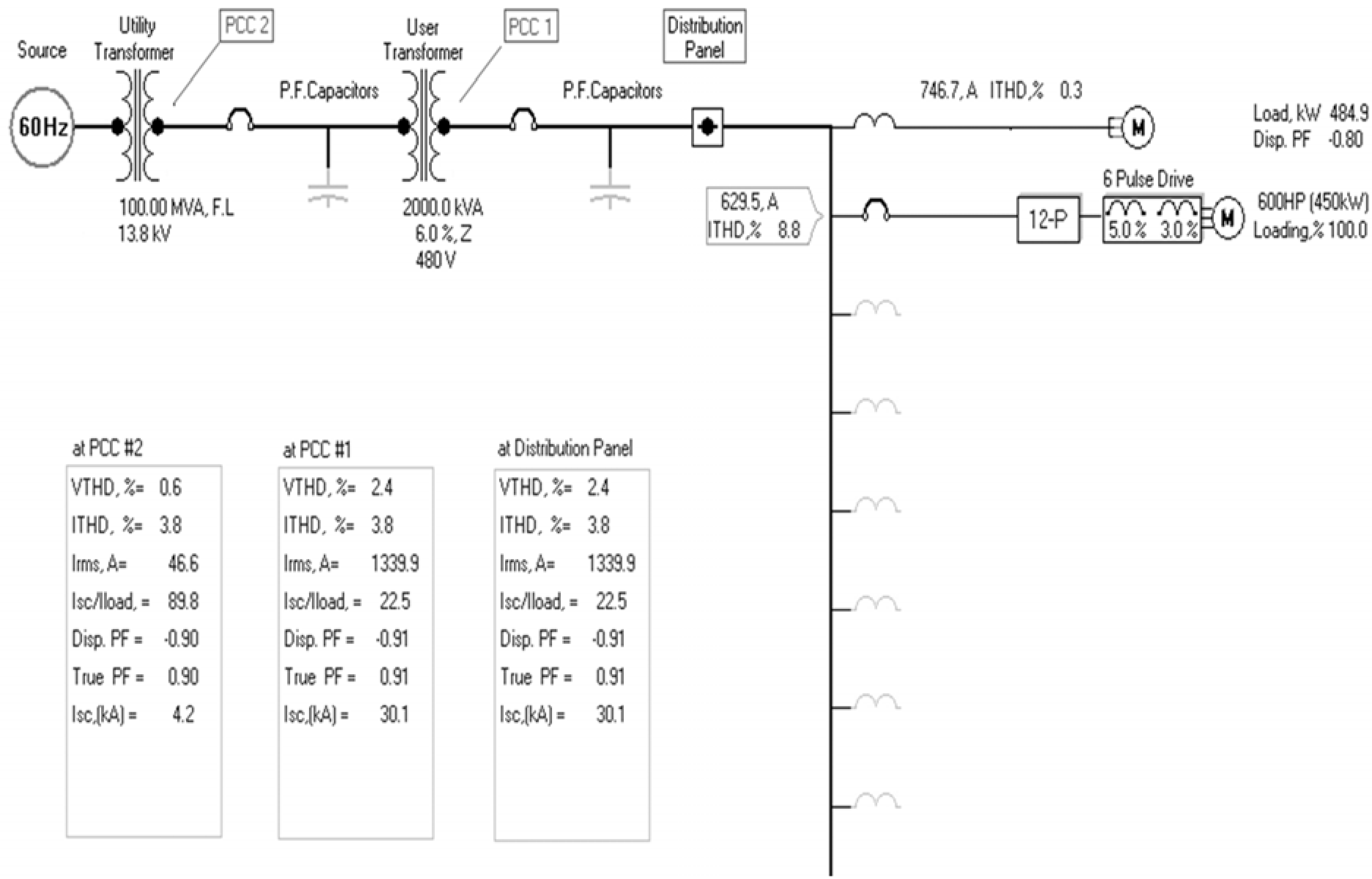
Short-circuit ratio 22.8

Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	3.3	5.0	PASS
Max.Individual voltage harmonic	2.1 {11}	3.0	PASS
Current Total Demand Distortion(Itdd)	5.0	8.0	PASS
Max.Individual current harmonic <11	0.1 { 5}	7.0	PASS
11 to 16	4.1 {11}	3.5	FAIL
17 to 22	0.0 {19}	2.5	PASS
23 to 34	1.0 {23}	1.0	PASS
>35	0.3 {35}	0.5	PASS

Based on the information provided, this application will NOT meet IEEE Std 519 harmonic limits

12 pulse with 5% AC reactor.



IEEE Std 519 Compliance Report

The following report describes the expected perfomance of a selected Variable Speed Drive(VSD) application under chosen conditions.
It includes a summary of the applications ability to meet IEEE Std 519 harmonic limits at the defined Point of Common Coupling (PCC) and has been prepared through the use of "SOLV" computer simulation software.
Calculations are approximate values. Actual performance may vary due to field conditions.

Project Name: **NEW**

Point of Coupling: **PCC #2**

Short-circuit ratio 89.8

Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	0.6	5.0	PASS
Max.Individual voltage harmonic	0.4 {11}	3.0	PASS
Current Total Demand Distortion(Itdd)	3.8	12.0	PASS
Max.Individual current harmonic <11	0.1 { 5}	10.0	PASS
11 to 16	3.1 {11}	4.5	PASS
17 to 22	0.0 {17}	4.0	PASS
23 to 34	0.5 {23}	1.5	PASS
>35	0.3 {35}	0.7	PASS

Based on the information provided, this application will meet IEEE Std 519 harmonic limits

Point of Coupling: **PCC #1**

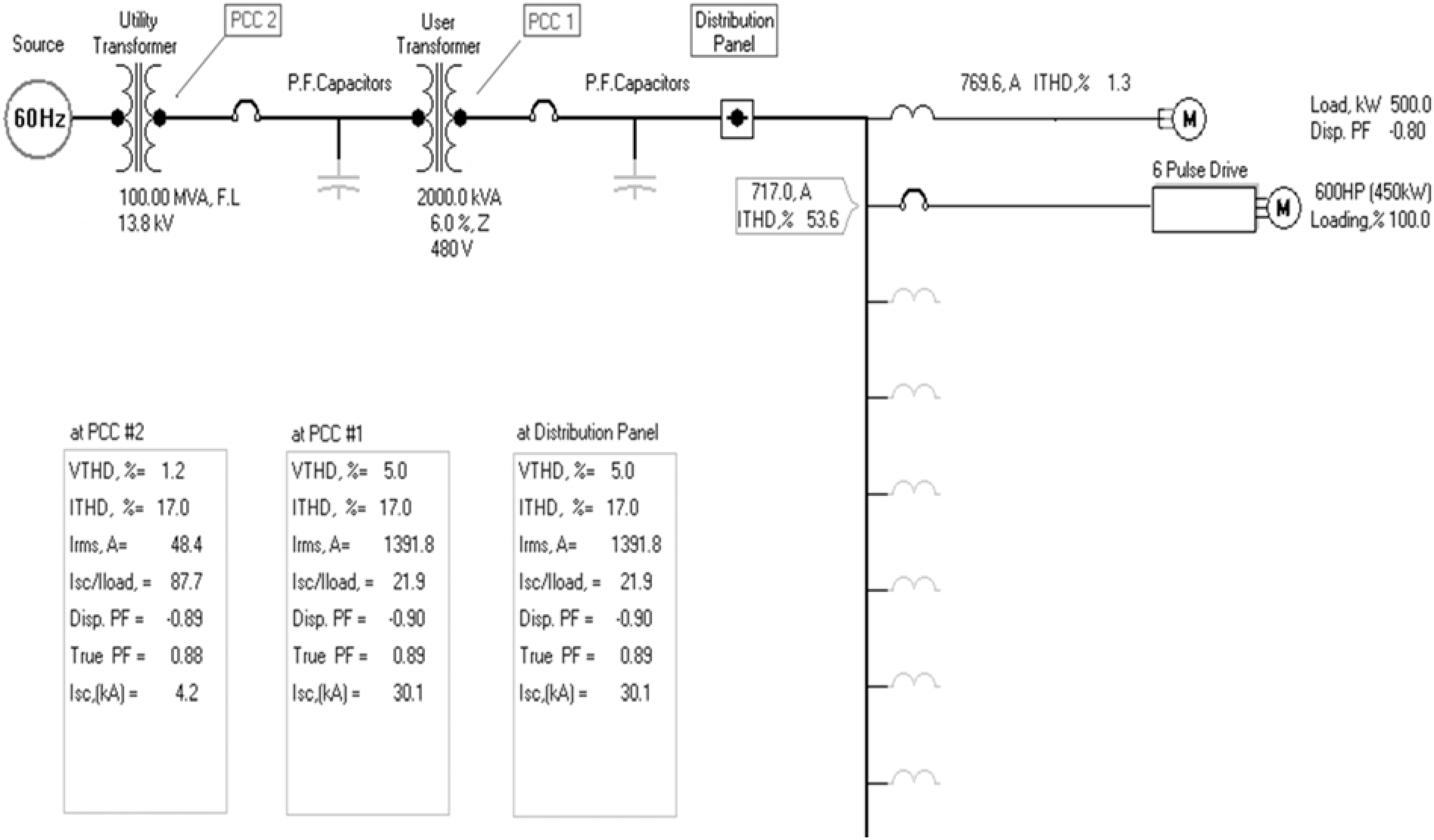
Short-circuit ratio 22.5

Summary of Compliance with IEEE Std 519 Harmonic Limits:

	Calculated Value, %	IEEE-519 Limit, %	
Voltage Total Harmonic Distortion(Vthd)	2.4	5.0	PASS
Max.Individual voltage harmonic	1.6 {11}	3.0	PASS
Current Total Demand Distortion(Itdd)	3.8	8.0	PASS
Max.Individual current harmonic <11	0.1 { 5}	7.0	PASS
11 to 16	3.1 {11}	3.5	PASS
17 to 22	0.0 {17}	2.5	PASS
23 to 34	0.5 {23}	1.0	PASS
>35	0.3 {35}	0.5	PASS

Based on the information provided, this application will meet IEEE Std 519 harmonic limits

Add PF Correction



at PCC #2

VTHD, %=	1.2
ITHD, %=	17.0
Irms, A=	48.4
Isc/Iload, =	87.7
Disp. PF =	-0.89
True PF =	0.88
Isc,(kA) =	4.2

at PCC #1

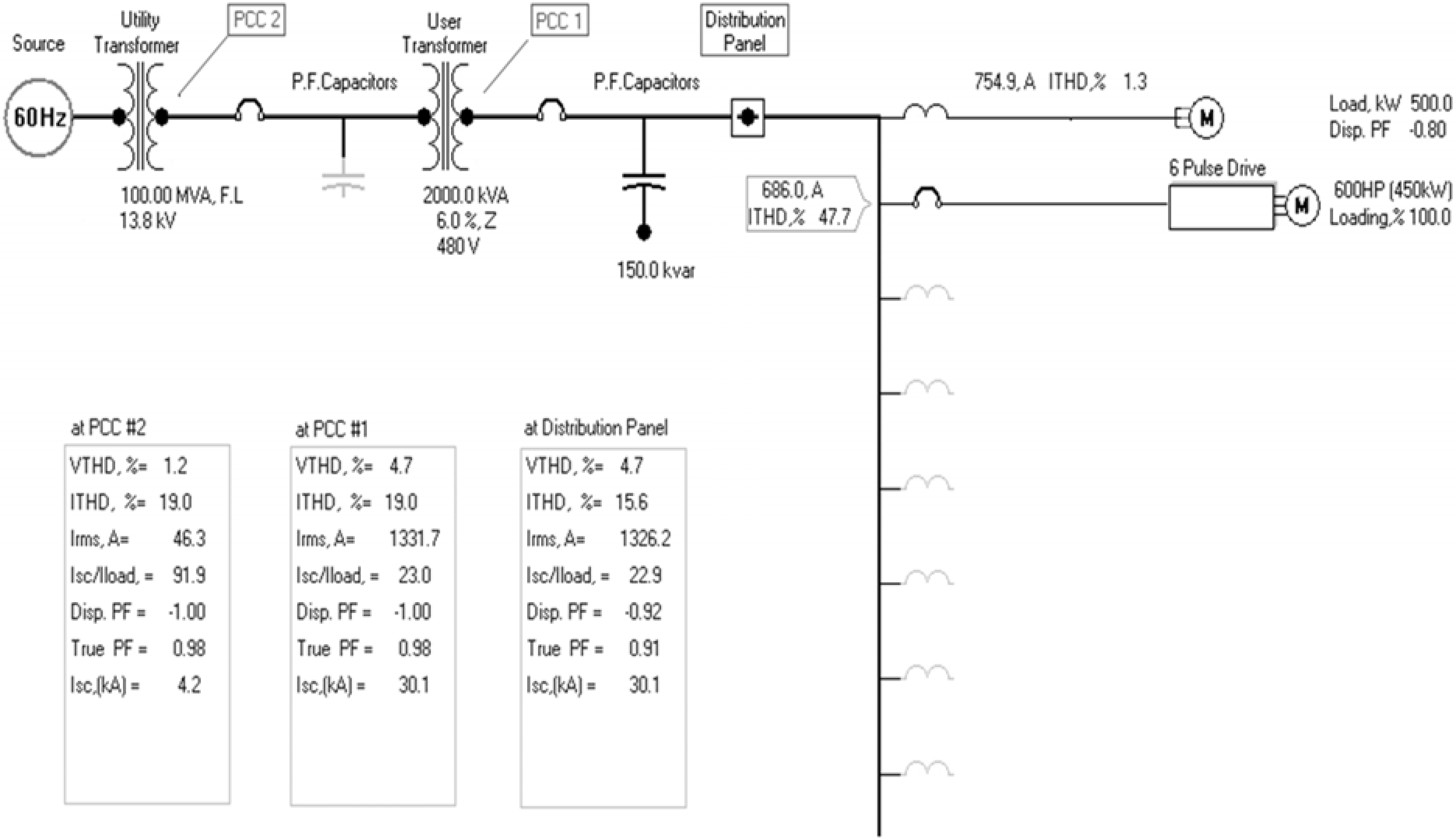
VTHD, %=	5.0
ITHD, %=	17.0
Irms, A=	1391.8
Isc/Iload, =	21.9
Disp. PF =	-0.90
True PF =	0.89
Isc,(kA) =	30.1

at Distribution Panel

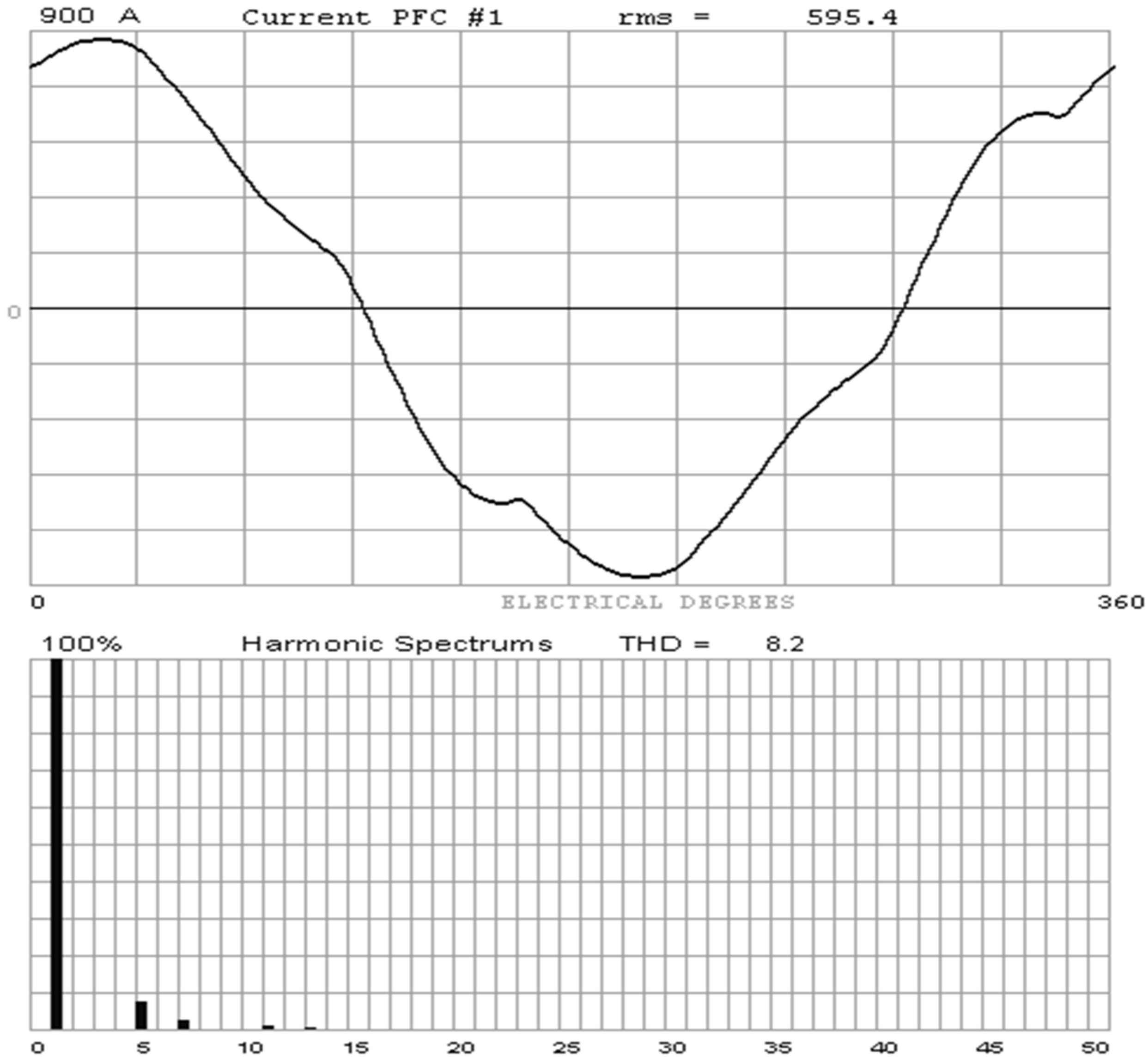
VTHD, %=	5.0
ITHD, %=	17.0
Irms, A=	1391.8
Isc/Iload, =	21.9
Disp. PF =	-0.90
True PF =	0.89
Isc,(kA) =	30.1

Cap no tuning

Add PF Correction



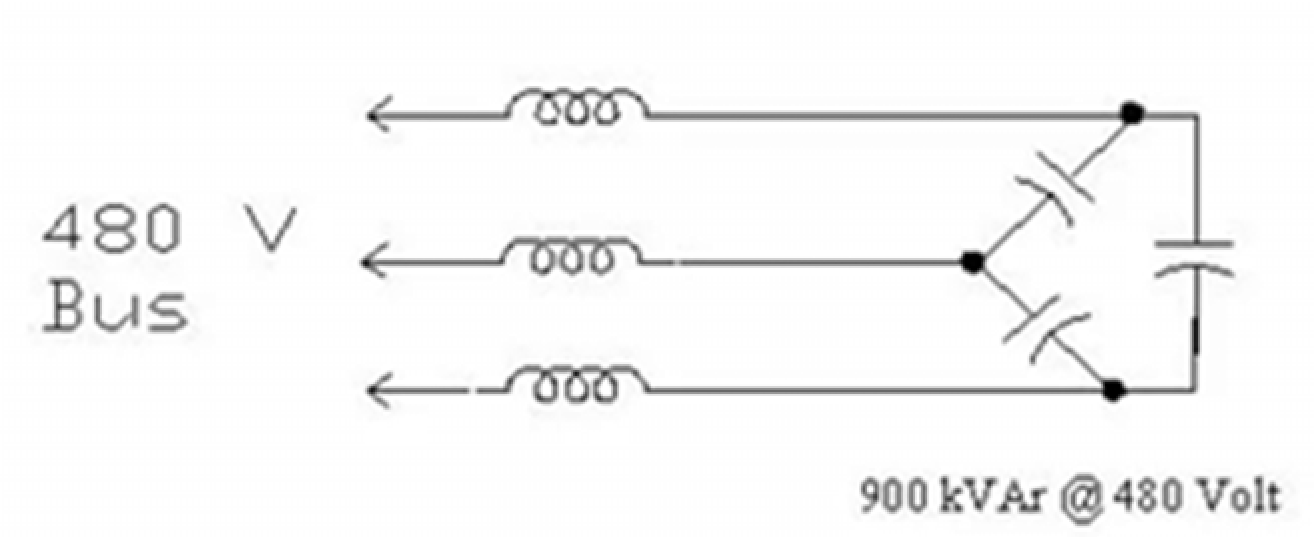
Cap tuned to 3rd harmonic



Harmonic Analysis

- Build a model of the system of interest
- Determine harmonic source characteristics
- Run simulation
- Examine results
- Design Solutions
- Check Solutions

- In general it is best to apply the filter at or below the lowest harmonic of concern
- The filter schematic is shown below.



- Harmonic control devices
  - In-line reactors (chokes)
  - Zigzag transformers
  - Passive filters
  - Active filters
  - Designing a harmonic filter

In-line reactors (chokes)

- Simply a series inductance
  - Presents a series impedance that is directly proportional to frequency
  - Forces DC bus capacitor to charge more slowly
  - Additional benefit:
    - Reduces DC bus overvoltages due to capacitor switching transients – reduced nuisance tripping

In-line reactors (chokes)

- Sizing the in-line reactor
  - Line reactors are typically described as "a 3% reactor", 3% to 5% are common
  - Size is based on the VA base of the drive

$$X_{L\_5\%} := 0.05 \frac{\left| V_{base} \right|^2}{VA_{base}}$$

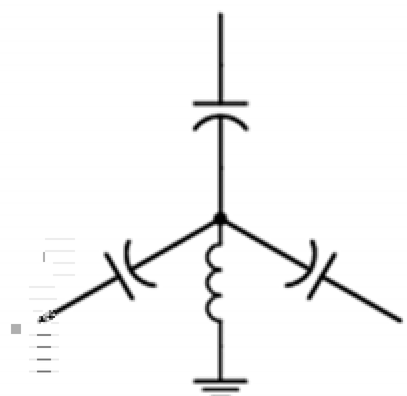
  - Inductance in Henrys is based on X_L at the fundamental frequency

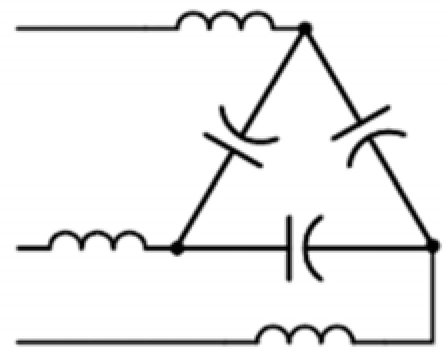
Passive filters

- Capacitors and inductors can be arranged to produce high or low impedances at certain frequencies
- Resistors can be added to provide damping
- Shunt passive filters – provide a low-impedance alternate path
- Series passive filters – increase the series impedance for certain frequencies

Passive filters

- Shunt passive filters
  - Notch filter is the most popular
  - May employ delta or wye connected capacitors connected to the line or neutral through inductors





Passive filters

- Series passive filters
  - Provide a high impedance to the target harmonic
  - Must carry full load current
  - Not practical for multiple harmonics
  - Useful in single-phase applications

General approach with passive filters

- Start at the lowest harmonic of concern
- Tune filters slightly lower than the target harmonic
- Check for resonant points creating high impedances
- If system impedance changes, re-evaluate filter

Active filters

- Use power-electronics to inject the missing current in the non-linear load’s current waveform
- Results in minimal distortion on the source side
- No resonance concerns
- May also correct power factor and flicker

Harmonic Summary

- Harmonics are persistent distortions in a waveshape.
- Power electronics are the prime source of harmonics.
- Power factor capacitors aggravate harmonic issues.
- Modeling and simulations can evaluation various solution alternatives.

Understanding Power Concepts

Part 3

- ***Motors***
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (*VFD* and *Harmonics)*
  - ***Application Considerations***
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

Application considerations

- **AC line harmonics**
- While harmonics in the PWM output can easily be filtered by carrier frequency related filter inductance to supply near-sinusoidal currents to the motor load,
- the VFD's diode-bridge rectifier converts AC line voltage to DC voltage output by super-imposing non-linear half-phase current pulses thus creating harmonic current distortion, and hence voltage distortion, of the AC line input.
- When the VFD loads are relatively small in comparison to the large, stiff power system available from the electric power company, the effects of VFD harmonic distortion of the AC grid can often be within acceptable limits.

Application considerations

- **AC line harmonics**

- Furthermore, in low voltage networks, harmonics caused by single phase equipment such as computers and TVs are partially cancelled by three-phase diode bridge harmonics because their 5th and 7th harmonics are in counterphase.

- However, when the proportion of VFD and other non-linear load compared to total load or of non-linear load compared to the stiffness at the AC power supply, or both, is relatively large enough, the load can have a negative impact on the AC power waveform available to other power company customers in the same grid.

Application considerations

- Two other harmonics mitigation techniques exploit use of passive or active filters connected to a common bus with at least one VFD branch load on the bus.

- Passive filters involve the design of one or more low-pass LC filter traps, each trap being tuned as required to a harmonic frequency (5th, 7th, 11th, 13th, . . . kq+/-1, where k=integer, q=pulse number of converter).

Application considerations

- When the power company's voltage becomes distorted due to harmonics, losses in other loads such as normal fixed-speed AC motors are increased. This may lead to overheating and shorter operating life.

- Also substation transformers and compensation capacitors are affected negatively. In particular, capacitors can cause resonance conditions that can unacceptably magnify harmonic levels.

Application considerations

- In order to limit the voltage distortion, owners of VFD load may be required to install filtering equipment to reduce harmonic distortion below acceptable limits.
- Alternatively, the utility may adopt a solution by installing filtering equipment of its own at substations affected by the large amount of VFD equipment being used.
- In high power installations harmonic distortion can be reduced by supplying multi-pulse rectifier-bridge VFDs from transformers with multiple phase-shifted windings.

Application considerations

- It is also possible to replace the standard diode-bridge rectifier with a bi-directional IGBT switching device bridge mirroring the standard inverter which uses IGBT switching device output to the motor.

- Such rectifiers are referred to by various designations including active infeed converter (AIC), active rectifier, IGBT supply unit (ISU), active front end (AFE) or four-quadrant operation.

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Application considerations

- With PWM control and suitable input reactor, AFE's AC line current waveform can be nearly sinusoidal. AFE inherently regenerates energy in four-quadrant mode from the DC side to the AC grid.

- Thus no braking resistor is needed and the efficiency of the drive is improved if the drive is frequently required to brake the motor.

Application considerations

Long lead effects

- The carrier frequency pulsed output voltage of a PWM VFD causes rapid rise times in these pulses, the transmission line effects of which must be considered.

- Since the transmission-line impedance of the cable and motor are different, pulses tend to reflect back from the motor terminals into the cable.

Application considerations

Long lead effects

- The resulting voltages can produce overvoltages equal to twice the DC bus voltage or up to 3.1 times the rated line voltage for long cable runs, putting high stress on the cable and motor windings and eventual insulation failure.

- Note that standards for three-phase motors rated 230 V or less adequately protect against such long lead overvoltages.

Application considerations

Long lead effects

- On 460 or 575 V systems and inverters with 3rd generation 0.1 microsecond rise time IGBTs, the maximum recommended cable distance between VFD and motor is about 50 m or 150 feet.

Application considerations

Long lead effects

- Solutions to overvoltages caused by long lead lengths include
  - minimizing cable distance,
  - lowering carrier frequency,
  - installing dV/dt filters,
  - using inverter duty rated motors (that are rated 600 V to withstand pulse trains with rise time less than or equal to 0.1 microsecond, of 1,600 V peak magnitude), and
  - installing LCR low-pass sine wave filters.

Application considerations

Long lead effects

- Regarding lowering of carrier frequency, note that audible noise is noticeably increased for carrier frequencies less than about 6 kHz and is most noticeable at about 3 kHz.

Application considerations

Long lead effects

- Note also that selection of optimum PWM carrier frequency for AC drives involves balancing
  - noise,
  - heat,
  - motor insulation stress,
  - common mode voltage induced motor bearing current damage,
  - smooth motor operation, and other factors.

Further harmonics attenuation can be obtained by using an LCR low-pass sine wave filter or dV/dt filter.

Bearing Currents

Application considerations

Motor bearing currents

- PWM drives are inherently associated with high frequency common mode voltages and currents which may cause trouble with motor bearings.

- When these high frequency voltages find a path to earth through a bearing, transfer of metal or electrical discharge machining (EDM) sparking occurs between the bearing's ball and the bearing's race.

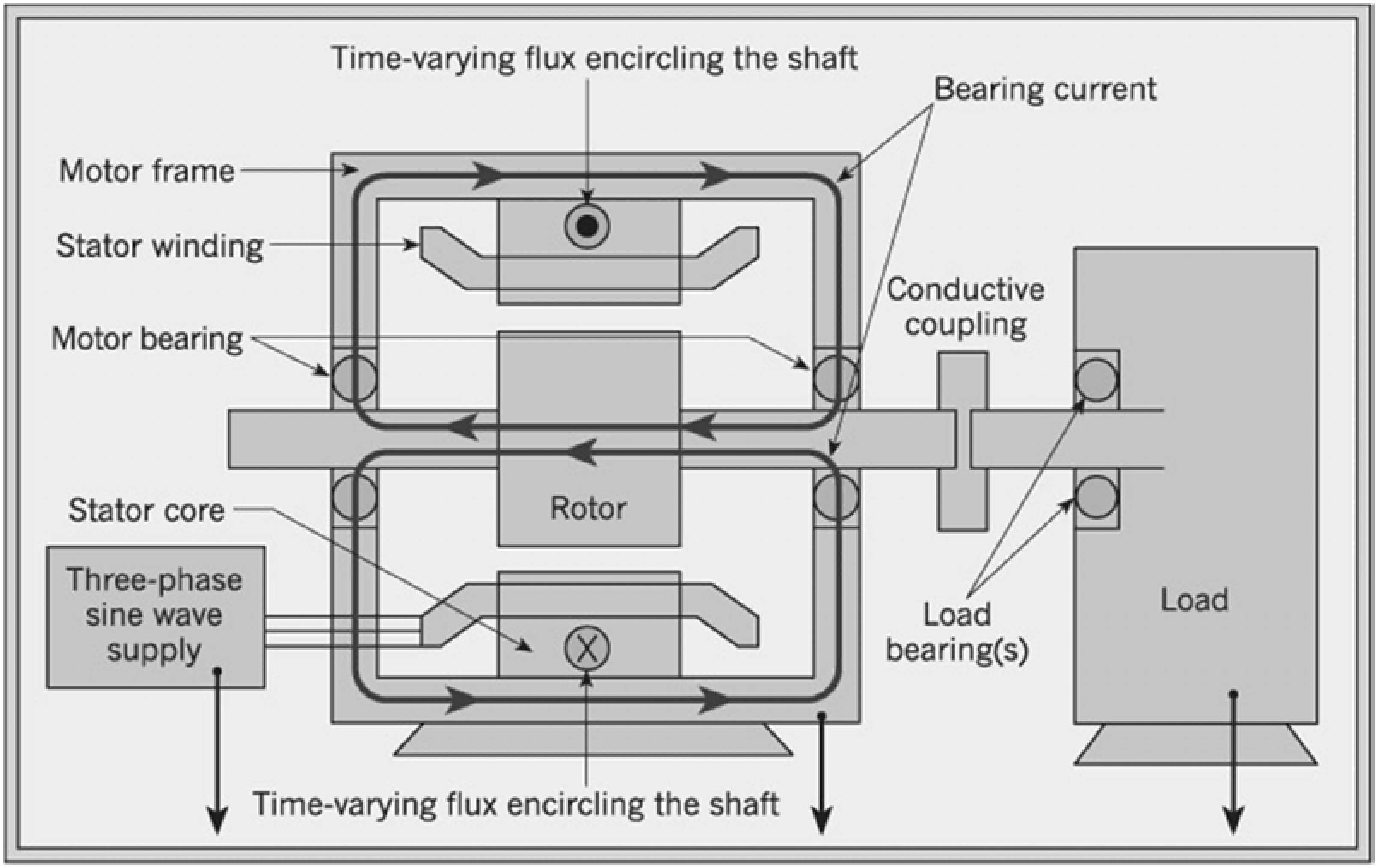
- Over time EDM-based sparking causes erosion in the bearing race that can be seen as a fluting pattern.

Bearing Currents

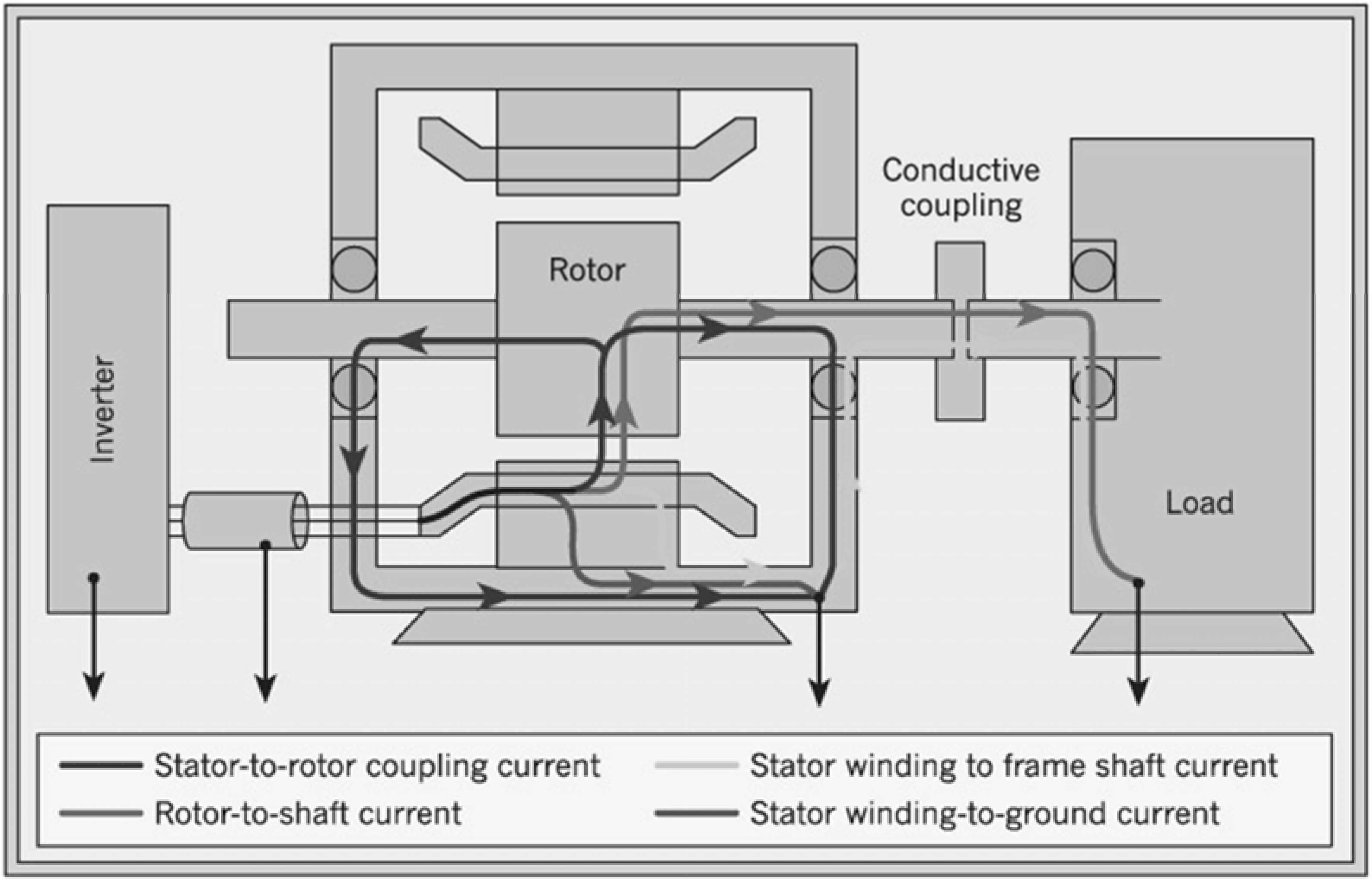
- Because the voltage output of the VFD is a result of high-speed switching, the waveform more closely resembles a square wave instead of a sine wave.

- As a consequence, an imbalance is present between the three phases that are entering the motor leads, referred to as common-mode voltage,

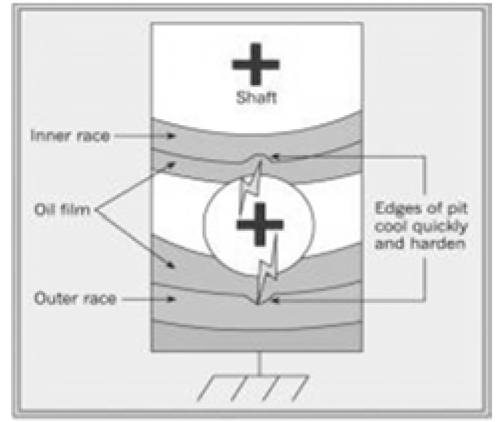
Bearing Currents



Bearing Currents



Bearing Currents



- As soon as the motor is started with a VFD, the common-mode voltage imbalance searches for a path to ground, and a parasitic coupling of the rotor and stator windings develops.

- Once the oil film in the dielectric breaks down, voltage levels increase on the motor shaft, and the lowest impedance path for the current imbalance becomes the motor bearings themselves.

- Voltage begins to arc across the bearing at high frequencies, leading to electrical discharge machining (EDM).

Application considerations

Motor bearing currents

- In large motors, the stray capacitance of the windings provides paths for high frequency currents that pass through the motor shaft ends, leading to a circulating type of bearing current.

- Poor grounding of motor stators can lead to shaft ground bearing currents. Small motors with poorly grounded driven equipment are susceptible to high frequency bearing currents.

Application considerations

Motor bearing currents

- Prevention of high frequency bearing current damage uses three approaches:
  - good cabling and grounding practices,
  - interruption of bearing currents, and
  - filtering or damping of common mode currents.

Application considerations

Motor bearing currents

Good cabling and grounding practices can include use of shielded, symmetrical-geometry power cable to supply the motor, installation of shaft grounding brushes, and conductive bearing grease.

Bearing currents can be interrupted by:

- installation of insulated bearings
- and specially designed electrostatic shielded induction motors.

Filtering and damping high frequency bearing, or, instead of using standard 2-level inverter drives, using either 3-level inverter drives or matrix converters.

Application considerations

Motor bearing currents

- Since inverter-fed motor cables' high frequency current spikes can interfere with other cabling in facilities, such inverter-fed motor cables should not only be of shielded, symmetrical-geometry design but should also be routed at least 50 cm away from signal cables.

Application considerations

- *Motor frame size* — Motor bearing currents have a direct relationship to motor size.

- Specifically, motors above 450 hp have been found to be the greatest candidates for bearing currents, due to the higher likelihood of magnetic asymmetry in the construction of the motor windings.

- While large motors will experience some amount of bearing currents, motors powered from VFDs introduce additional magnetic asymmetry from common-mode voltage.

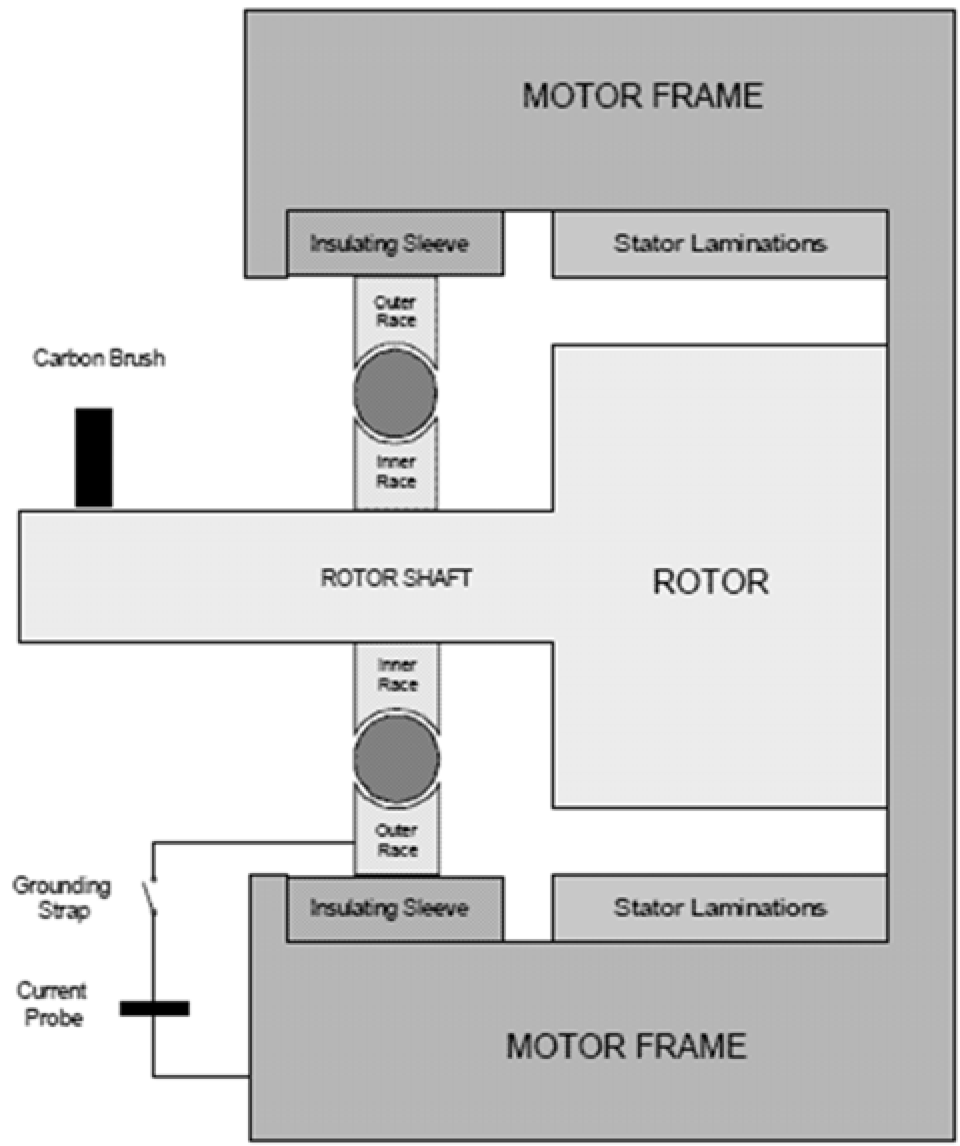
Application considerations

- *Rough handling*

- Motors are at an increased risk of shaft voltage if they were handled roughly during shipment.

- Oftentimes, damage can occur in the factory, in transit, or when the motor is being lifted onto its pedestal.

- Minor motor damage during shipment may not cause noticeable problems with motor performance; however, it increases the likelihood of magnetic asymmetry leading to bearing current development.



Physical Construction of the Test Motor

Measuring for Bearing Currents

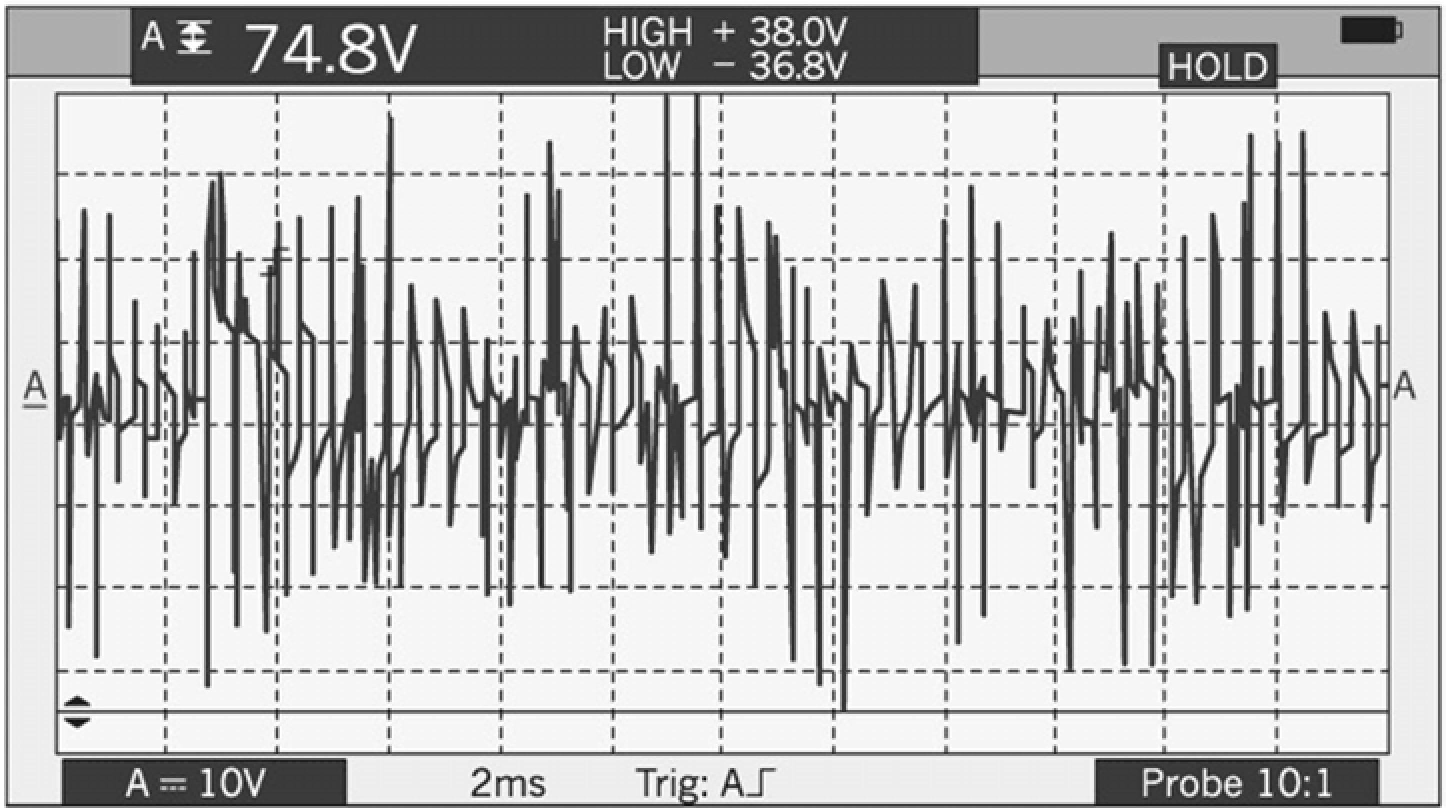
- After the ambient noise measurement has been completed, the carbon brush is placed directly to the spinning motor shaft.
- Several measurements should be recorded, with efforts to ensure the entire waveform can be viewed on the oscilloscope.

Measuring for Bearing Currents

- Careful observation of the waveform should reveal if a sharp spike in voltage is present, which would be indicative of a shaft voltage discharge.

- Voltage in excess of 0.5mV (peak-to-peak) is oftentimes cause for further investigation. However, in VFDs, the nominal value will almost always be in excess of 0.5mV. The examples discussed below indicate various examples of shaft voltage tests.

Motor A



Measuring for Bearing Currents

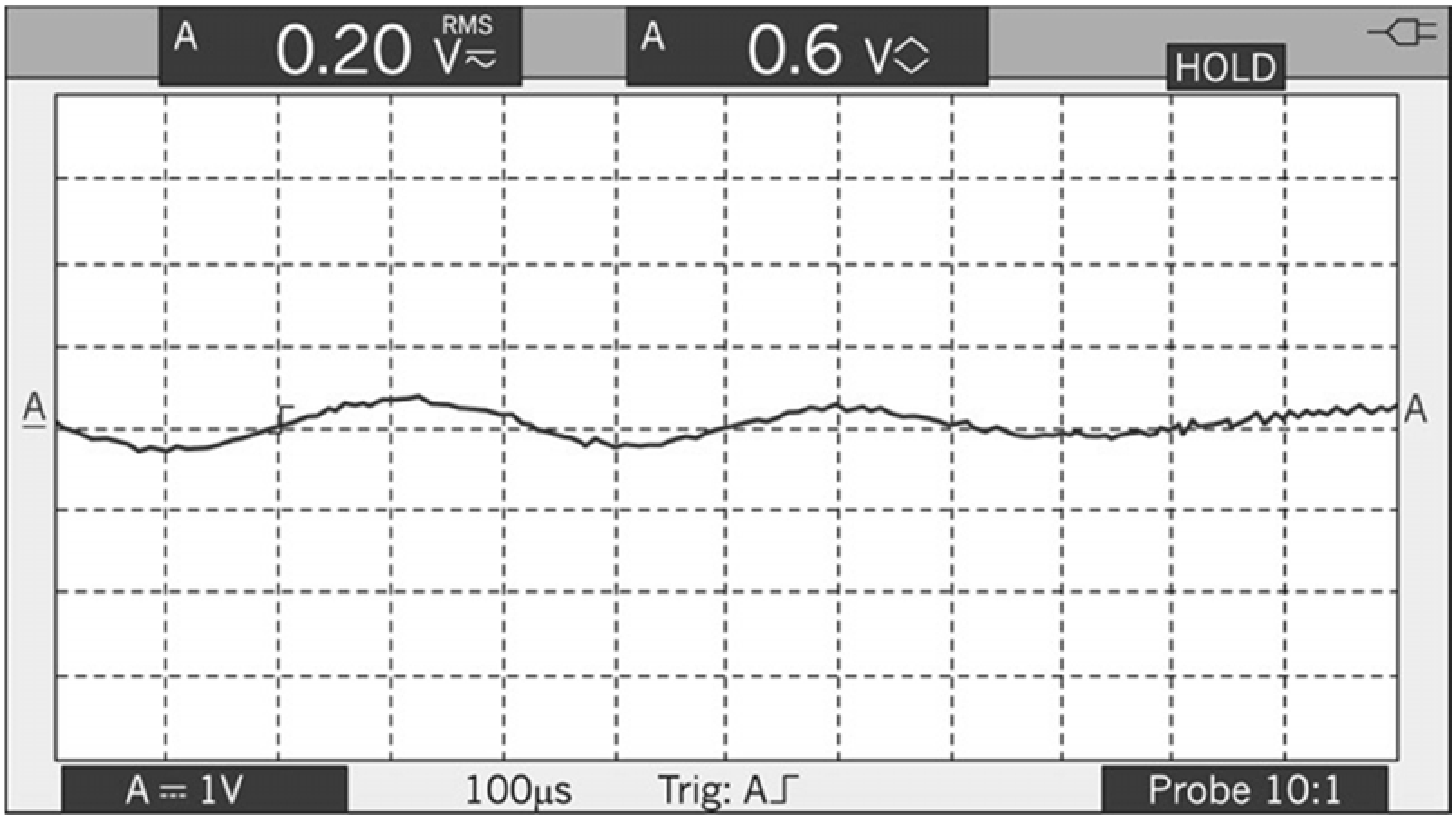
- The oscilloscope screenshot shown in presents clear evidence of shaft voltage, with a peak-to-peak value of 74.3V.
- This is well above the IEEE 112 allowable value of 0.5mV, as well as the manufacturer's allowable voltage of 1V to 2V for VFDs.
- A peak voltage of 74.3V imposed upon the shaft likely means that the bearing will not survive much longer unless remedied.

Compare Similar Motors

- When testing a motor, it is often useful to test the “B” motor to compare values.

- The screenshot shown in is the “B” motor of the across-the-line motor that was dropped during shipment.

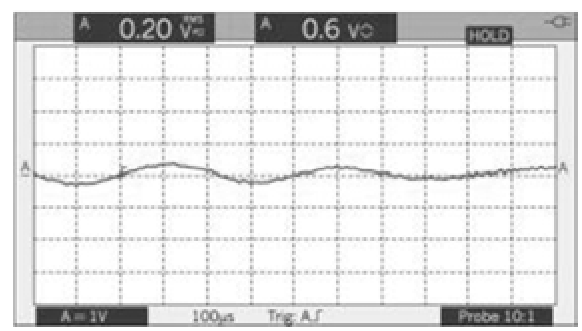
Motor B



Compare Similar Motors

- Clearly, there is no evidence of shaft voltage or damage to the bearing in this waveform.

- Oftentimes, comparing two similar motors can help pinpoint if the problem lies in the motor itself, with transient voltage power supplies, or in a faulty grounding system.



Application considerations

Dynamic braking

- Torque generated by the drive causes the induction motor to run at synchronous speed less the slip.

- If load inertia energy is greater than the energy delivered to the motor shaft, motor speed decreases as negative torque is developed in the motor and the motor acts as a generator, converting output shaft mechanical power back to electrical energy.

Application considerations

Dynamic braking

- This power is returned to the drive's DC link element (capacitor or reactor).

- A DC-link-connected electronic power switch or braking DC chopper (either built-in or external to the drive) transfers this energy to external resistors to dissipate the energy as heat.

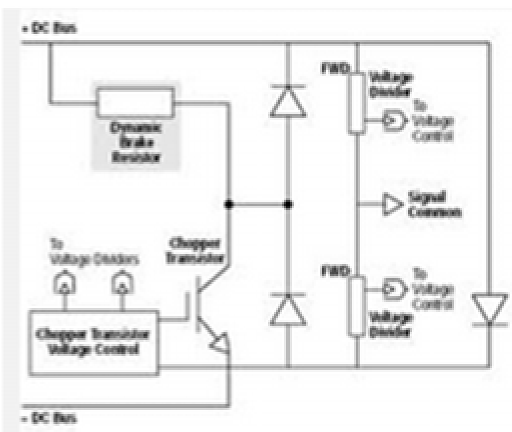
Application considerations

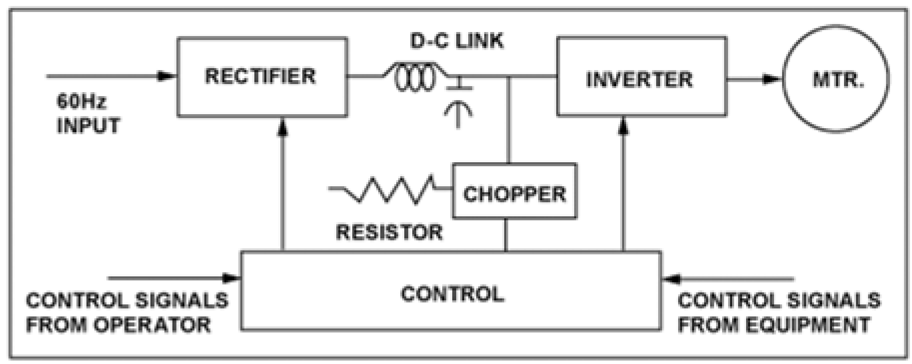
Dynamic braking

- Cooling fans may be used to prevent resistor overheating.
- Dynamic braking wastes braking energy by transforming it to heat. By contrast, regenerative drives recover braking energy by injecting this energy on the AC line.
- The capital cost of regenerative drives is however relatively high.

Application considerations

- **Dynamic braking**





Application considerations

- **Regenerative drives**
- Regenerative AC drives have the capacity to recover the braking energy of a load moving faster than the designated motor speed (an *overhauling* load) and return it to the power system.

- Current Source (Cycloconverter, Scherbius, matrix, CSI and LCI) drives inherently allow return of energy from the load to the line

- while voltage-source inverters require an additional converter to return energy to the supply.

Application considerations

Regenerative drives

- Regeneration is only useful in VFDs where the value of the recovered energy is large compared to the extra cost of a regenerative system, and if the system requires frequent braking and starting.

- Regenerative VFDs are widely used where speed control of overhauling loads is required.

Application considerations

Regenerative drives

Some examples:

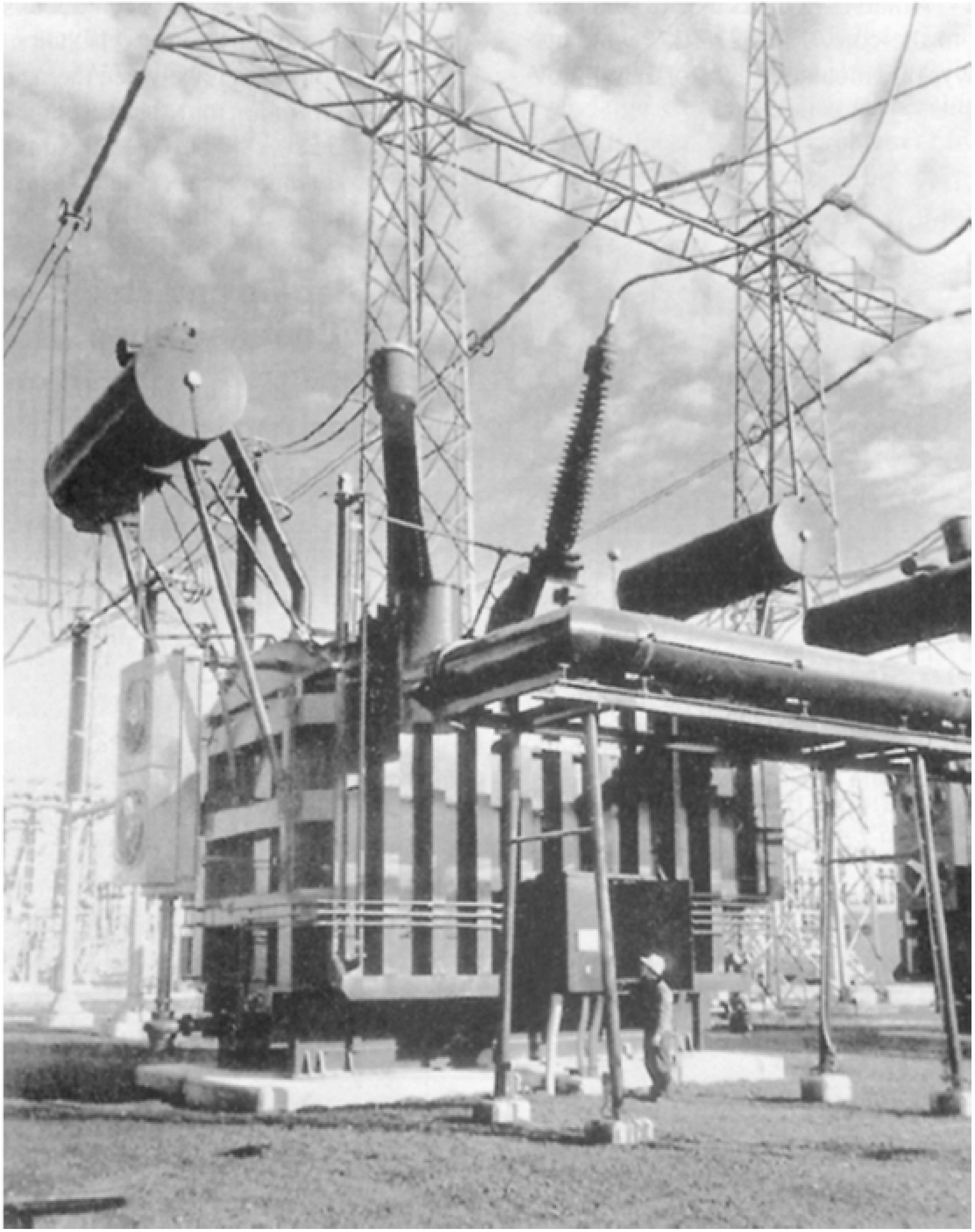
- Conveyor belt drives for manufacturing, which stop every few minutes. While stopped, parts are assembled correctly; once that is done, the belt moves on.

- A crane, where the hoist motor stops and reverses frequently, and braking is required to slow the load during lowering.

Understanding Power Concepts

Part 3

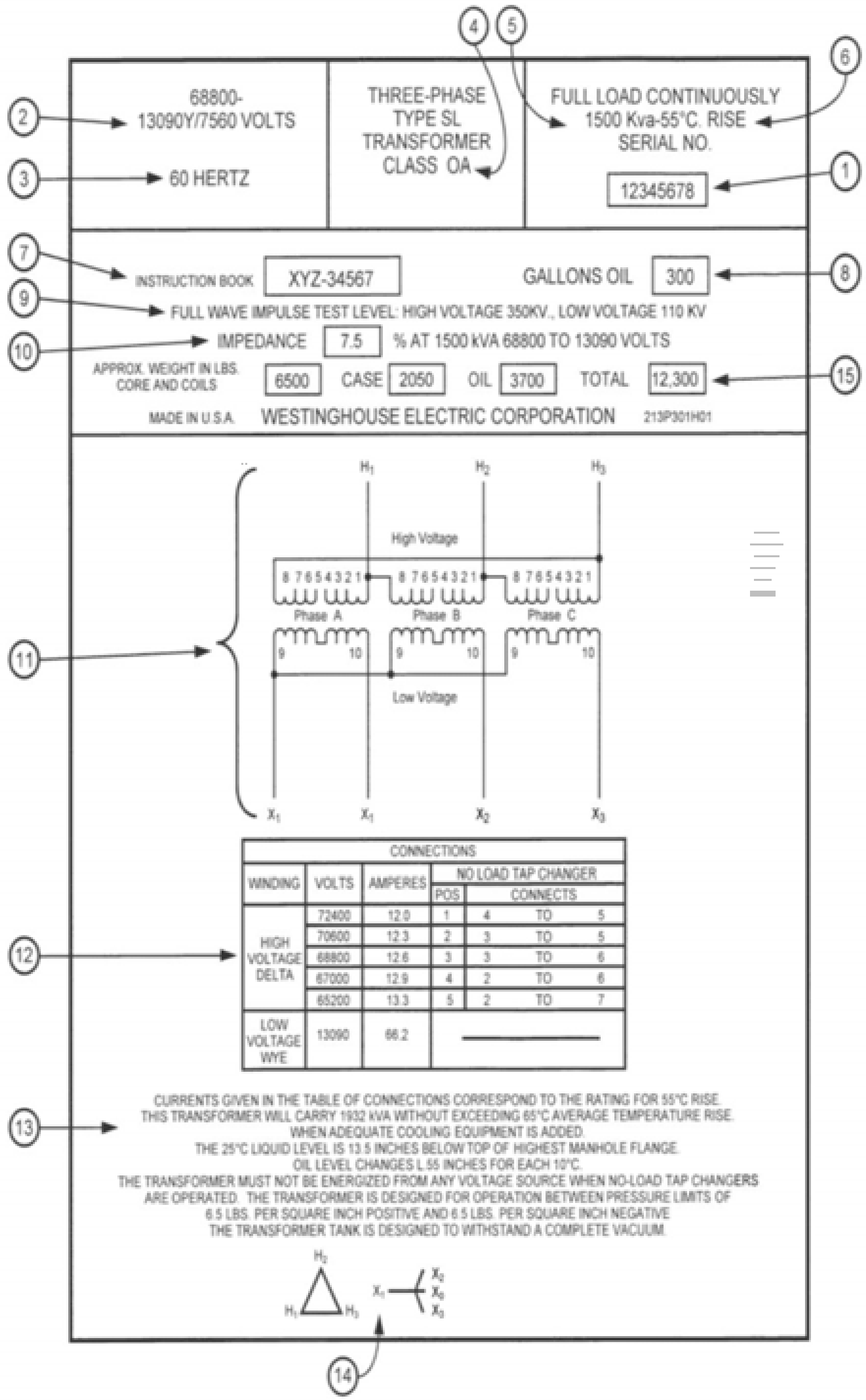
- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- ***Transformers***
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems



Introduction

- A transformer is an electrical device that can raise or lower a voltage of alternating current.

- Transformers are extensively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current (per ANSI C57.12.80).



Item No.	Item	Item Description
1	Serial Number	Identifies specific transformer
2	Voltage	Rated terminal-to-terminal voltage for the primary and secondary windings
3	Frequency	Frequency at which transformer is designed to operate
4	Cooling Class	Method used to dissipate the heat generated during operation
5	kVA	The kVA capacity transformer can transmit without exceeding stated temperature rise
6	Temperature Rise	Average winding rise above ambient temperature at rated kVA
7	Instruction Book	Instruction book that applies to the specific transformer
8	Gallons of Fluid	Liquid volume of oil in transformer
9	Impulse Levels	Full wave FIL (basic insulation level) in kilovolts of line and neutral terminals
10	Impedance	Percent impedance measured by test
11	Winding Connection Diagram	Winding connection diagram to show relative location of bushings and internal terminals
12	Connection Chart	Chart showing voltage, current, and connection of each tap changer position
13	Notes	Contains valuable information about operation and maintenance of transformer
14	Phase Relation	Phase rotation and phase angle shift between high voltage and low voltage windings
15	Approximate Weights	Information itemized to facilitate untanking and shipping

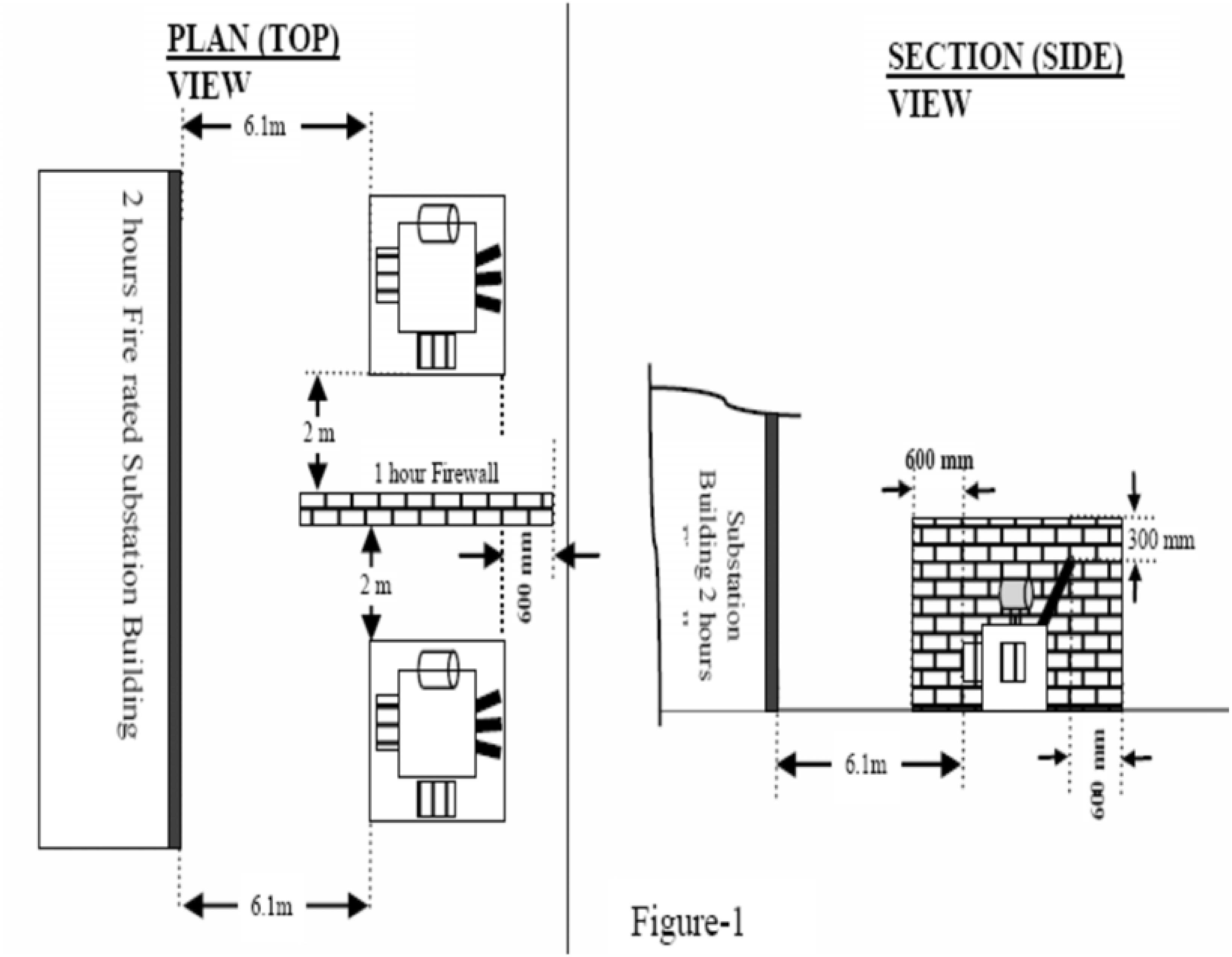
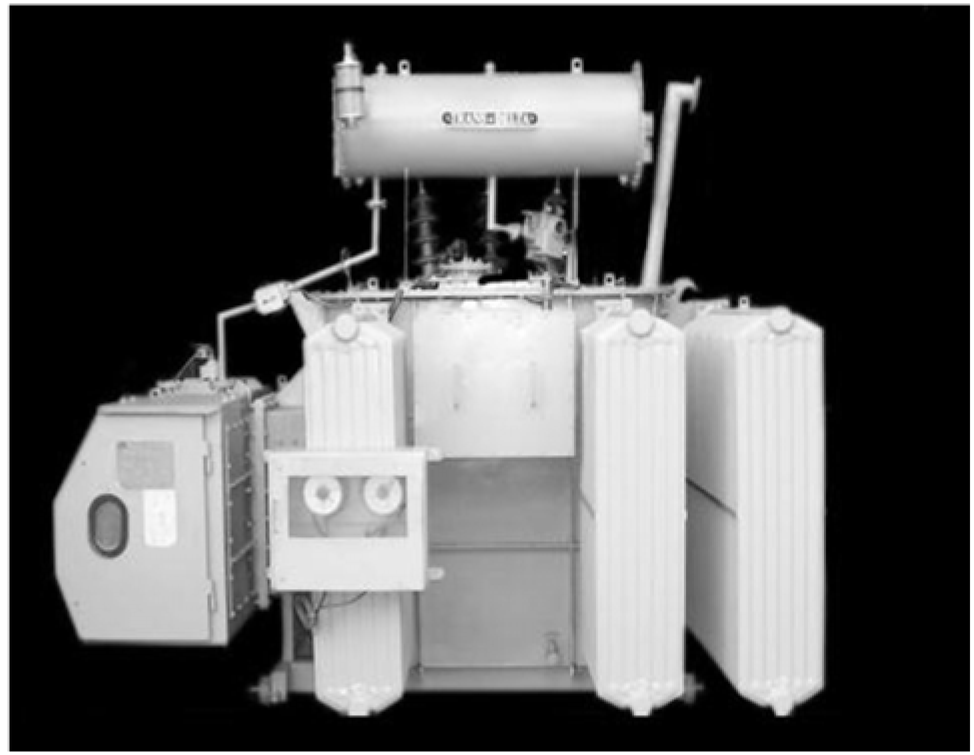

PLAN (TOP) VIEW
6.1m
2 hours Fire rated Substation Building
2 m
1 hour Firewall
2 m
600 mm
6.1m
SECTION (SIDE) VIEW
600 mm
300 mm
Substation Building 2 hours
6.1m
600 mm

Figure-1

WHAT IS A TRANSFORMER?

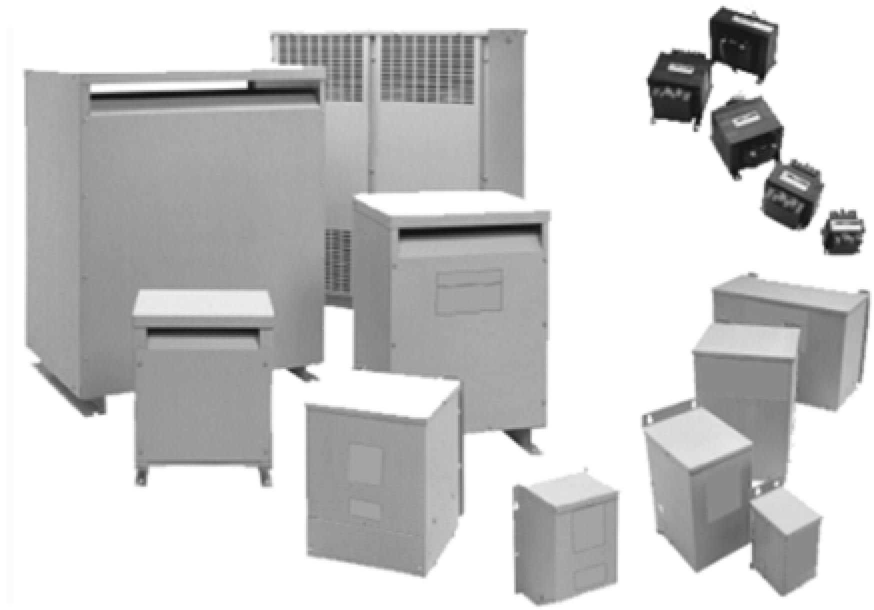
- TRANSFORMER IS A STATIC DEVICE WHICH TRANSFORMS A.C. ELECTRICAL POWER FROM ONE VOLTAGE TO ANOTHER VOLTAGE KEEPING THE FREQUENCY SAME BY ELECTROMAGNETIC INDUCTION.

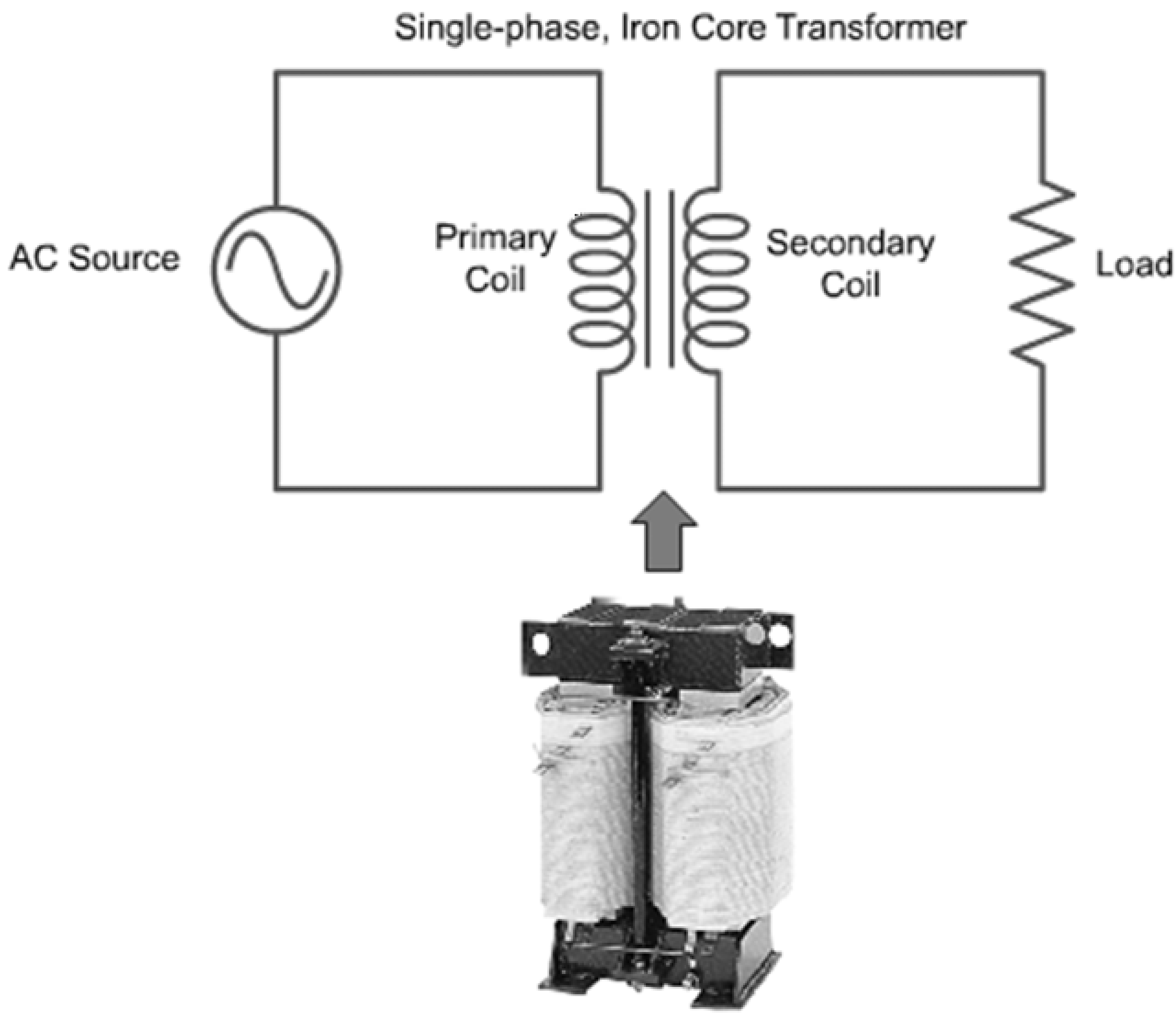


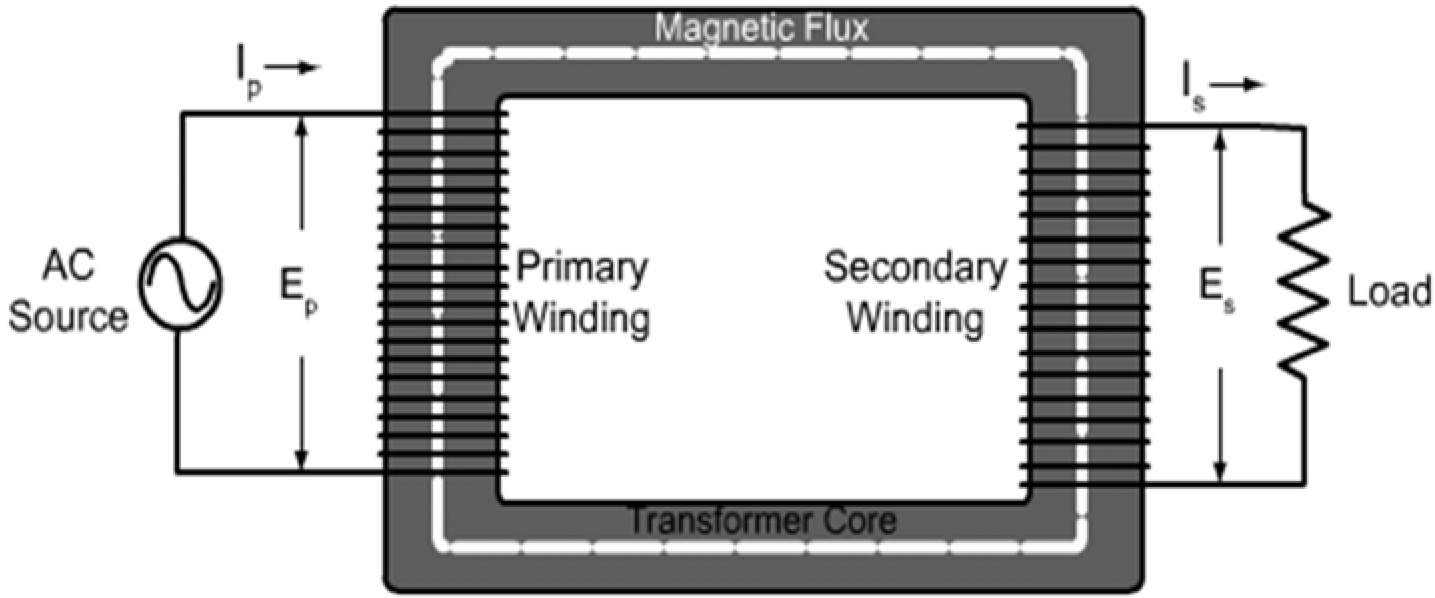
Dry Type Transformers

- Transformers come in a variety of sizes and ratings.

- Dry type transformers are rated for 600 VAC and below and intended for supplying appliance, lighting, and power loads. Typical supply voltages are 600, 480, 277, 240, and 208 VAC and typical load voltages are 480, 277, 240, 208,and 120 VAC.




Single-phase, Iron Core Transformer
AC Source
Primary
Coil
Secondary
Coil
Load



E_p = Primary Voltage

I_p = Primary Current

E_s = Secondary Voltage

I_s = Secondary Current

Step-up Transformer Example

Primary Voltage (E_p) = 120 V

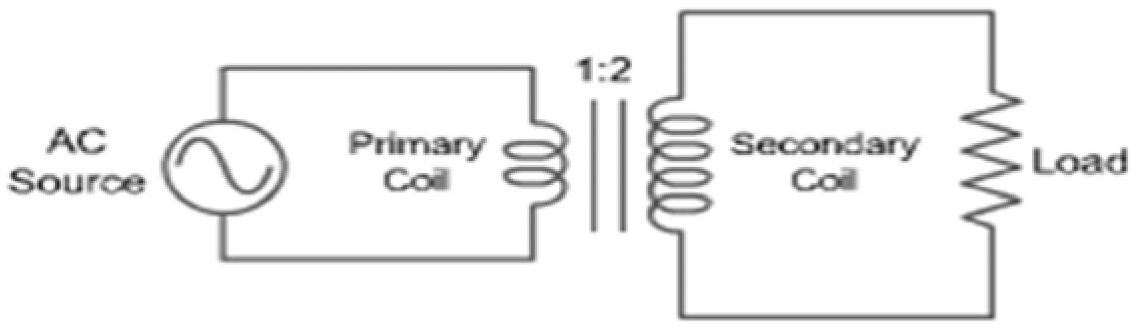
Primary Current (I_p) = 10 A

Number of Primary Turns (N_p) = 900

Secondary Voltage (E_s) = 240 V

Secondary Current (I_s) = 5 A

Number of Secondary Turns (N_s) = 1800



$$\frac{N_P}{N_S} = \frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$E_S = \frac{N_S E_P}{N_P}$$

$$I_S = \frac{N_P I_P}{N_S}$$

Step-down Transformer Example

Primary Voltage (E_p) = 240 V

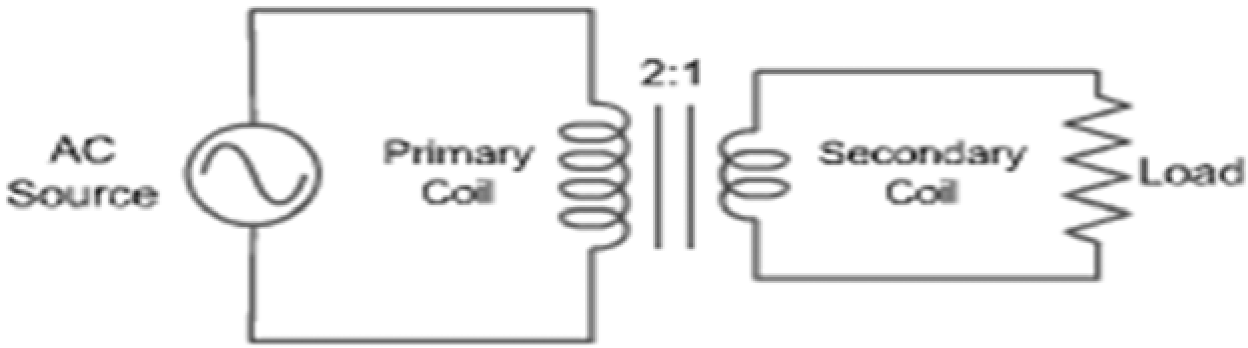
Primary Current (I_p) = 5 A

Number of Primary Turns (N_p) = 1800

Secondary Voltage (E_s) = 120 V

Secondary Current (I_s) = 10 A

Number of Secondary Turns (N_s) = 900

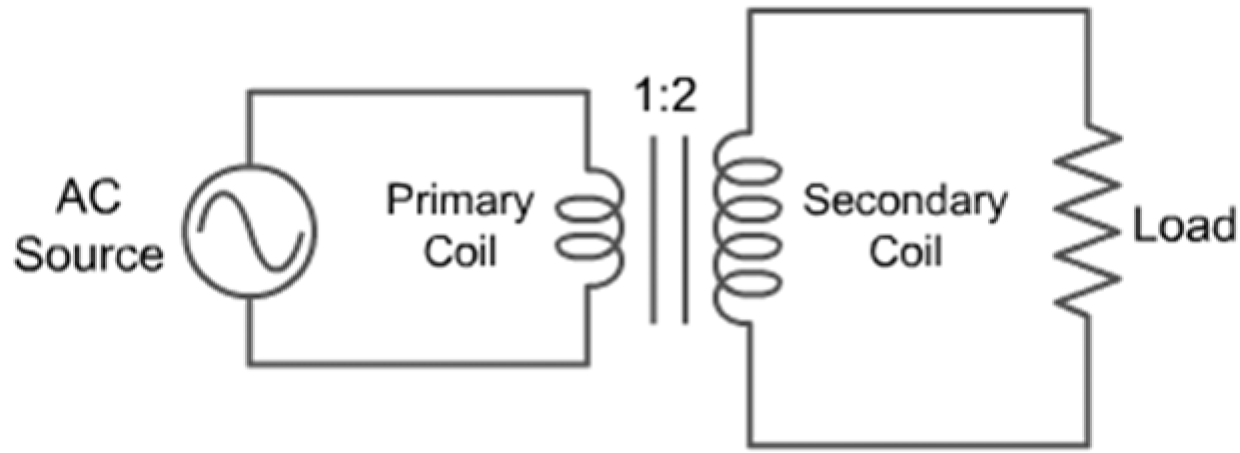


$$\frac{N_P}{N_S} = \frac{E_P}{E_S} = \frac{I_S}{I_P}$$

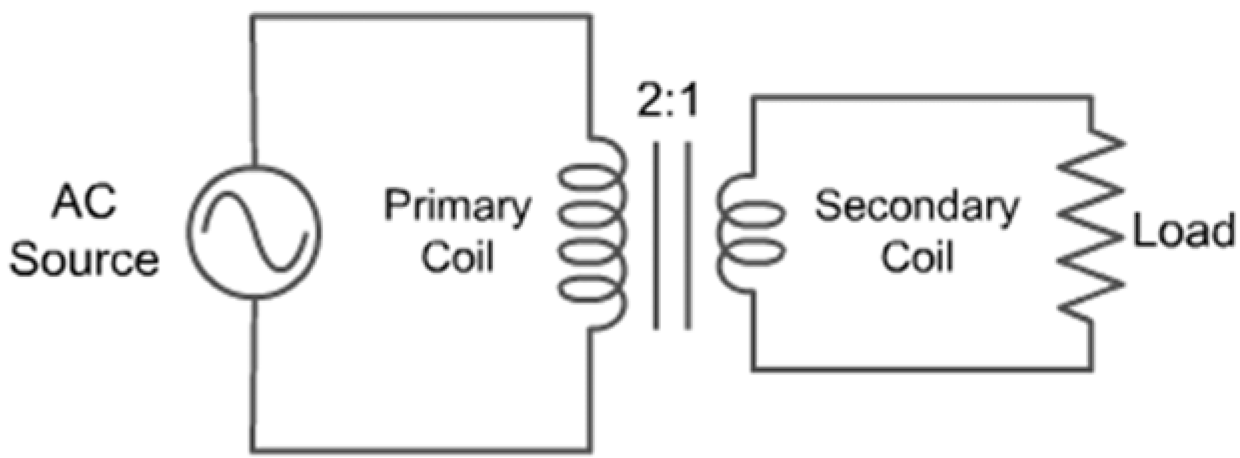
$$E_S = \frac{N_S E_P}{N_P}$$

$$I_S = \frac{N_P I_P}{N_S}$$

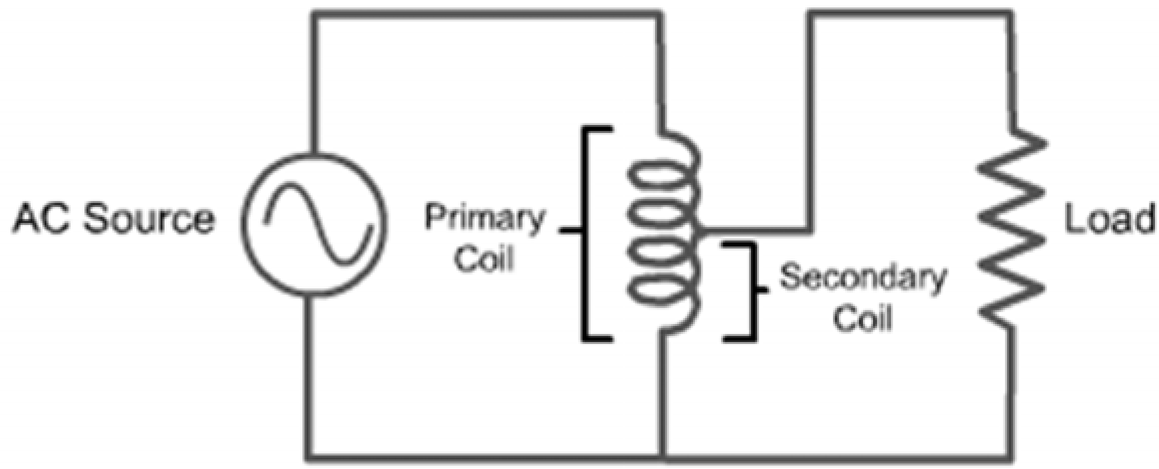
Step-up Transformer



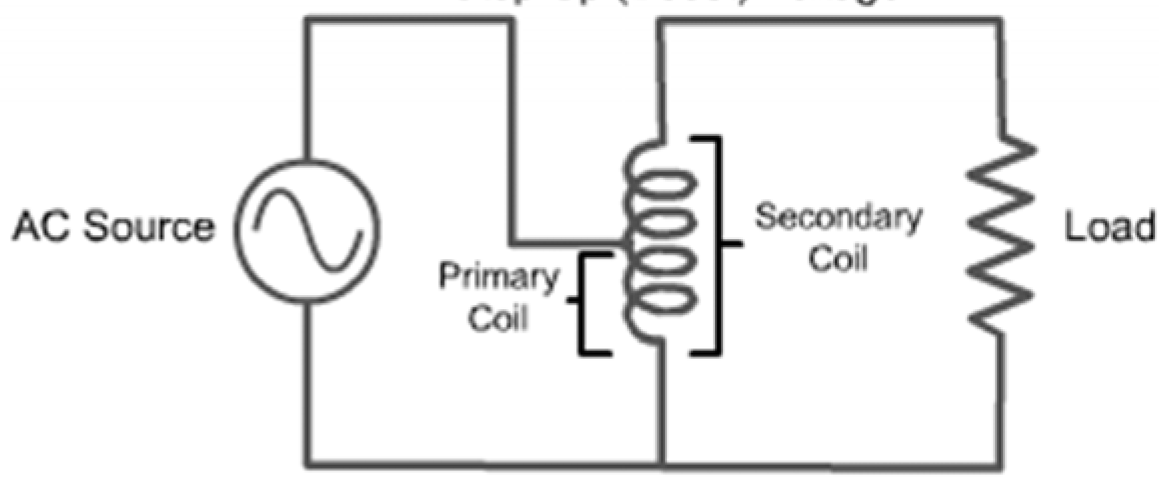
Step-down Transformer



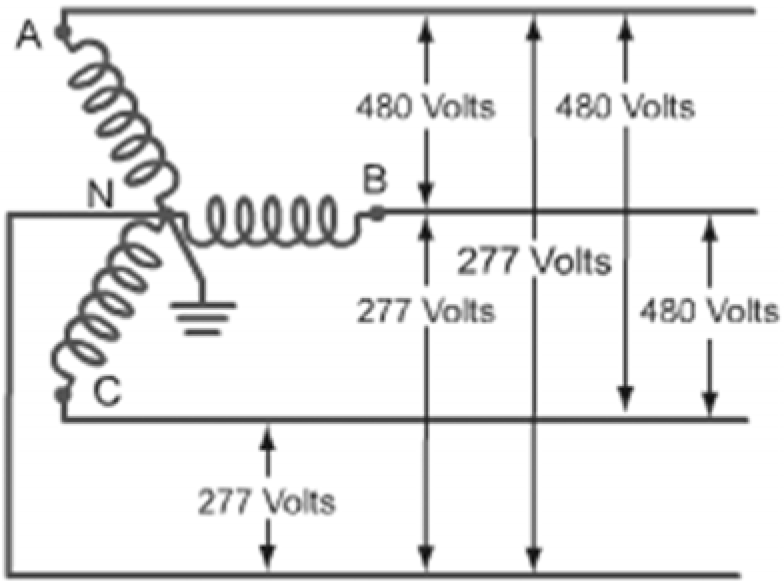
Autotransformer Used to
Step Down (Buck) Voltage



Autotransformer Used to
Step Up (Boost) Voltage

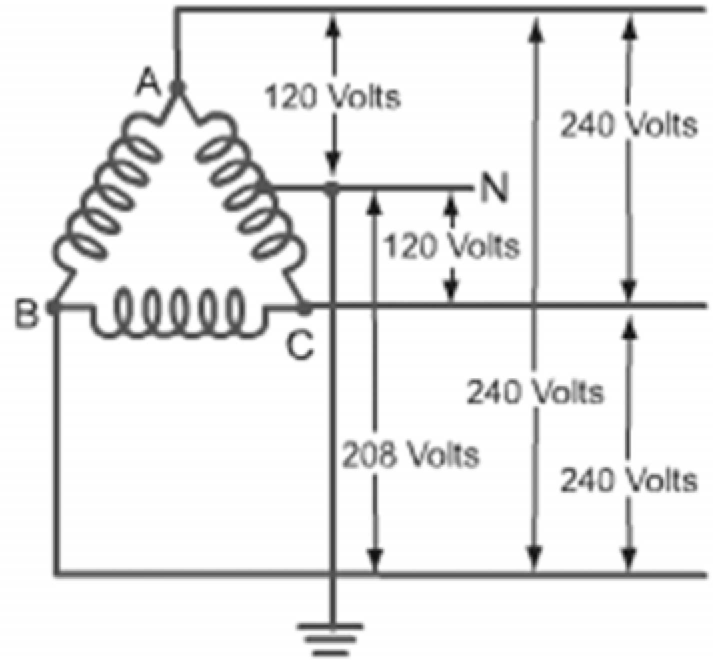


Wye Transformer Secondary



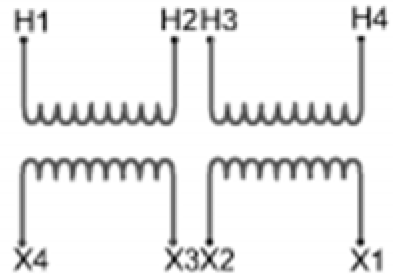
A - B 480 Volts
B - C 480 Volts
C - A 480 Volts
A - N 277 Volts
B - N 277 Volts
C - N 277 Volts

Delta Transformer Secondary

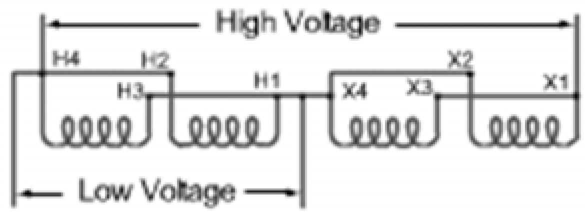


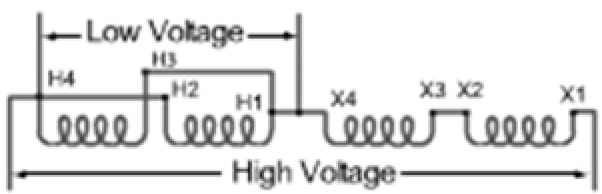
A - B 240 Volts
B - C 240 Volts
C - A 240 Volts
A - N 120 Volts
B - N 208 Volts
C - N 120 Volts

Single-phase Transformer without Field Connections

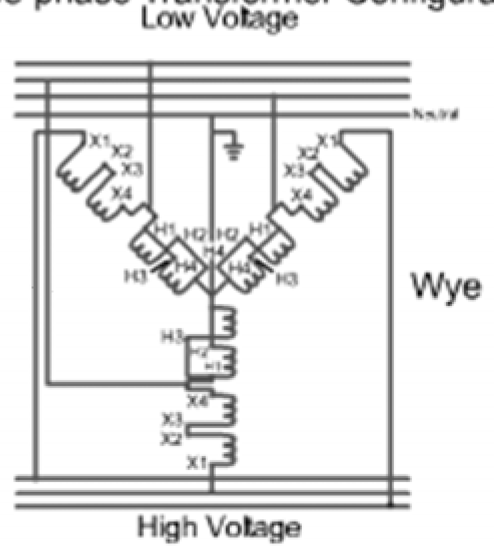


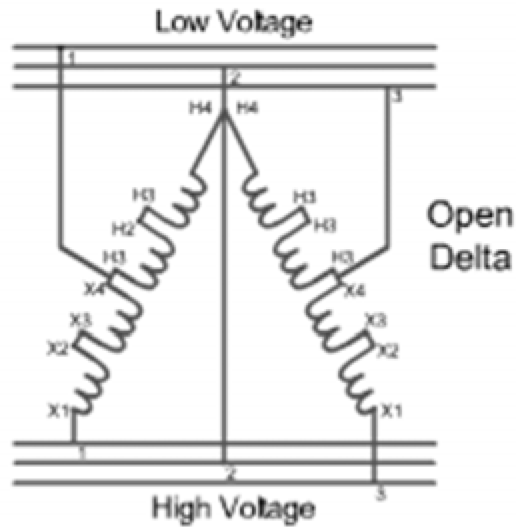
Examples of Possible Single-Phase Configurations





Examples of Several Possible Three-phase Transformer Configurations





CPT or control power transformer

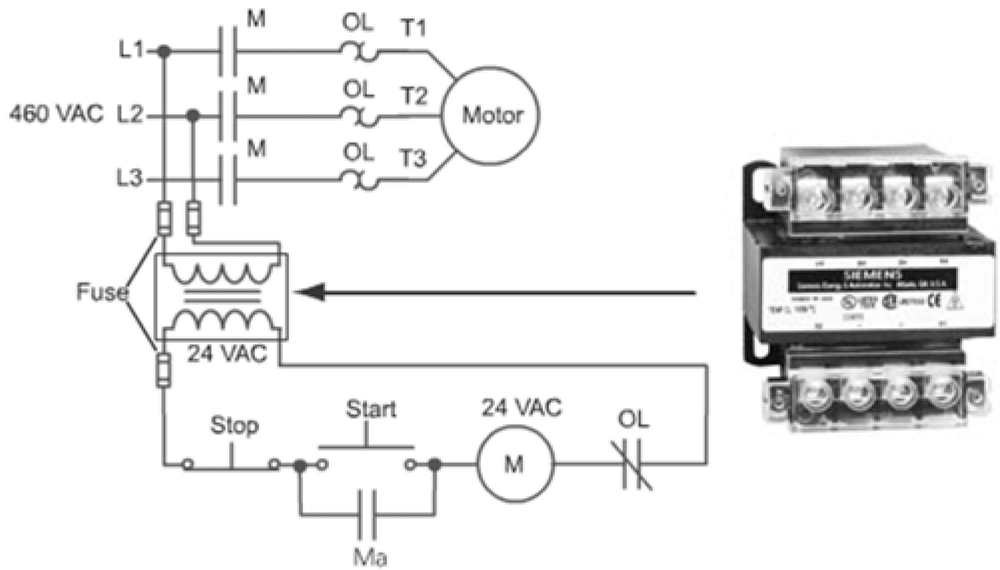
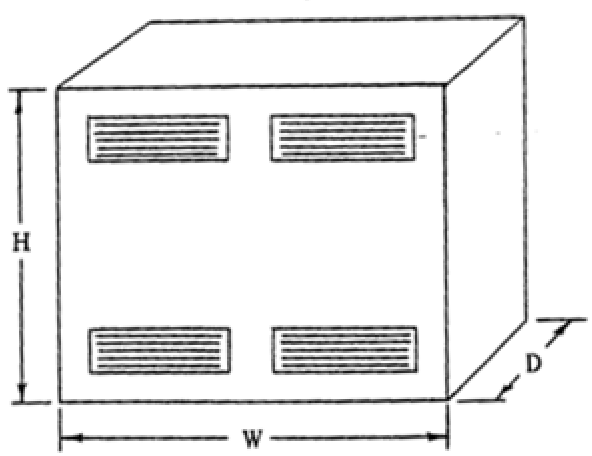


TABLE 15.1 Ratings and Typical Cubicle Dimensions for Dry-Type Transformers Used with Unit Substations

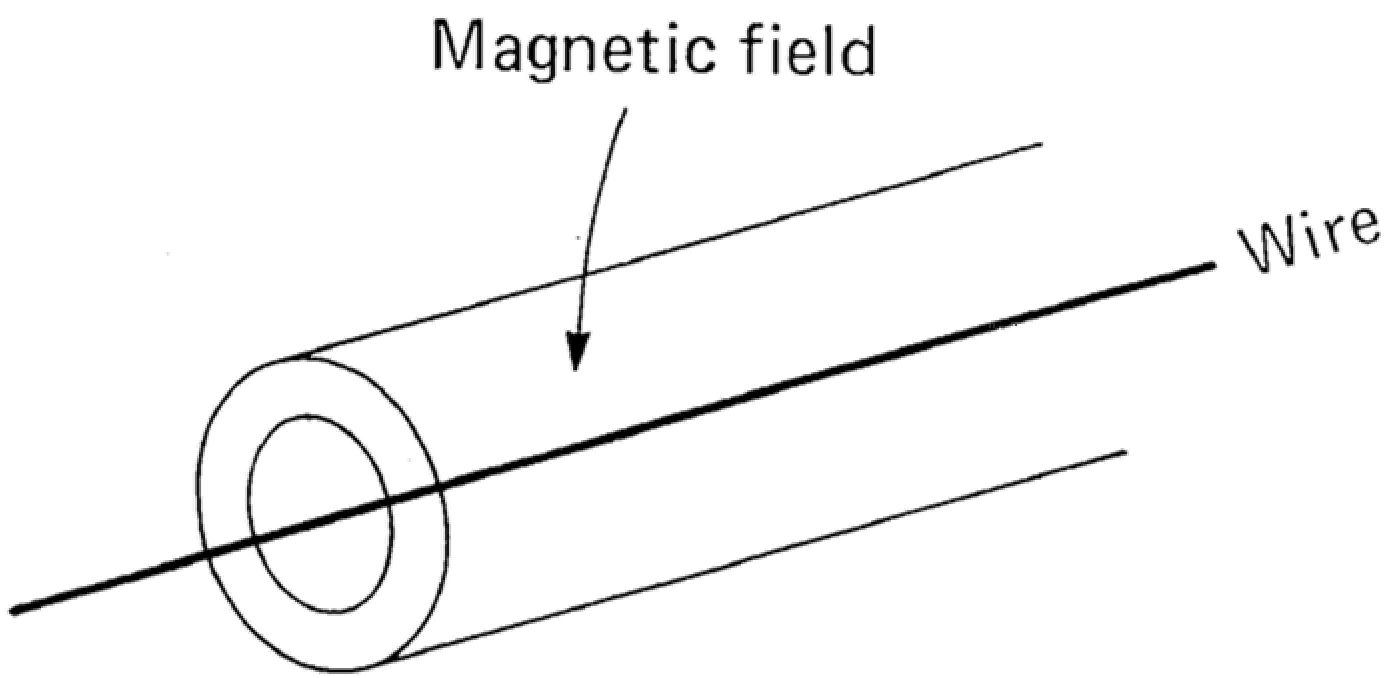
kVA Rating[a]	Dimensions of Transformer Cubicle (in.)					
	5 kV Class			15 kV Class		
	H	W	D[b]	H	W	D[b]
112½	90	30	54	90	30	54
150	90	30	54	90	30	54
225	90	30	54	90	42	54
300	90	42	54	90	90	54
500	90	42	54	90	90	54
750	90	90	54	90	90	54
1000	90	90	54	90	100	54
1500	90	100	54	90	100	54
2000	90	100	54	100	100	54
2500	90	100	54	100	100	54

[a] Some manufacturers offer additional ratings to those listed.

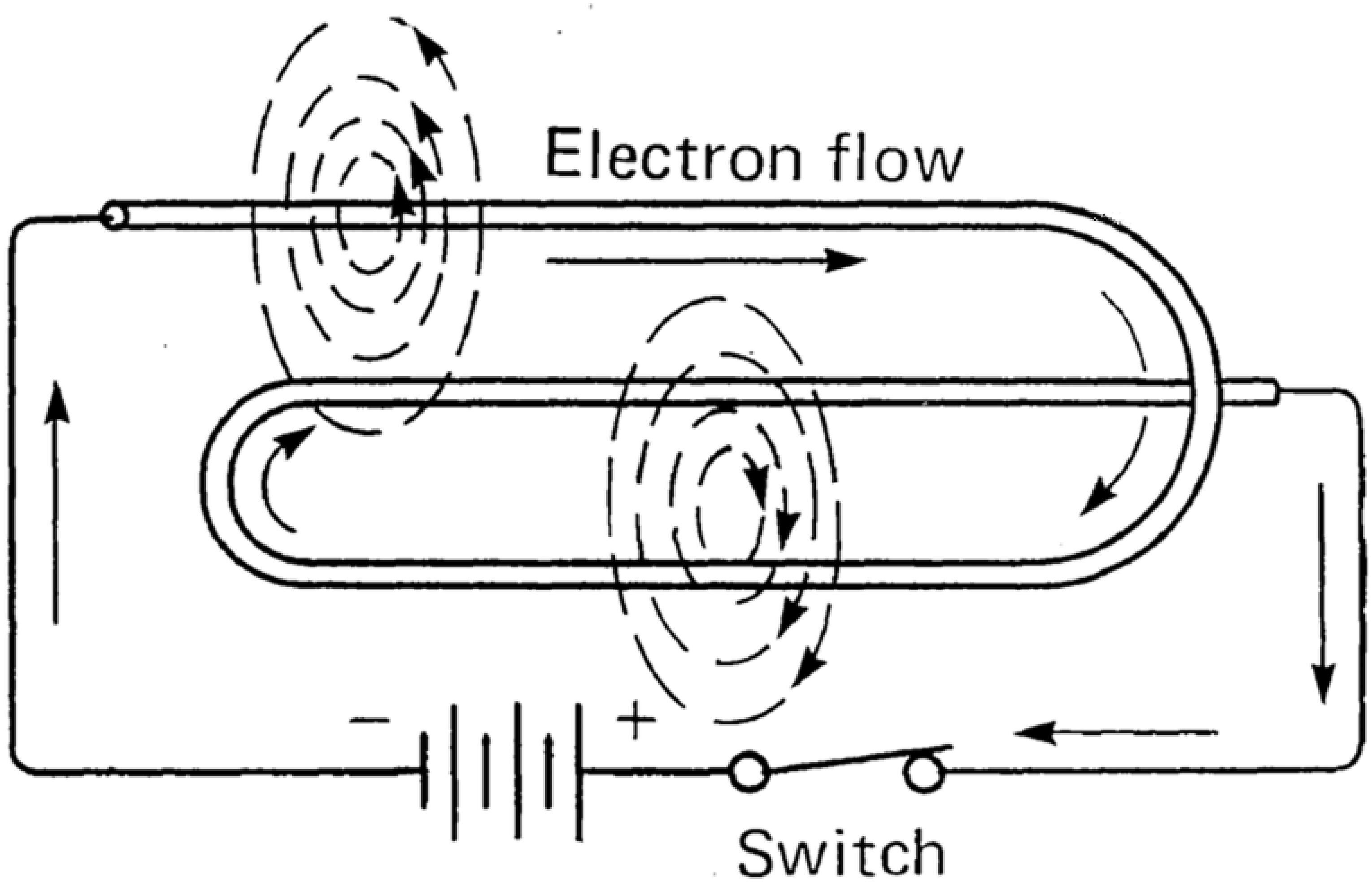
[b] Depth can be increased to match other sections of unit substation where required.



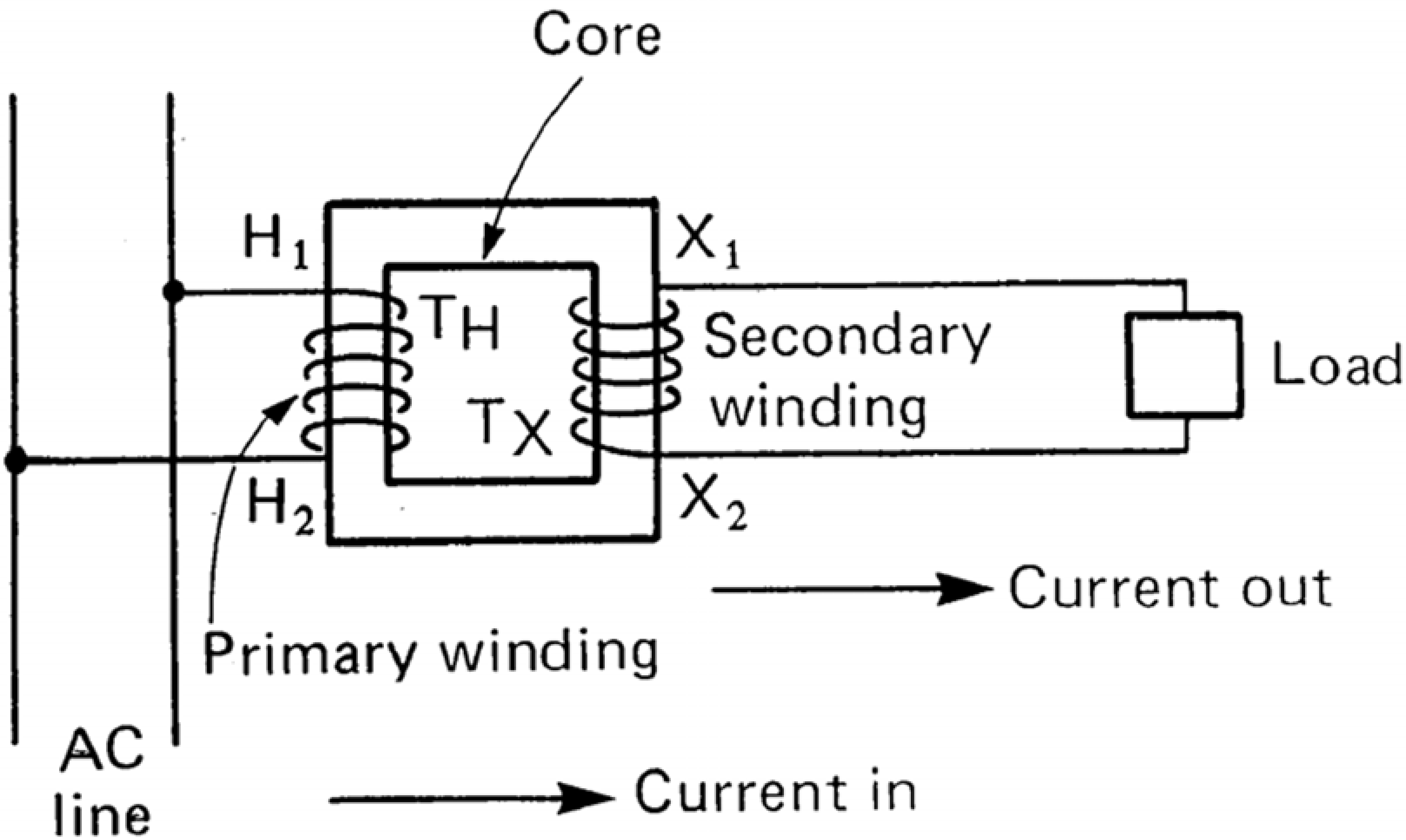
Magnetic field of a current -carrying wire



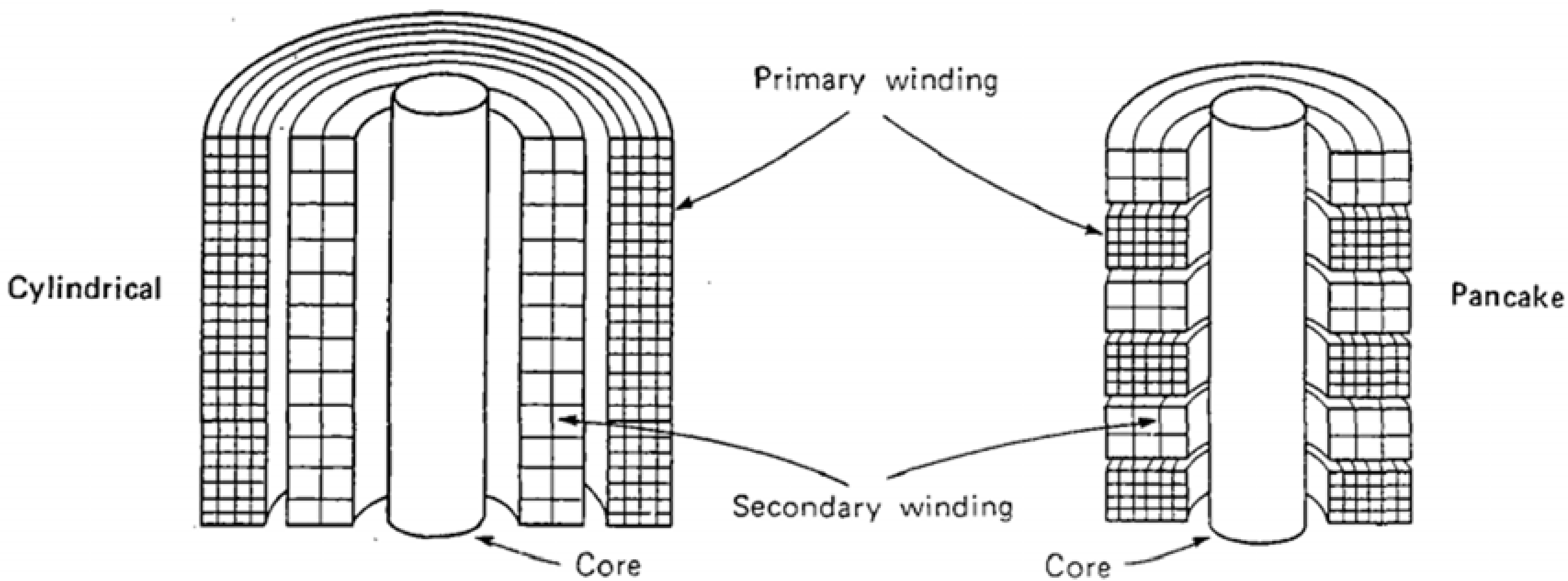
Magnetic field of a conductor

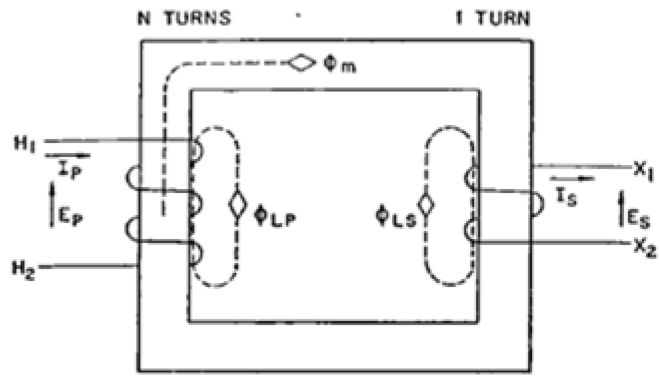


Simple transformer

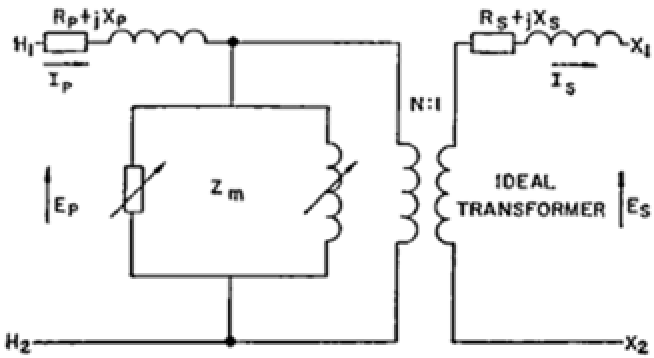


Transformer windings

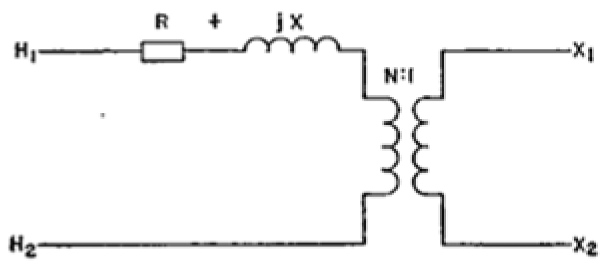




(a) SCHEMATIC REPRESENTATION

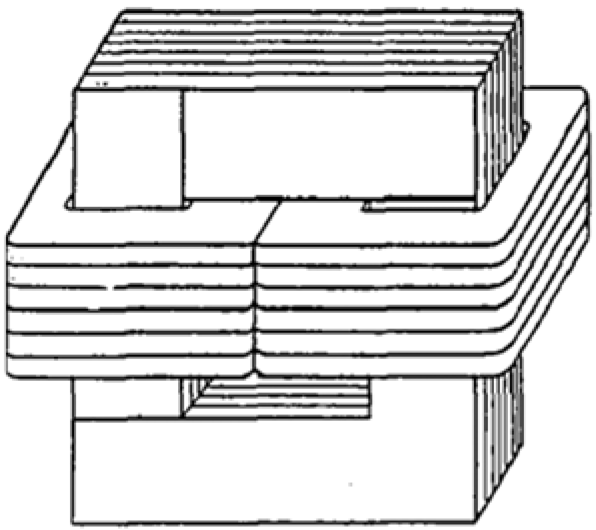


(b) COMPLETE EQUIVALENT CIRCUIT

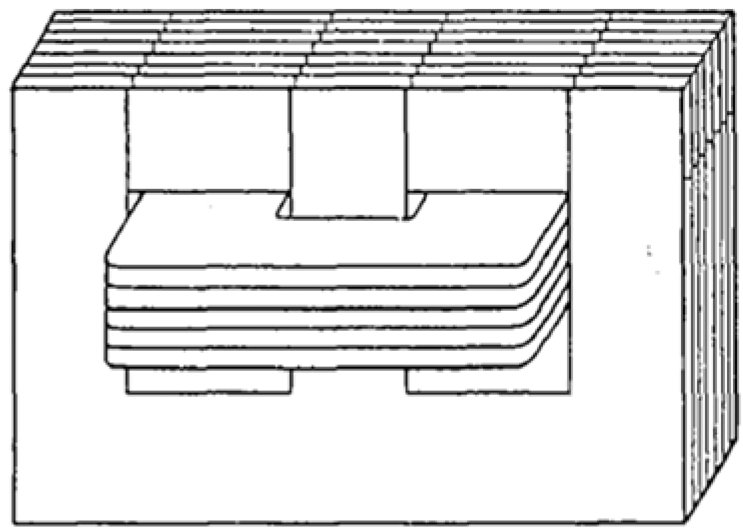


(c) SIMPLIFIED EQUIVALENT CIRCUIT
NEGLECTING SHUNT BRANCH

Types of transformer cores

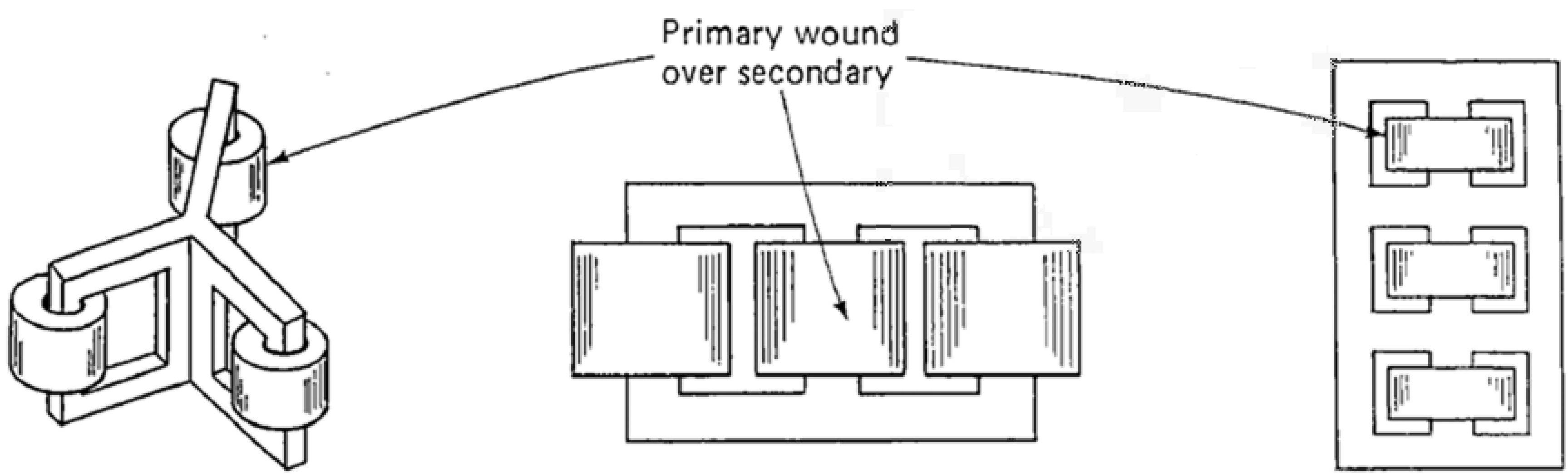


Core-type

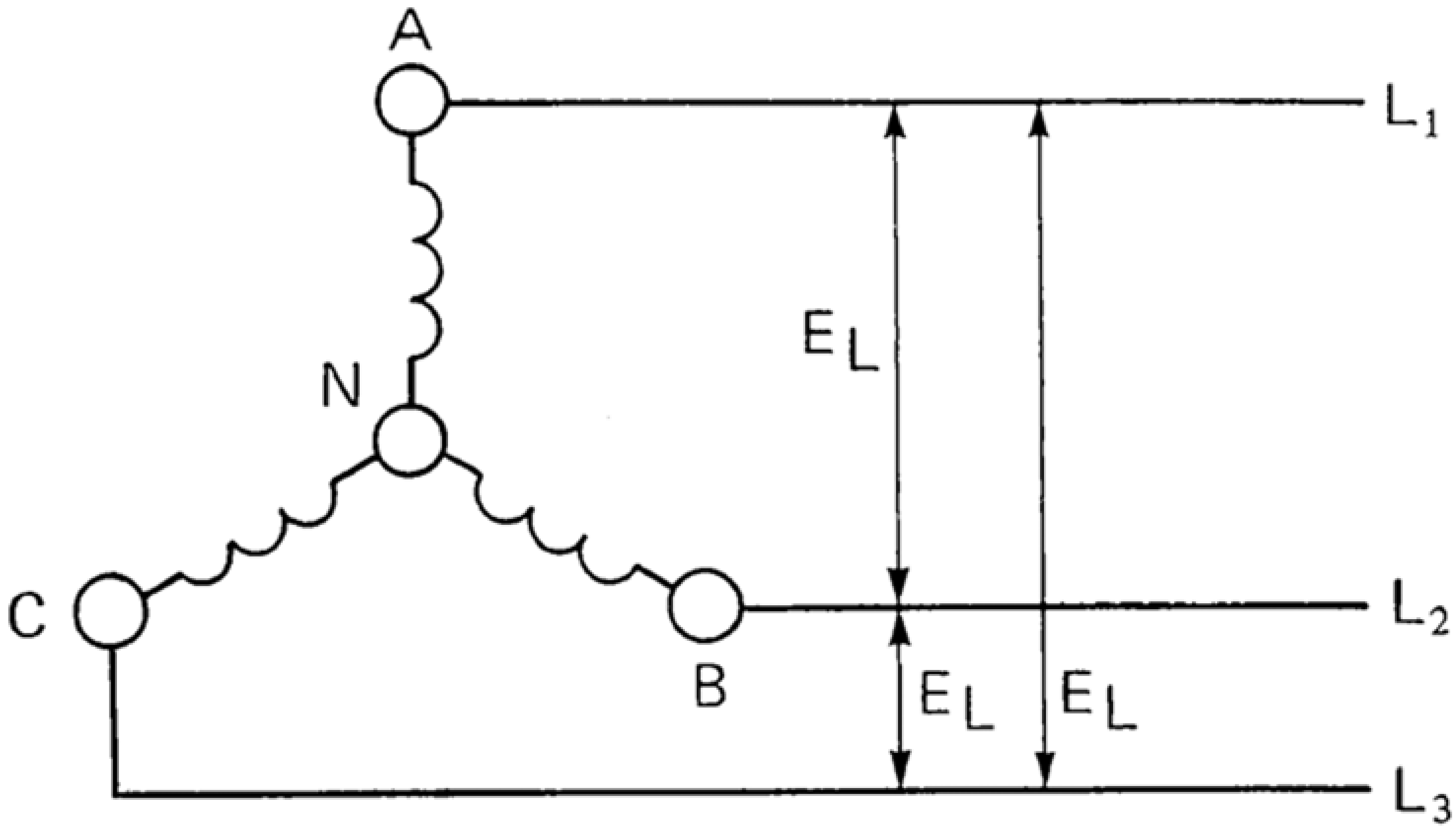


Shell-type

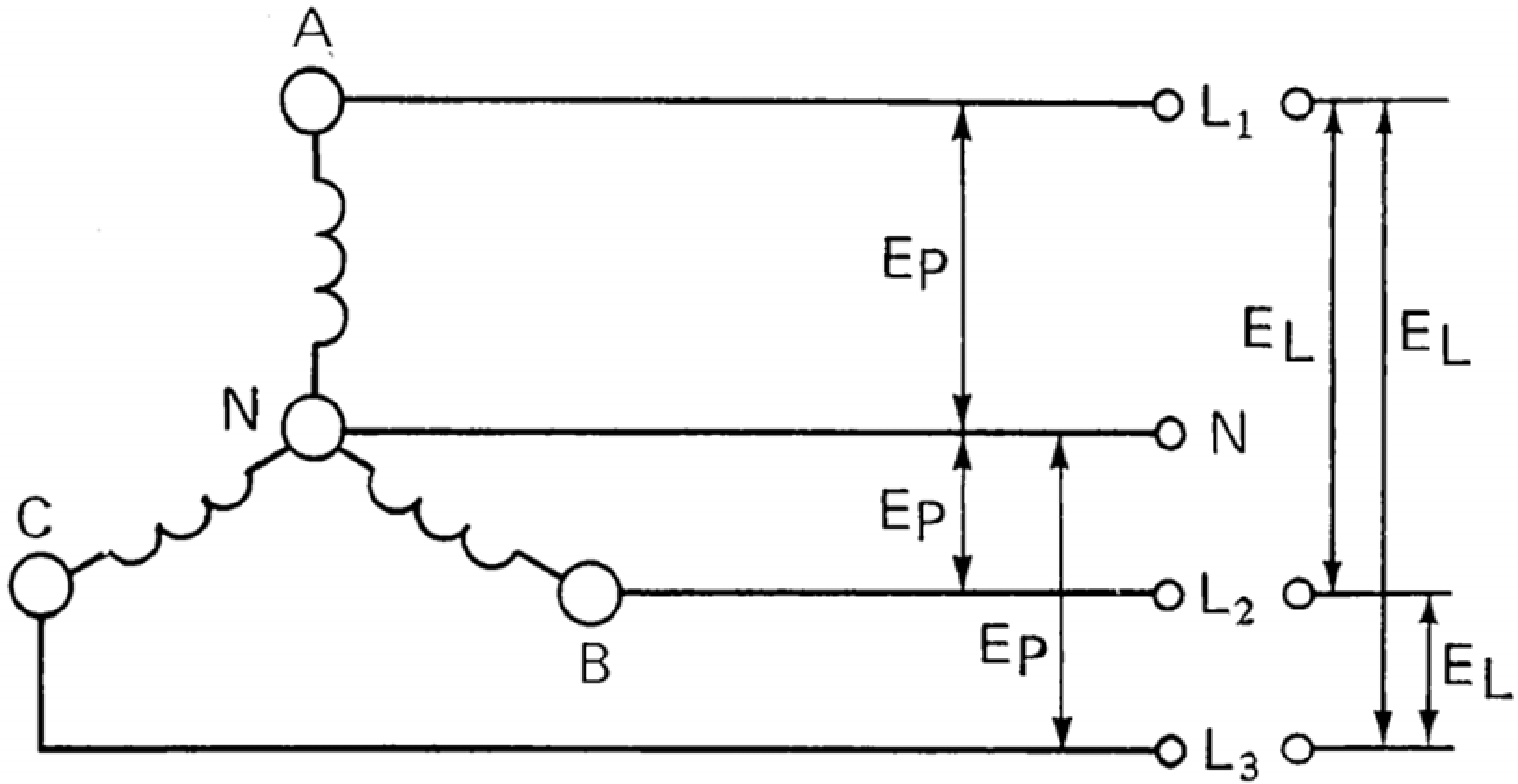
Three-phase transformer constructions



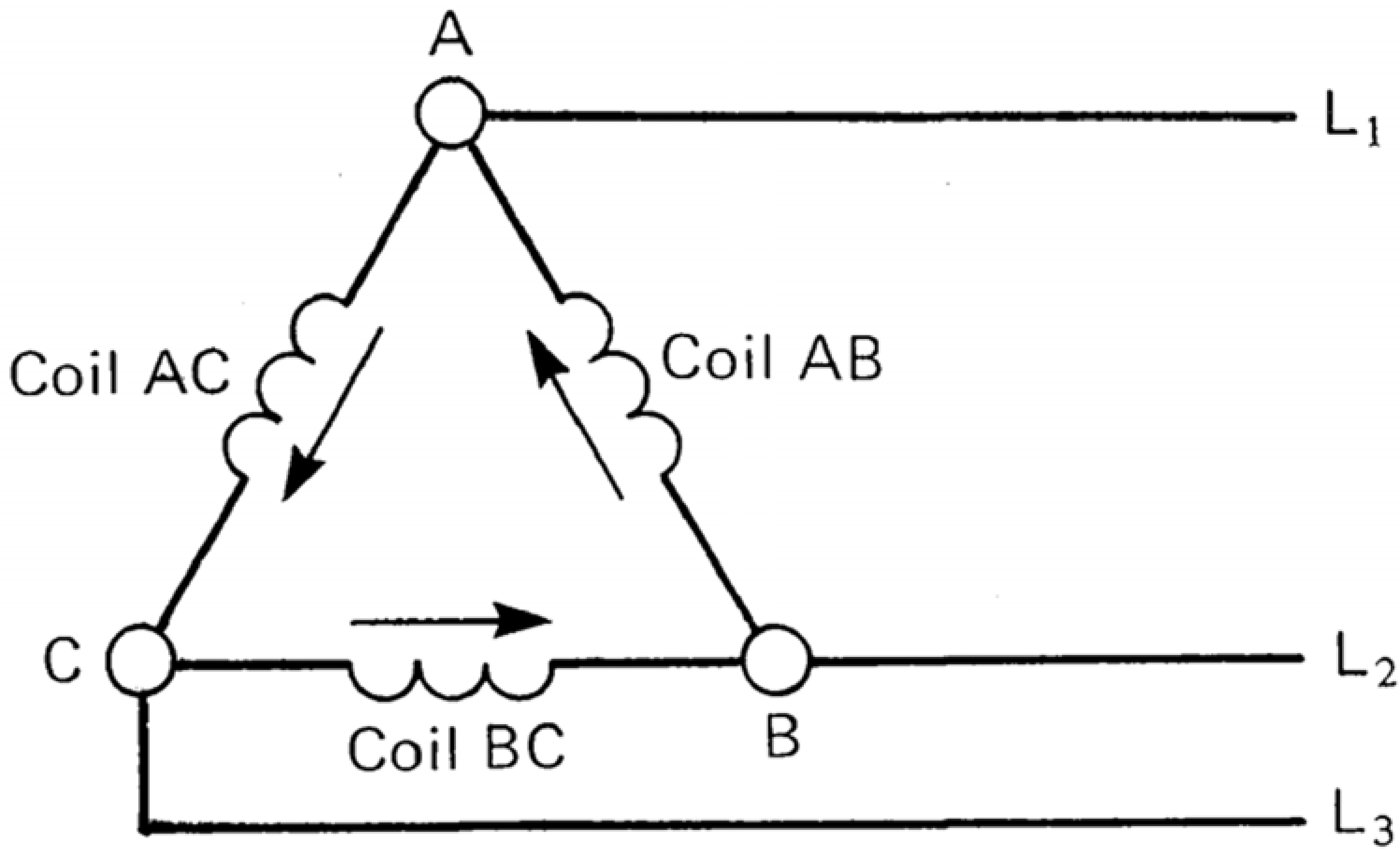
Three-wire Y **-connected**



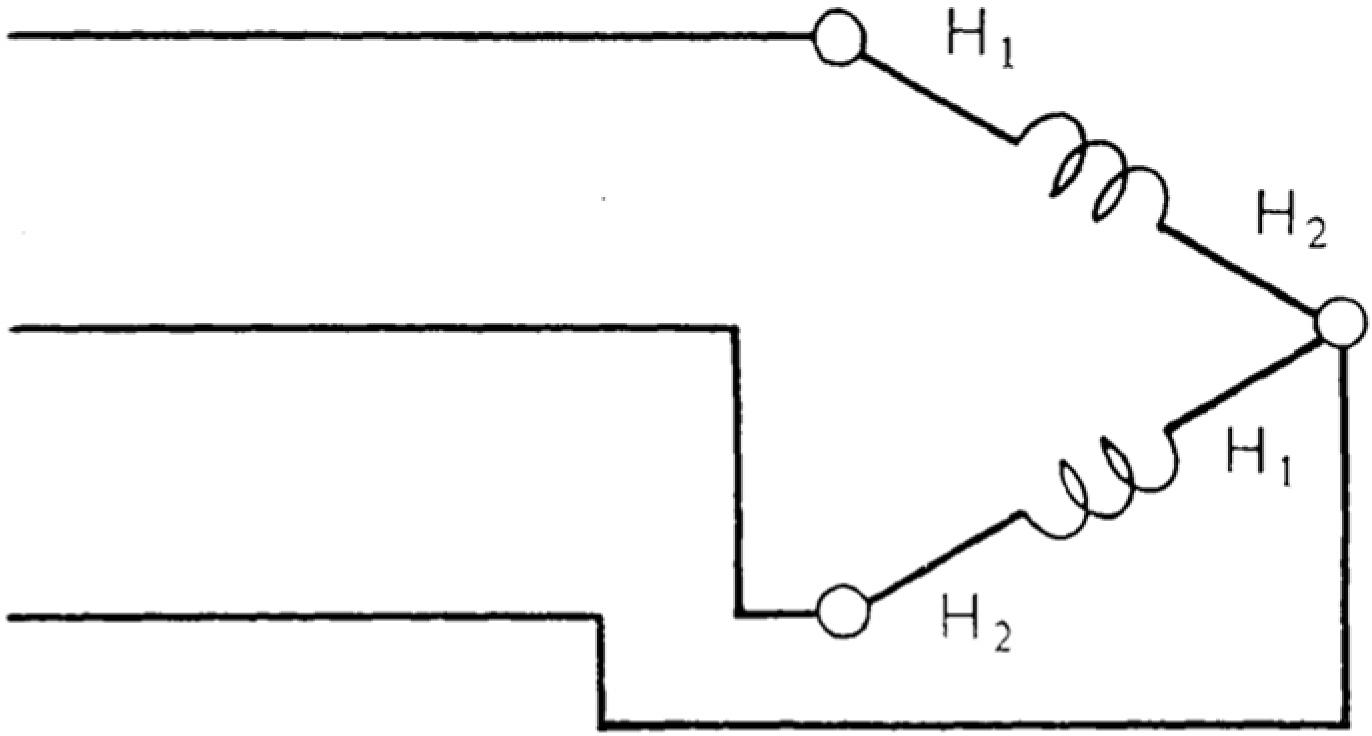
Four-wire Y -connected



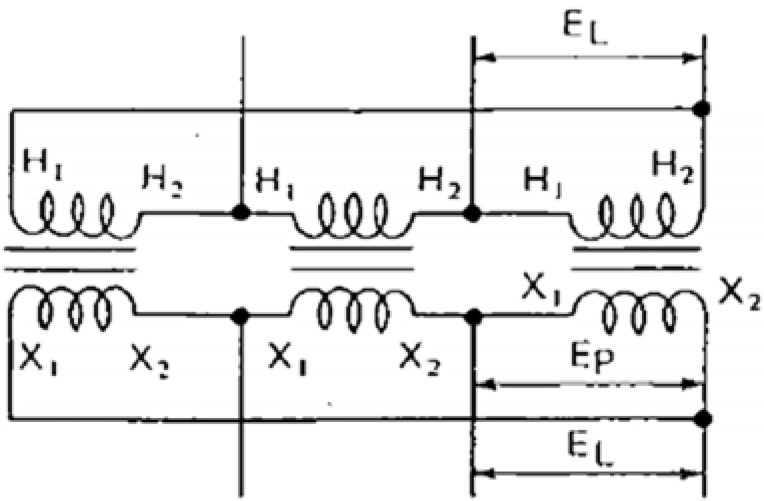
Three-phase delta-connected alternator



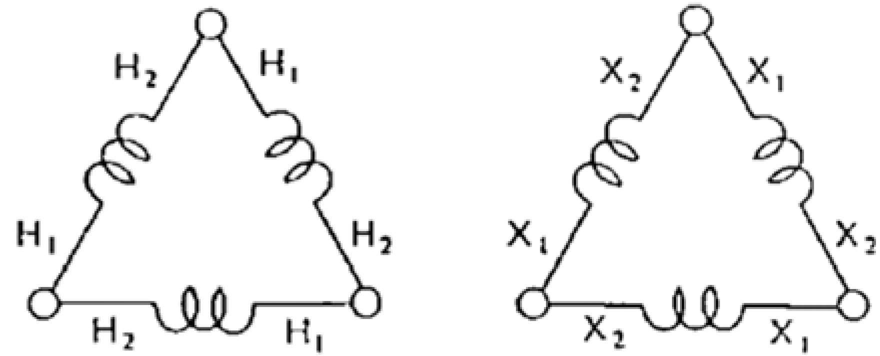
Open-delta connection

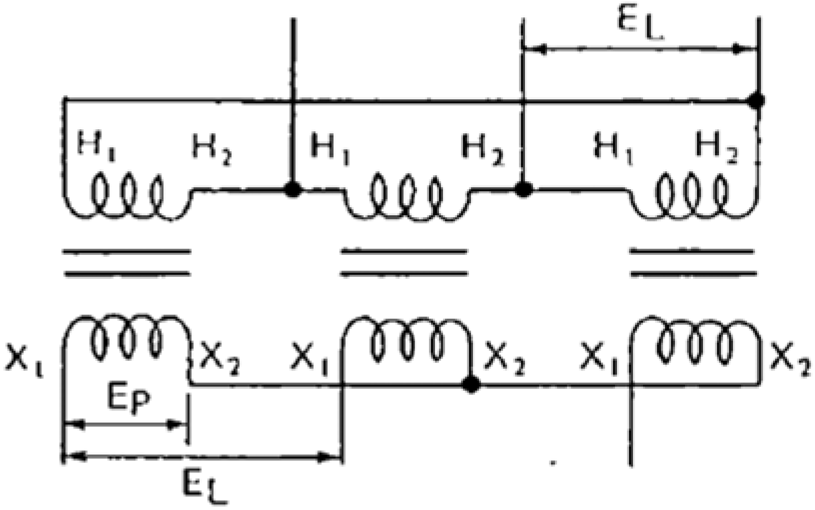


Single-phase transformers for three- phase systems

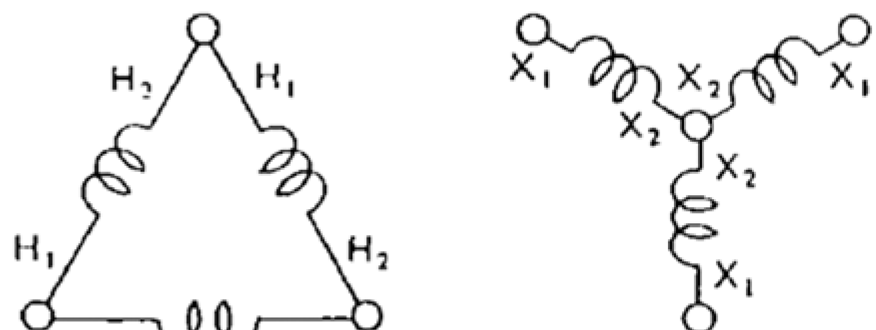


Delta-delta connection

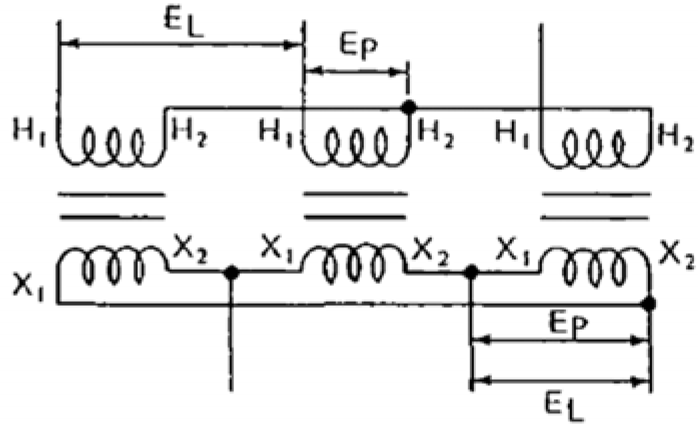




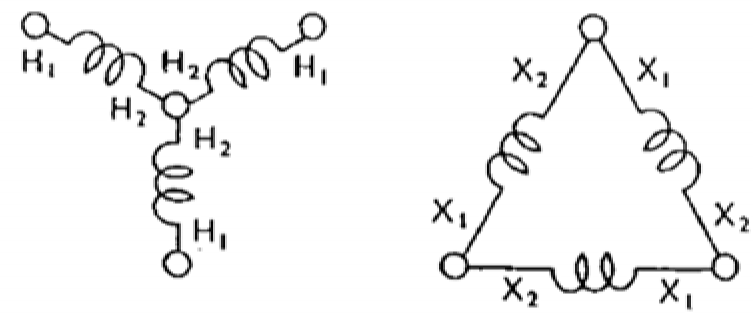
Delta-Y connection

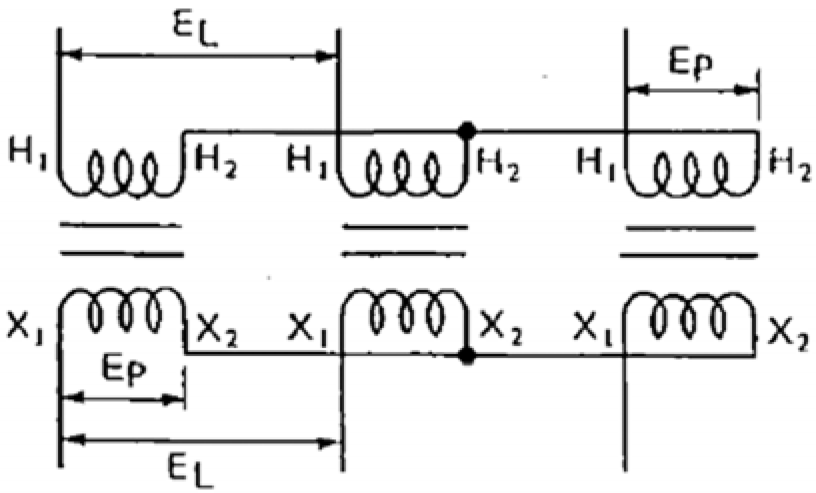


Single-phase transformers for three- phase systems

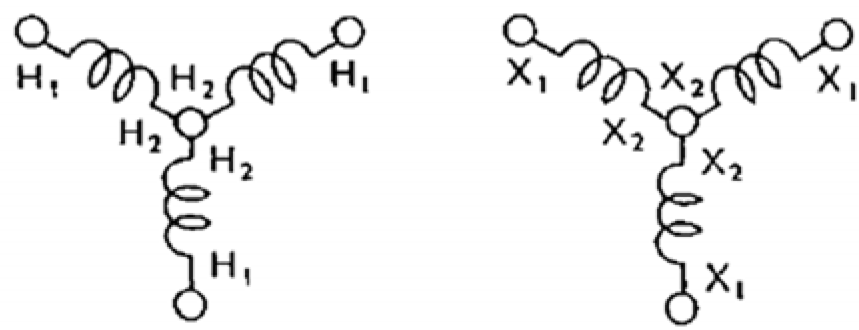


Y-delta connection





Y-Y connection



Potential differences across coils

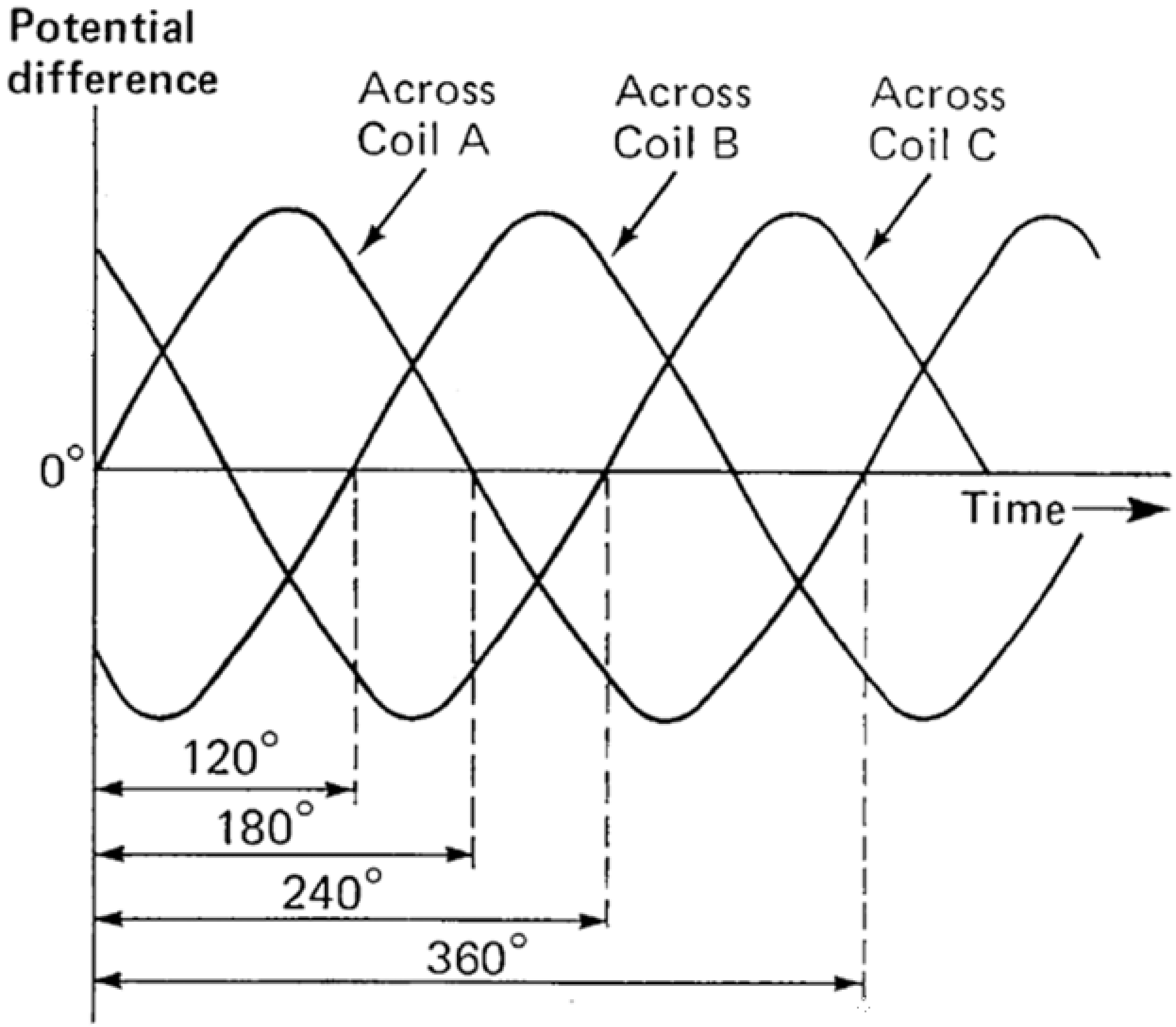
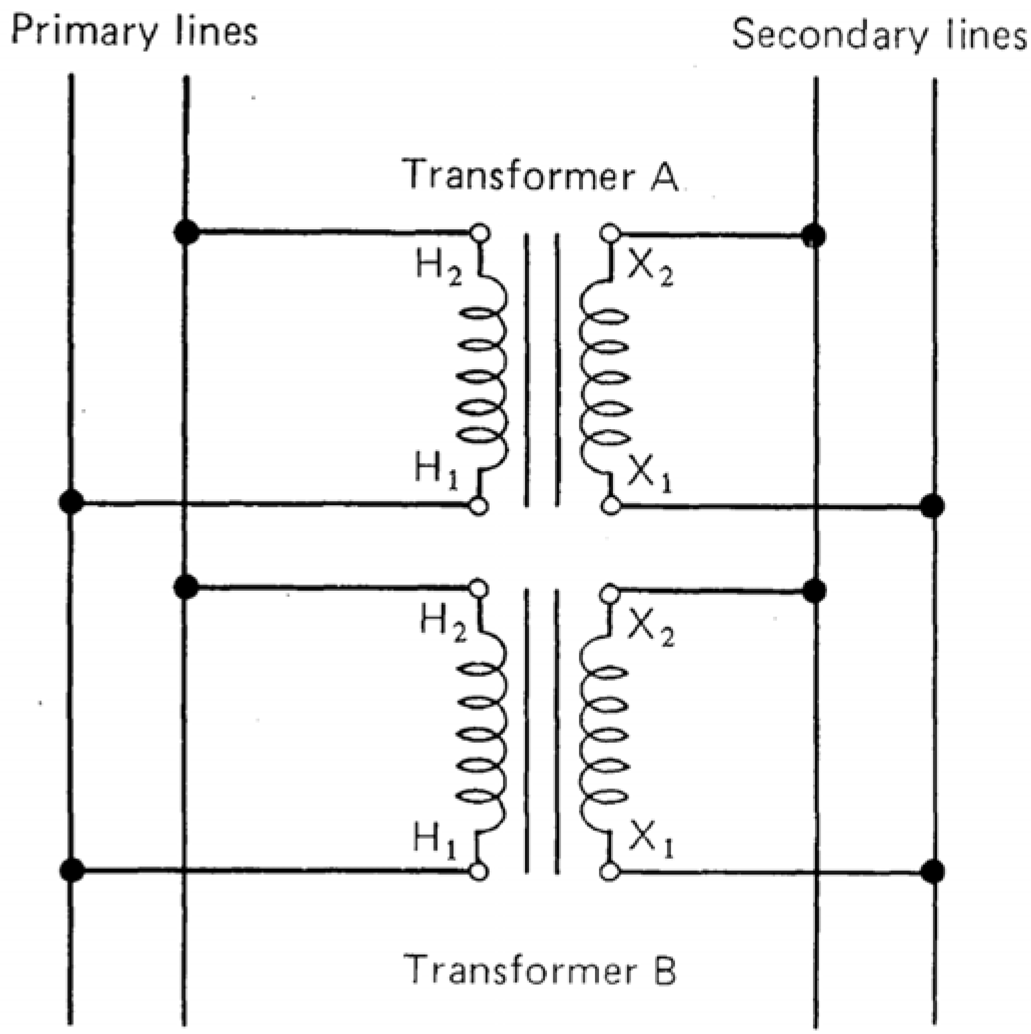


Table 10—Typical Impedances of Distribution Transformers of Standardized Design

	KVA Rating	Voltage Rating of Primary Winding: 2.4 KV		4.8 KV		7.2 KV		12 KV		24.9/14.4 Grd Y		23 KV		34.5 KV		46 KV		69 KV	
		% R	% Z	% R	% Z	% R	% Z	% R	% Z	% R	% Z	% R	% Z	% R	% Z	% R	% Z	% R	% Z
Single-Phase	5	1.9	2.3	2.1	2.4	2.1	2.6	2.3	2.7	2.8	4.0	—	—	—	—	—	—	—	—
	10	1.4	1.9	1.6	2.0	1.9	2.3	1.9	2.1	2.3	3.0	—	—	—	—	—	—	—	—
	15	1.4	1.8	1.6	1.9	1.7	2.1	1.7	2.0	2.1	2.6	—	—	—	—	—	—	—	—
	25	1.3	1.8	1.5	1.8	1.6	2.2	1.5	1.9	1.9	2.0	2.0	5.2	2.2	5.2	—	—	—	—
	50	1.2	2.1	1.3	2.2	1.3	2.2	1.3	2.3	1.9	1.7	1.7	5.2	1.7	5.2	1.8	5.7	—	—
	100	1.1	2.0	1.2	1.9	1.2	2.0	1.2	2.2	—	—	1.4	5.2	1.5	5.2	1.5	5.7	1.4	6.5
	333	1.1	4.8	1.1	4.8	1.0	5.0	1.0	5.0	—	—	1.0	5.2	1.1	5.2	1.1	5.7	1.1	6.5
	500	1.0	4.8	1.0	4.8	1.0	5.0	1.0	5.0	—	—	0.9	5.2	1.0	5.2	1.0	5.7	1.0	6.5
Three-Phase	9	2.0	2.4	2.2	2.4	2.5	2.5	—	—	—	—	—	—	—	—	—	—	—	—
	15	1.9	2.5	2.1	2.5	2.2	2.6	2.4	2.8	—	—	—	—	—	—	—	—	—	—
	30	1.6	2.4	1.8	2.5	1.9	2.6	2.1	3.1	—	—	—	—	—	—	—	—	—	—
	75	1.5	3.2	1.6	3.2	1.6	2.9	1.6	3.3	—	—	—	—	—	—	—	—	—	—
	150	1.2	4.2	1.4	4.3	1.3	3.5	1.4	4.3	—	—	1.6	5.2	—	—	—	—	—	—
	300	1.3	4.8	1.3	4.8	1.3	5.0	1.3	5.0	—	—	1.3	5.2	1.4	5.2	1.4	5.7	—	—
	500	1.2	4.8	1.2	4.8	1.1	5.0	1.1	5.0	—	—	1.2	5.2	1.2	5.2	1.3	5.7	1.2	6.5

Transformers connected in parallel



Loss Ratio =
(Total Loss/No load loss)

Table 12—Typical Values of No-Load Loss and Total Loss in Per Cent for Distribution Transformers of Standardized Design (At 75°C)

	KVA Rating	2.4 KV		4.8 KV		7.2 KV		12 KV		24.9 Grd Y/14.4 KV		23 KV		34.5 KV		46 KV		69 KV	
		No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss	No Load Loss	Total Loss
Single Phase	5	.72	2.60	.77	2.84	.86	3.00	.90	3.24	1.02	3.82	—	—	—	—	—	—	—	—
	10	.57	2.00	.57	2.20	.67	2.50	.68	2.60	.84	3.10	—	—	—	—	—	—	—	—
	15	.52	1.95	.51	2.08	.60	2.30	.60	2.30	.70	2.80	—	—	—	—	—	—	—	—
	25	.43	1.74	.43	1.88	.52	2.02	.52	2.04	.60	2.48	.80	2.92	.88	3.18	—	—	—	—
	50	.35	1.58	.35	1.68	.43	1.77	.45	1.78	.58	2.06	.64	2.45	.72	2.54	.84	2.70	—	—
	100	.32	1.45	.32	1.51	.37	1.54	.40	1.55	—	—	.52	1.97	.57	2.10	.66	2.23	.83	2.35
	333	.34	1.42	.34	1.46	.34	1.36	.34	1.42	—	—	.37	1.41	.40	1.50	.44	1.59	.47	1.64
	500	.29	1.25	.29	1.30	.29	1.25	.29	1.27	—	—	.33	1.27	.35	1.34	.38	1.38	.41	1.44
Three Phase	9	1.00	2.94	1.00	3.17	1.00	3.47	—	—	—	—	—	—	—	—	—	—	—	—
	15	1.80	2.66	.80	2.94	.96	3.14	1.04	3.46	—	—	—	—	—	—	—	—	—	—
	30	.62	2.27	.62	2.46	.75	2.65	.79	2.84	—	—	—	—	—	—	—	—	—	—
	75	.46	1.96	.46	2.08	.59	2.14	.63	2.20	—	—	—	—	—	—	—	—	—	—
	150	.37	1.58	.37	1.72	.52	1.86	.54	1.92	—	—	.71	2.33	—	—	—	—	—	—
	300	.36	1.63	.36	1.69	.46	1.77	.48	1.78	—	—	.58	1.93	.64	2.02	.75	2.15	—	—
	500	.36	1.52	.36	1.54	.44	1.57	.45	1.57	—	—	.51	1.74	.55	1.75	.62	1.91	.74	1.96

Table 14—-Typical Published Values of Exciting Current in Per Cent at Rated Voltage for Distribution Transformers of Standardized Design

	KVA Rating	4.8 KV and Below	7.2 KV	12 KV	24.9 Grd.Y/14.4 KV	23 KV	34.5 KV	46 KV	69 KV
		Voltage Rating of Primary Winding							
Single Phase	5	3.2	3.5	3.5	4.0	—	—	—	—
	10	2.7	3.0	3.0	3.0	—	—	—	—
	15	2.1	2.6	2.6	2.6	—	—	—	—
	25	1.7	2.0	2.0	2.0	3.5	3.5	—	—
	50	1.5	1.6	1.6	1.7	2.5	2.5	3.5	—
	100	1.5	1.5	1.5	—	2.0	2.0	3.0	3.0
	333	2.0	2.0	2.0	—	2.0	2.0	2.0	2.0
	500	2.0	2.0	2.0	—	2.0	2.0	2.0	2.0
Three Phase	9	7.0	7.0	—	—	—	—	—	—
	15	6.0	6.0	6.0	—	—	—	—	—
	30	3.8	3.8	4.5	—	—	—	—	—
	75	3.0	3.0	3.3	—	—	—	—	—
	150	2.1	2.2	2.3	—	3.5	—	—	—
	300	2.0	2.1	2.3	—	2.6	2.8	3.1	3.7

For Operation Above Rated Voltage, Multiply Values Above and In Table 12 by Following Factors

% Operating Voltage	Correction Factors		
	No-Load Loss	Exciting Current	
105%	1.15	1.5	For 167 KVA and Below, 1-phase;
110	1.30	2.2	and 150 KVA and Below, 3-phase.
105%	1.5	2.3	For 250 KVA and Above, 1-phase;
110	2.4	4.6	and 225 KVA and Above, 3-phase.

Table 16—Permissible Short-Time Transformer Loading Based on Reduced Life Expectancy (OA, OW)[7]

Period of Increased Loading, Hours	Following 50 Per Cent or Less of Rated KVA				Following 100 Per Cent of Rated KVA			
	Probable Sacrifice In Per Cent Of Normal Life Caused By Each Overload							
	0.10	0.25	0.50	1.00	0.10	0.25	0.50	1.00
	Maximum Load In Per Unit Of Transformer Rating							
0.5	2.00	2.00	2.00	2.00	1.75	1.92	2.00	2.00
1.0	1.76	1.91	2.00	2.00	1.54	1.69	1.81	1.92
2.0	1.50	1.62	1.72	1.82	1.35	1.48	1.58	1.68
4.0	1.27	1.38	1.46	1.53	1.20	1.32	1.40	1.48
8.0	1.13	1.21	1.30	1.37	1.11	1.20	1.28	1.35
24.0	1.05	1.10	1.15	1.23	1.05	1.09	1.15	1.23

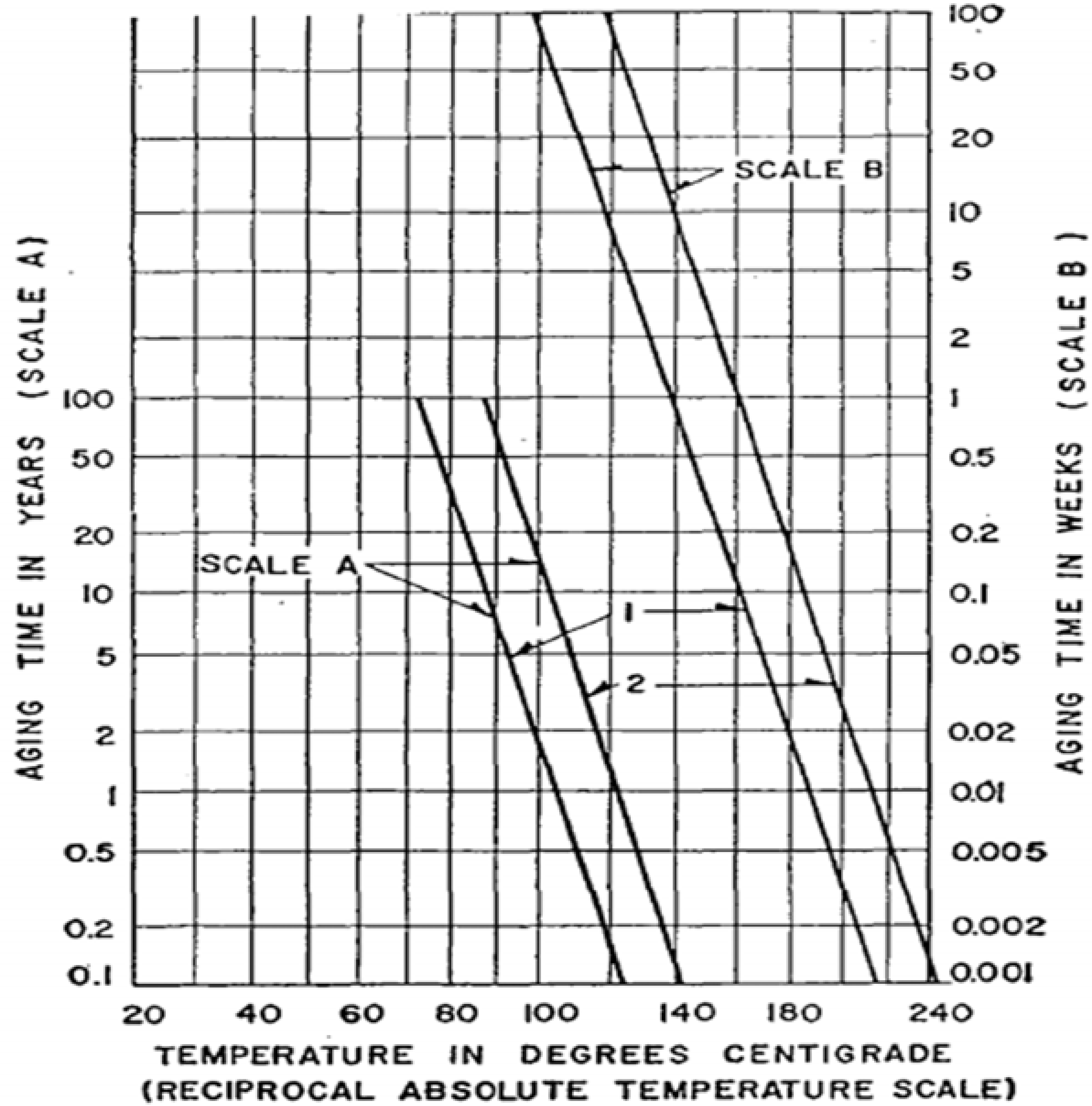


Fig. 35—Aging time of manila paper in oil, based on tensile strength[14]. Curve 1—Time to reach 80 per cent of residual tensile strength. Curve 2—Time to reach 20 per cent of residual tensile strength.

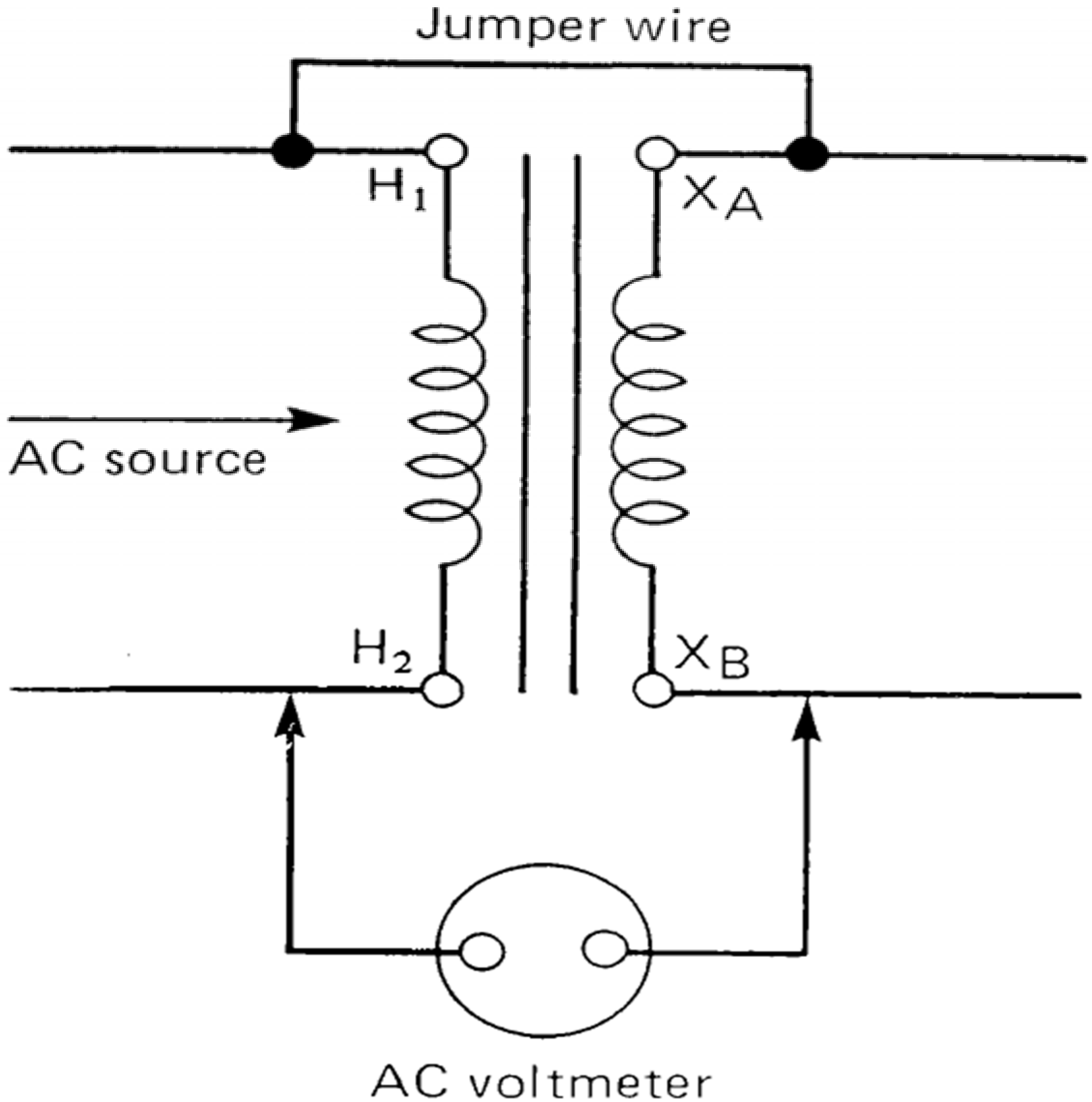
Table 15—Permissible Daily Short-Time Transformer Loading Based on Normal Life Expectancy [7]

Period of Increased Loading, Hours	Maximum Load in Per Unit of Transformer Rating*		
	Average** Initial Load in Per Unit of Transformer Rating		
	0.90	0.70	0.50
0.5	1.59	1.77	1.89
1.0	1.40	1.54	1.60
2.0	1.24	1.33	1.37
4.0	1.12	1.17	1.19
8.0	1.06	1.08	1.08

*Figures are for OA, OW cooling only

**Use either average load for two hours previous to overload period, or average load for 24 hours (less the overload period), whichever is greater.

Phasing a transformer



$$\% \text{ Regulation} = \left[pr + qx + \frac{(px - qr)^2}{200}\right] \times \frac{\text{operating current}}{\text{rated current}} \qquad (12)$$

where:

r = per cent resistance = $\dfrac{\text{rated load losses in watts}}{10 \times \text{rated kva}}$

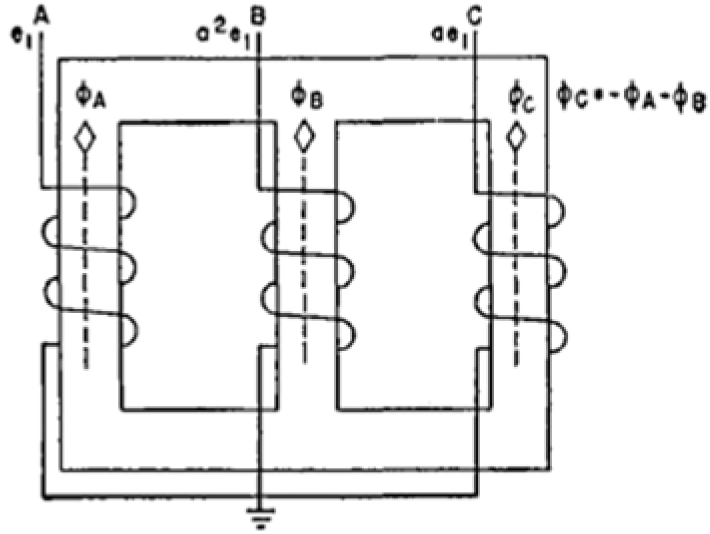
z = per cent impedance

x = per cent reactance = $\sqrt{z^2 - r^2}$

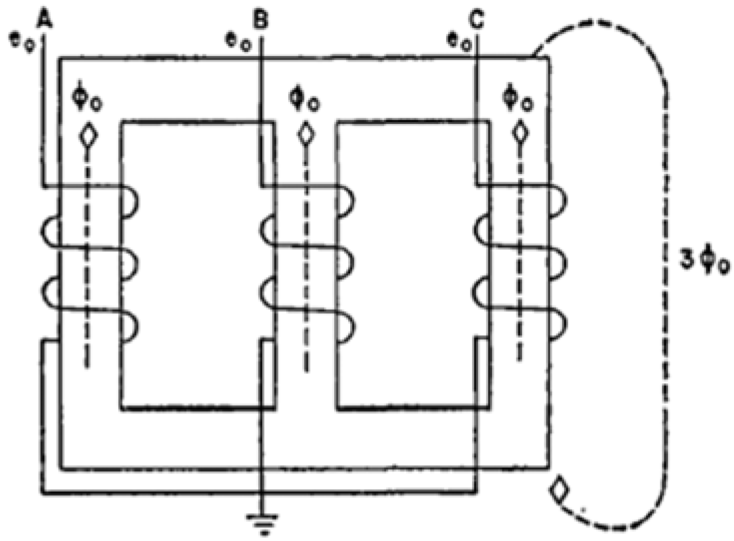
θ = power factor angle of load (positive when current lags voltage)

$p = \cos\theta$

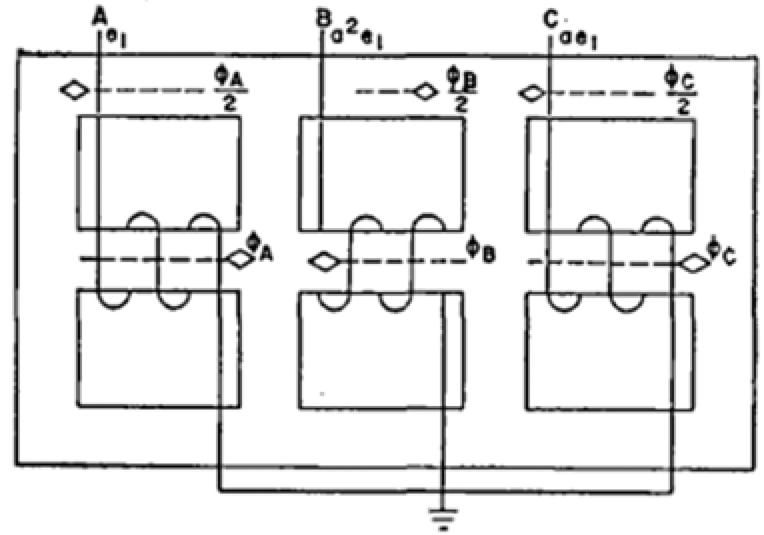
$q = \sin\theta$



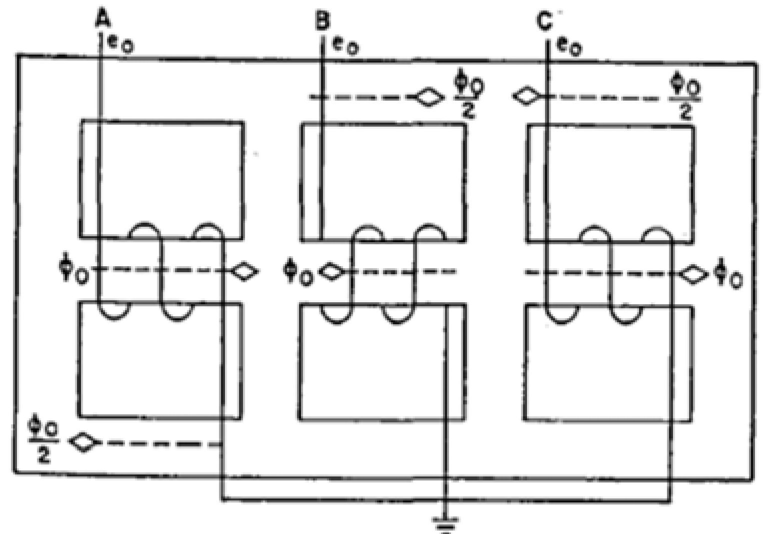
(a) CORE FORM-POSITIVE SEQUENCE



(b) CORE FORM-ZERO SEQUENCE



(c) SHELL FORM-POSITIVE SEQUENCE



(d) SHELL FORM-ZERO SEQUENCE

Table 3—Insulation Levels and Dielectric Tests for Oil-Immersed Distribution Transformers[1]

Nominal System Voltage, KV	Basic Insulation Level (BIL) KV	Rated Voltage Between Terminals: Single Phase: For Wye Connection on 3-Phase System, KV	Rated Voltage Between Terminals: Single Phase: For Delta Connection on 3-Phase System, KV	Rated Voltage Between Terminals: Three Phase: For Wye or Delta Connection, KV	Low Frequency Test** Voltage KV	Impulse Tests: Full Wave Crest KV	Impulse Tests: Chopped Wave Crest KV	Impulse Tests: Minimum Time to Elashover sec.
1.2	30	0 to 0.69	0 to 0.69*	0 to 1.2	10	30	36	1.0
2.5	45	—	—	2.5	15	45	54	1.25
5.0	60	2.89	2.89*	5.0	19	60	69	1.5
8.66	75	5.0	5.0*	8.66	26	75	88	1.6
15	95	8.66	15	15	34	95	110	1.8
18	125	14.4	—	—	40	125	145	1.9
25	150	14.4	25	25	50	150	175	3.0
34.5	200	19.9	34.5	34.5	70	200	230	3.0
46	250	26.6	46	46	95	250	290	3.0
69	350	39.8	69	69	140	350	400	3.0

*Single-phase transformers rated 8.66 kv and below are insulated for the wye connection so that a single line of apparatus serves both the wye and delta connection. Hence the test voltages for such delta-connected apparatus are one step higher than required for their voltage rating.

**This is an applied potential test for fully insulated windings. For graded insulation, applied potential is in accordance with the insulating class of the neutral end. Induced potential test employs twice normal voltage developed in winding, but is subject to certain limitations. See ASA C57.12-1956, Section 12-06.230.

TRANSFORMER CONNECTION'S ADVANTAGES AND DISADVANTAGES SUMMARY

Connection	Advantages	Disadvantages
Wye_{Gnd}:Delta	Prohibits single phasing Normal voltage regulation Neutral stability	Bank serves as a grounding bank Unbalanced primary voltage causes circulating currents in the delta
Wye:Delta	Provides path for harmonic currents Neutral stability on primary Voltage regulation normal	Single phasing can occur
Delta:Delta	Eliminates problems from ground currents and harmonic currents Can be operated with two transformers if one fails	Circulating currents will exist if transformer voltage ratios different Provides poor regulation if transformer impedances are not matched Single phasing can occur Increased transformer cost
Wye:Wye_{Gnd}	Reduced line current	Single phasing can occur No path for harmonic currents resulting in large harmonic voltages Poor voltage regulation for single phase loads Neutral instability Line-to-ground fault causes neutral shift Requires special motors rated for higher line-to-line voltage
Wye_{Gnd}:Wye_{Gnd}	Neutral stability Voltage regulation normal Reduced line current Prohibits single phasing	Harmonics supplied over primary which may cause telephone interference Requires special motors rated for higher line-to-line voltage

TRANSFORMER CONNECTION'S ADVANTAGES AND DISADVANTAGES SUMMARY

Connection	Advantages	Disadvantages
Delta:Wye$_{Gnd}$	Neutral stability Normal voltage regulation Reduced line current Prohibits single phasing Harmonics do not appear on primary line	Requires special motors rated for higher line-to-line voltage Increased transformer cost
Open Wye	Operates on two transformers	Utilizes only 86.6% of the capacity of the two transformers Inherent voltage unbalance on secondary Possible telephone interference
Open Delta	Operates on two transformers	Utilizes only 86.6% of the capacity of the two transformers Inherent voltage unbalance on secondary Increased transformer cost

PREFERRED CONTINUOUS KVA RATINGS
(ANSI C57.12.00 TABLE 2)

SINGLE PHASE	THREE PHASE
5	15
10	30
15	45
25	75
37.5	112.5
50	150
75	225
100	300
167	501
250	750
333	1000
500	1500

TRANSFORMER CONNECTIONS

Primary	Secondary	Suitable for ungrounded source	Suitable for four wire service	Displacement Note 1	Subject to primary grounding duty	Primary triple harmonic suppressed	Problem connection Note 2
Delta	Delta	Yes	No	0°	No	Yes	
	Wye	Yes	No	-30°	No	Yes	
	Wye_{gnd}	Yes	Yes	-30°	No	Yes	
Wye	Delta	Yes	No	-30°	No	Yes	
	Wye	Yes	No	0°	No	Yes	
	Wye_{gnd}	Yes	No	0°	No	Yes	Note #3
Wye_{gnd}	Delta	Note 4	No	-30°	Yes	Yes	Note #4
	Wye	No	No	0°	No	No	
	Wye_{gnd}	No	Yes	0°	No	No	Note #5

Source: ANSI/IEEE C57.105-1978

Note 1: Based on standard connections and phasor diagrams.

Note 2: Note "problem" connections should receive very careful consideration.

Note 3: Incapable of furnishing a stable neutral. Very susceptible to phase to neutral over voltage as a result of unbalanced phase to neutral loads.

Note 4: Connections act as primary grounding transformer. Should not be used unless designed to do so.

Note 5: Three phase transformer with a three legged core form construction may heat the tank under certain phase to neutral unbalance or fault conditions.

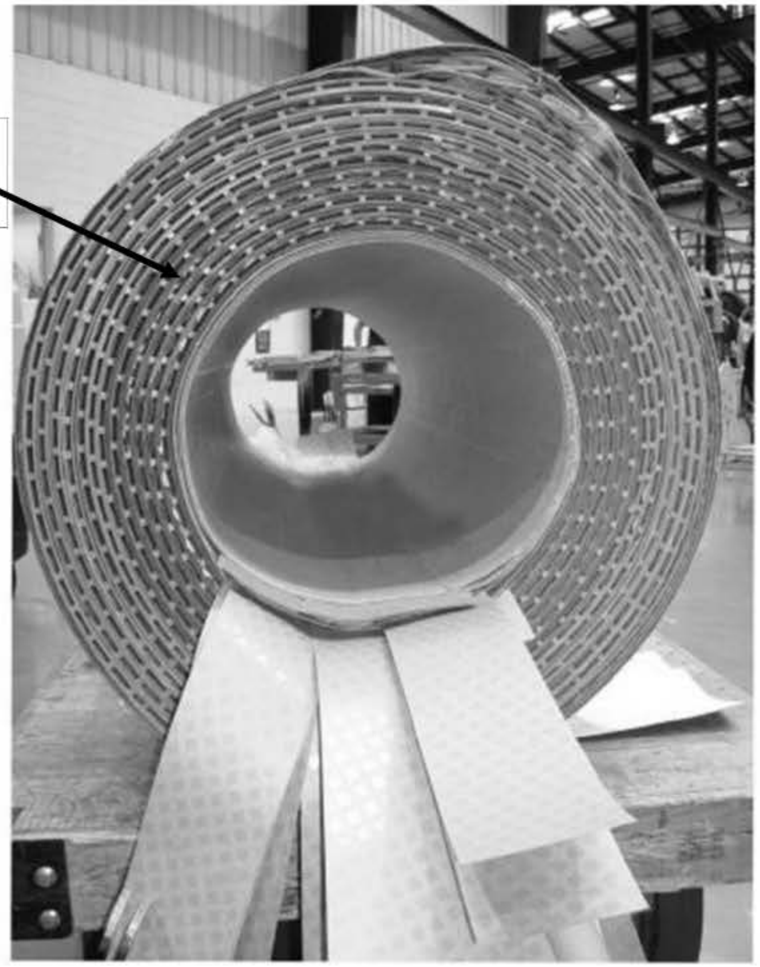
TYPES OF TRANSFORMER BY APPLICATION

- 1. DISTRIBUTION TRANSFORMER
- 2.POWER TRANSFORMER
- 3.CURRENT TRANSFORMER
- 4.POTENTIAL TRANSFORMER
- 5.FURNACE TRANSFORMER
- 6.BOOSTER TRANSFORMER
- 7.RECTIFIER TRANSFORMER
- 8.LOCOMOTIVE TRANSFORMER
- 9.MINING TRANSFORMER
- 10.PHASE SHIFTING TRANSFORMER
- 11.WELDING TRANSFORMER
- 12.HIGH VOLTAGE TESTING/SC TESTING TRF.
- 13.GROUNDING TRANSFORMERS
- 14.CONVERTER TRANSFORMER

Pictures of Liquid Filled Transformer

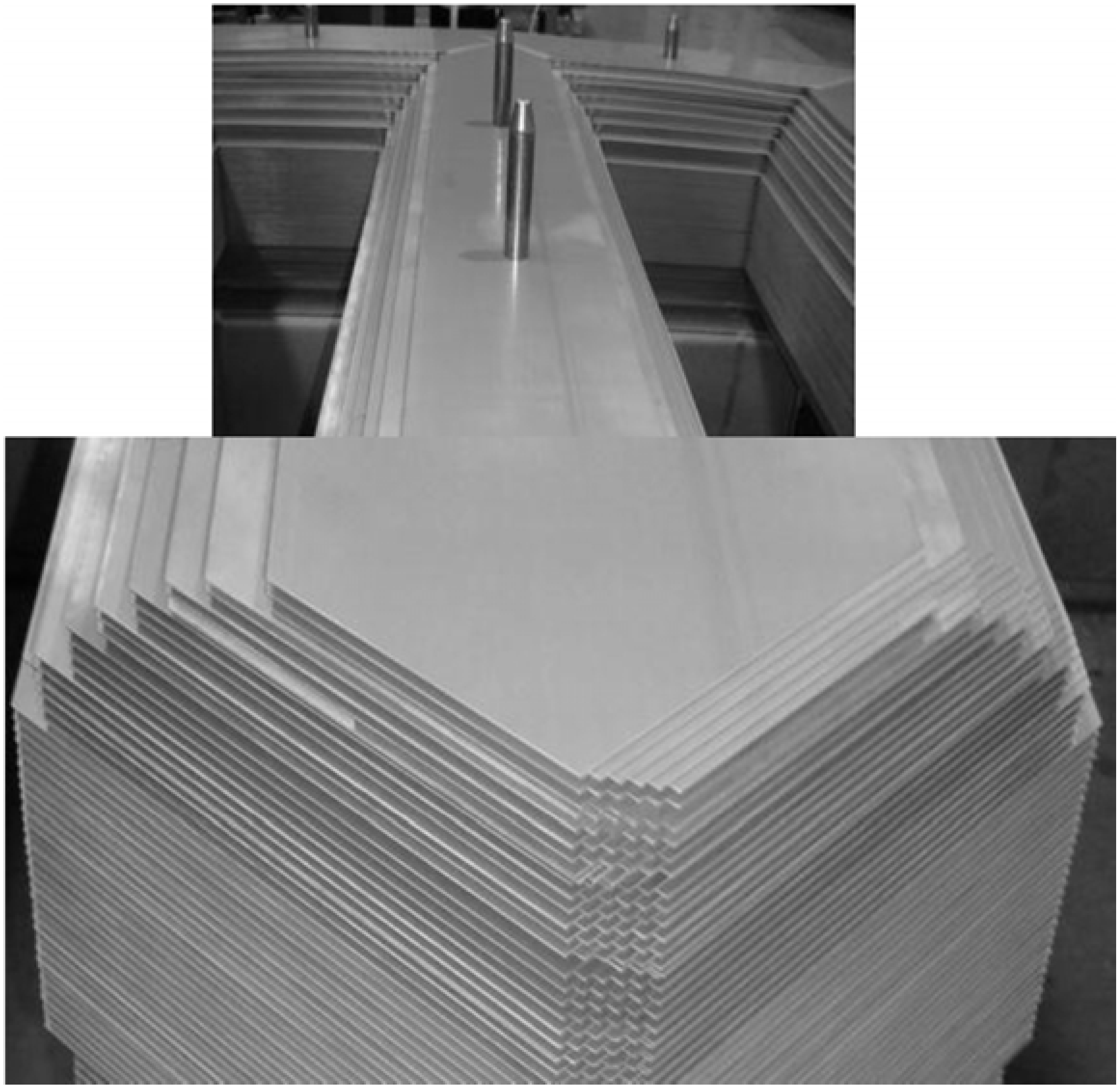
Round Coils

360 degree cooling ducts

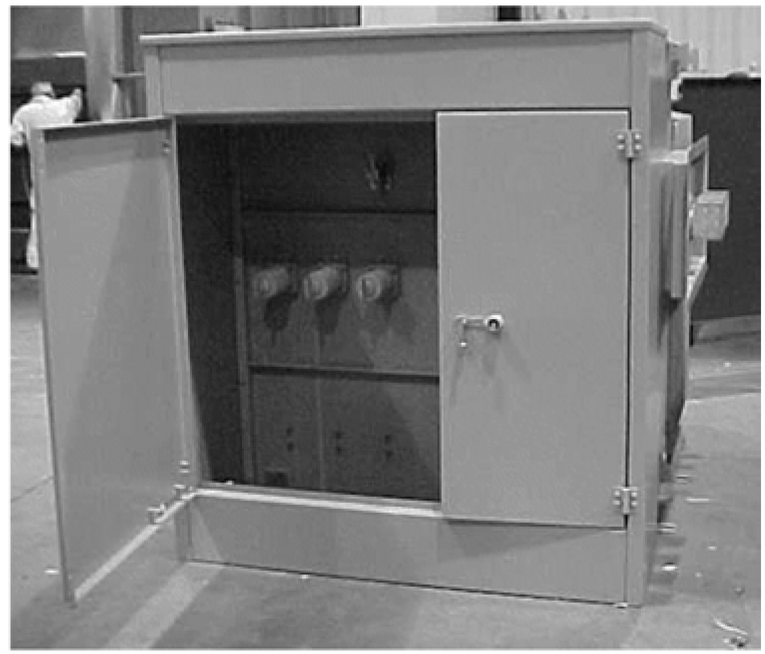


Radial forces are equalized during short circuits & overloads

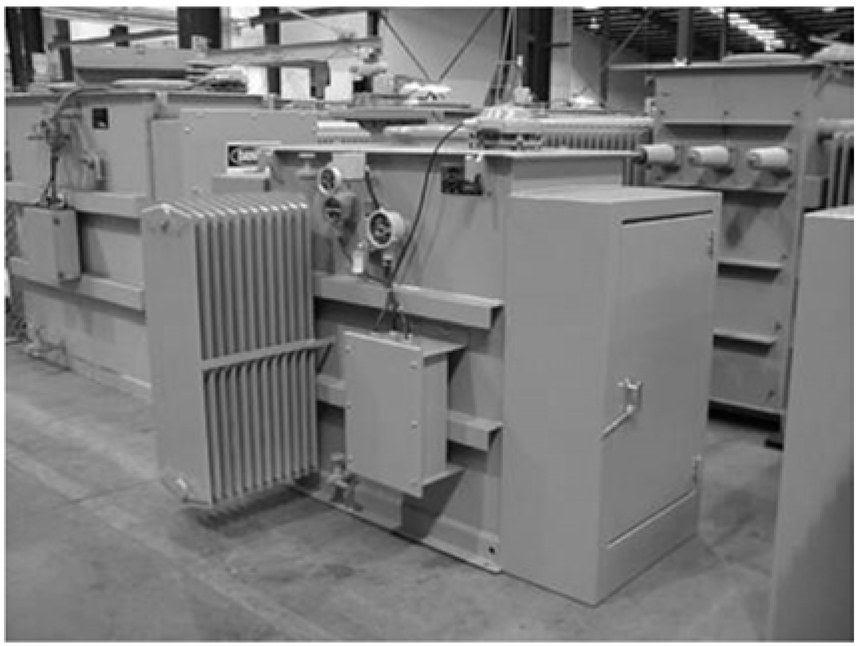
Cruciform stacked core construction



Padmount Transformer



Unit Substation and Substation Transformer

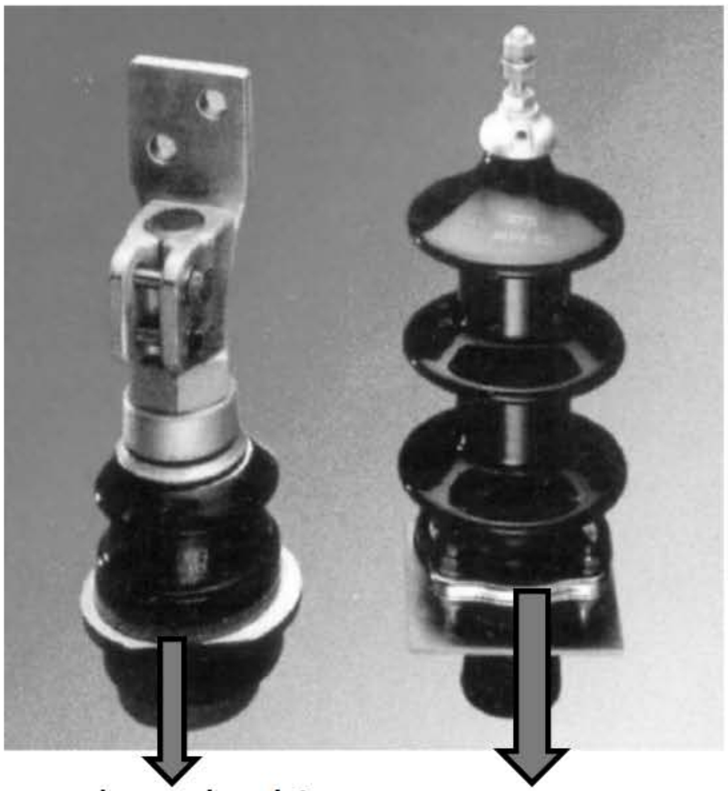


Transformer

Classification

- Step down transformer
- Step up transformer
- Core type Transformer
- Shell type transformer
- Spiral core type transformer
- Distribution Transformer
- Power Transformer
- Current transformer
- Potential transformer
- Single phase transformers
- Poly phase transformer

Bushing



Low voltage bushing

High voltage bushing

- The bushing provides insulation of the terminals of winding. These bushings are made of well china clay. These are housed on the upper side of tank through gasket. Service line and terminals of the winding is connected through bushing.
- High side bushings are large and low side bushings are small

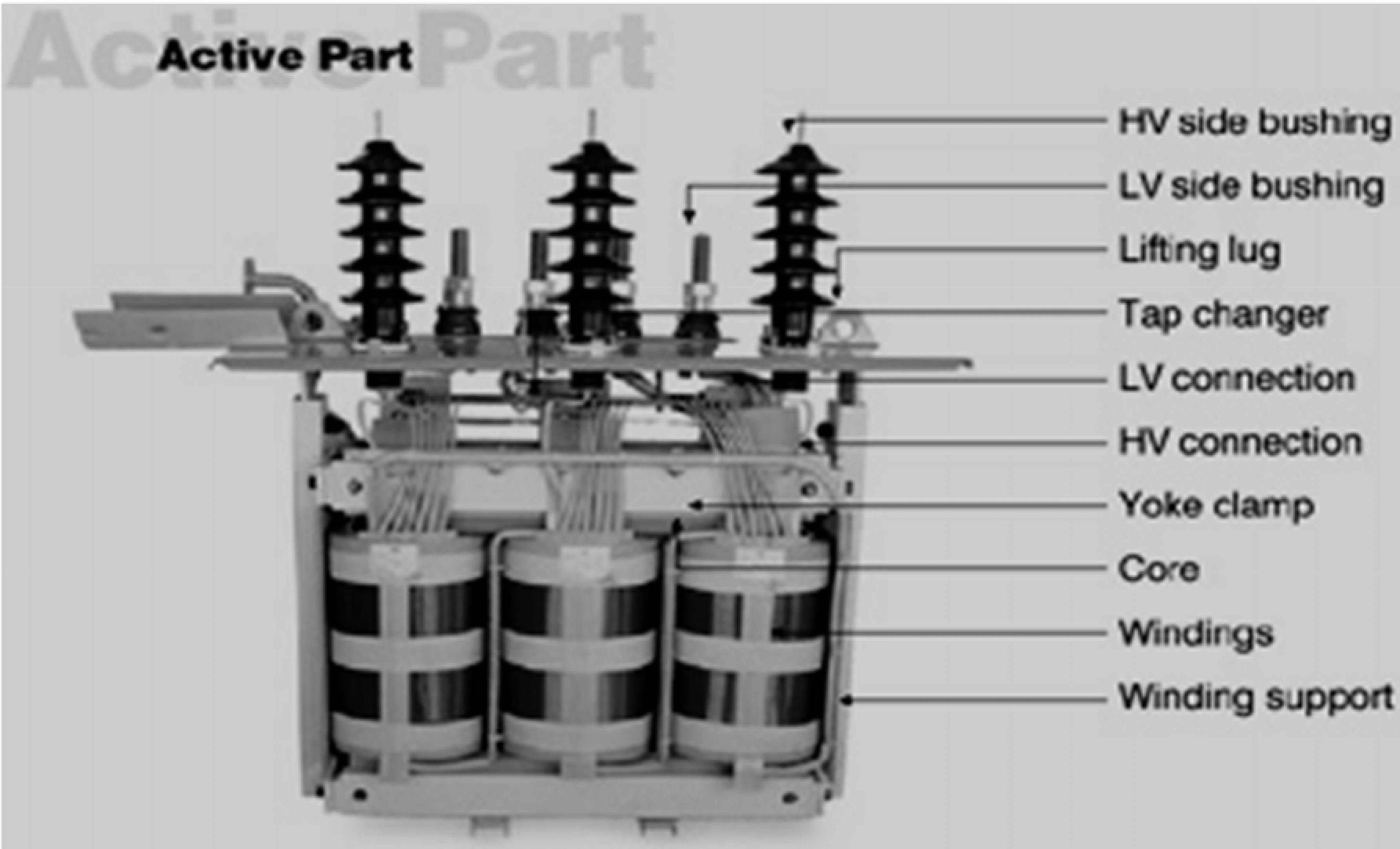
Conservator

- It is transformer oil storage tank and if the main tank oil reduces the conservator will feed the oil to main tank.

- And if the oil get expansion that oil will go to conservator

Fig: Conservator

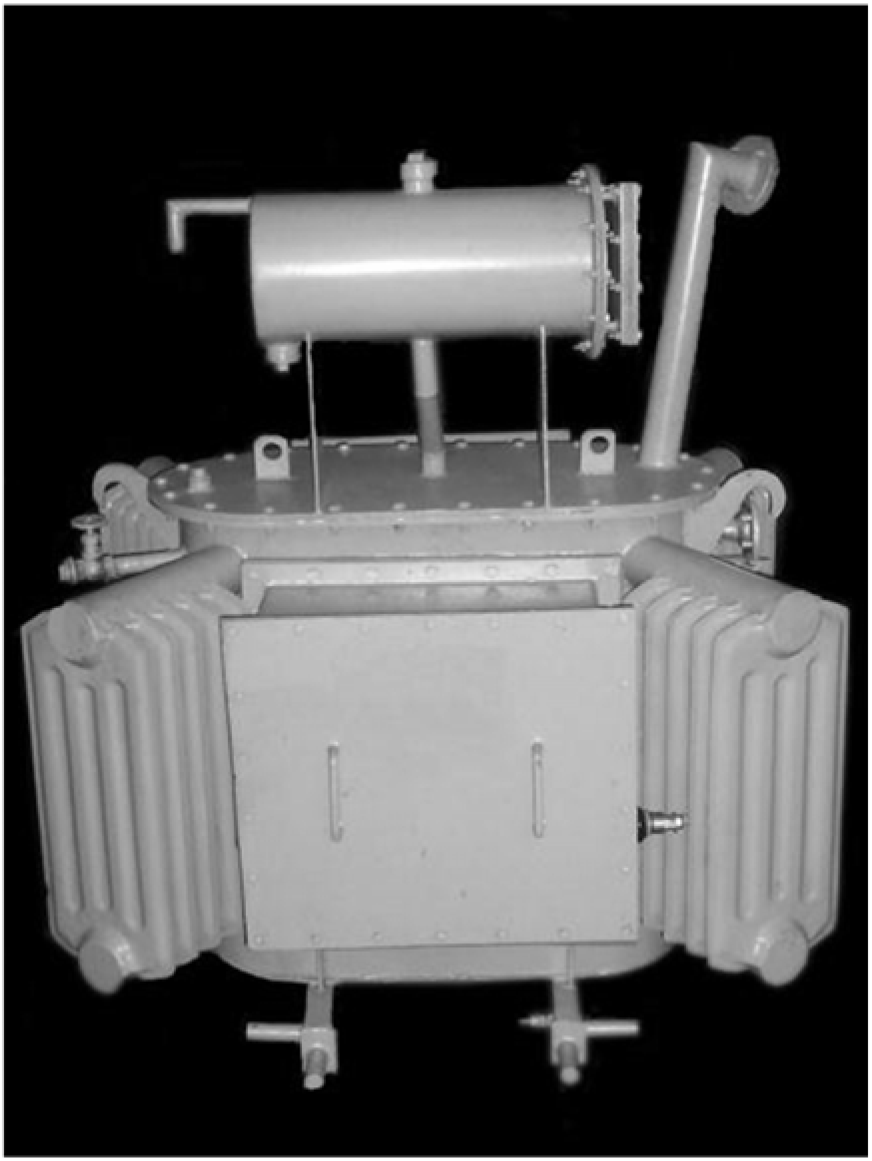
Assembling of Transformer



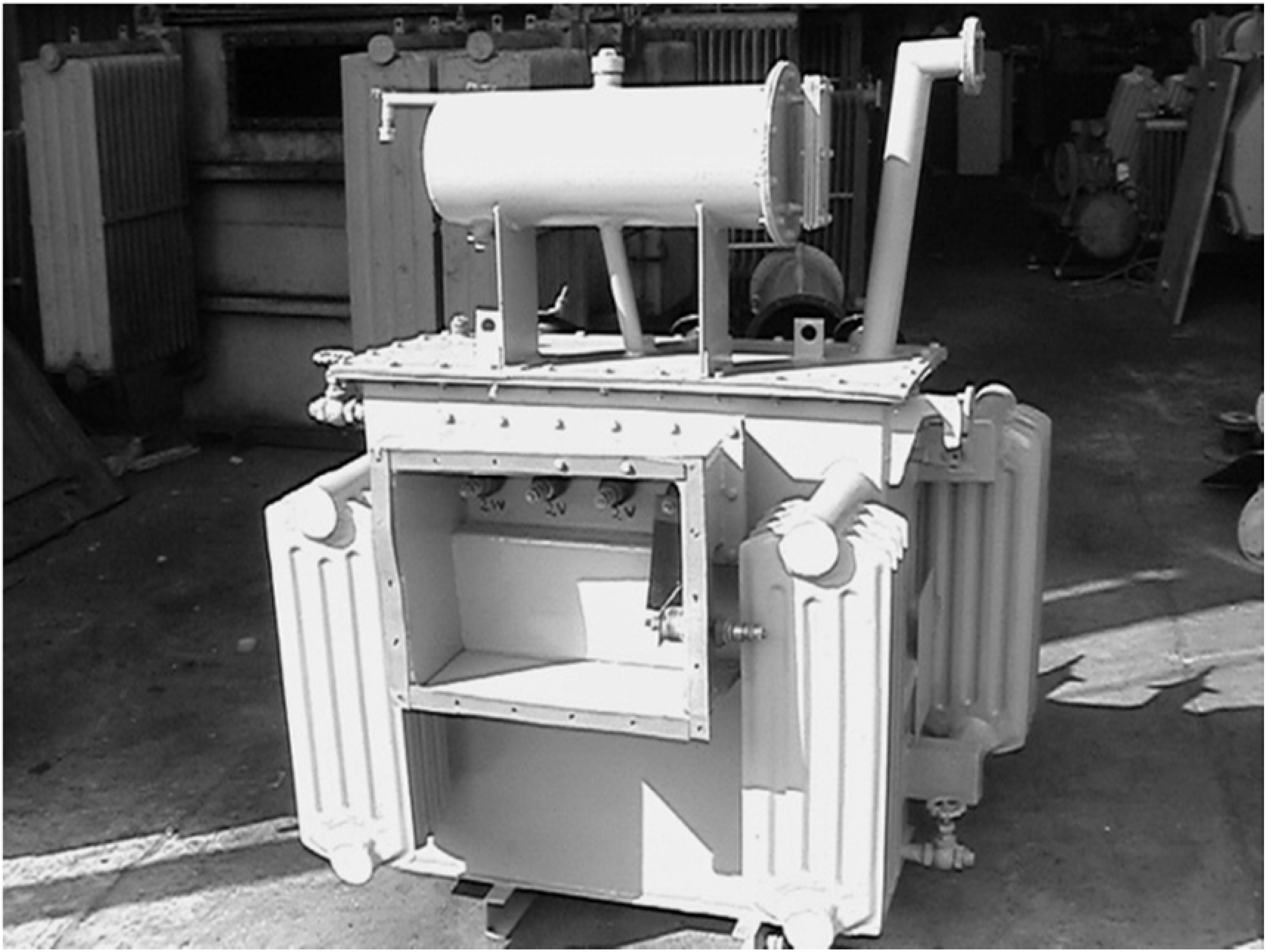
MAIN FEATURES

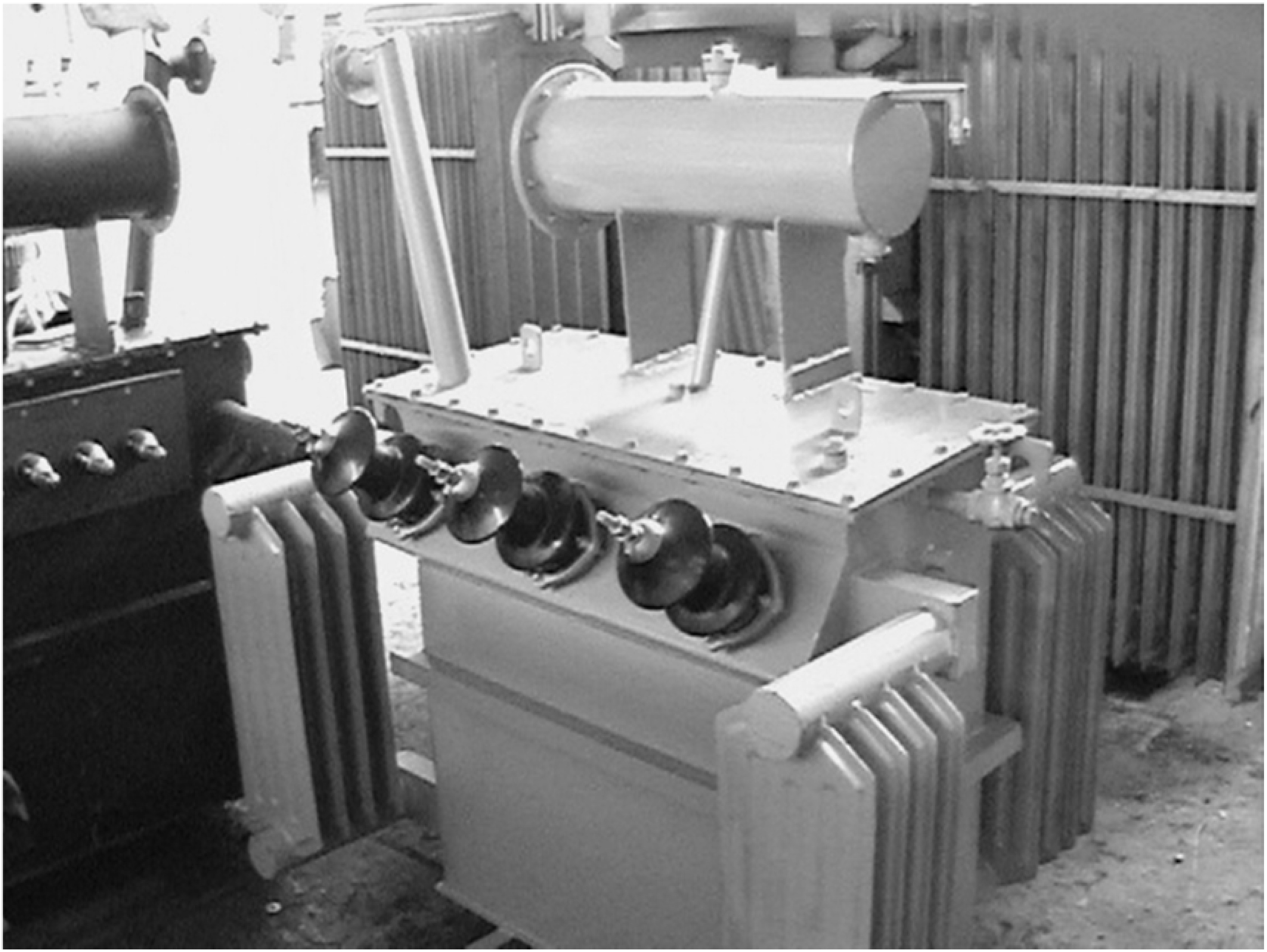
- OUTDOOR,OIL COOLED, 3 PHASE,50/60HZ
- PRIMARY IS DELTA CONNECTED AND SECONDARY IS STAR CONNECTED.
- NATURALY COOLED (ONAN TYPE).
- AMONGST ALL THE TYPES OF TRANSFORMERS THIS IS THE MOST REQUIRED AND MOST USED TYPE.

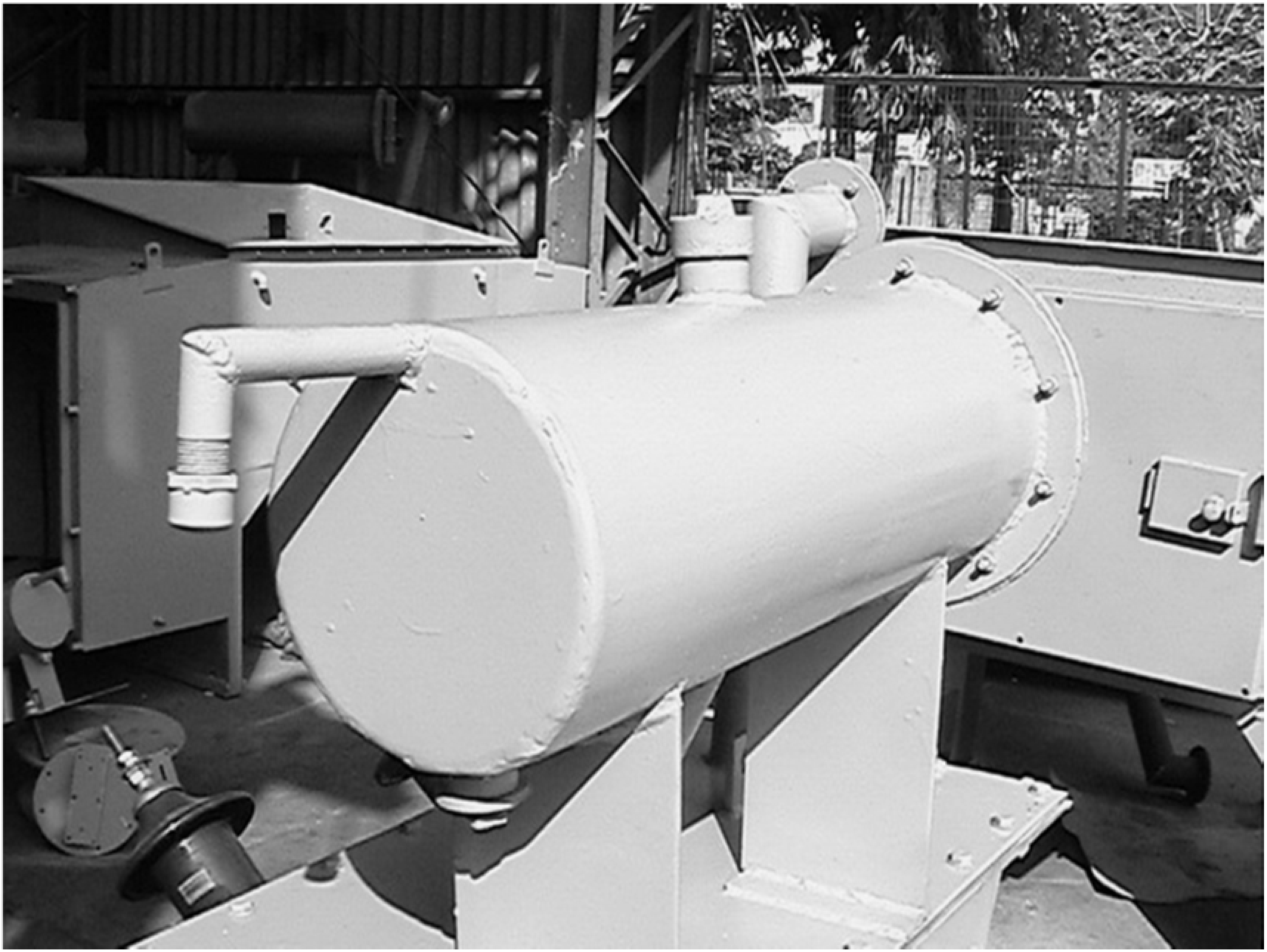
PARTS OF TRANSFORMER

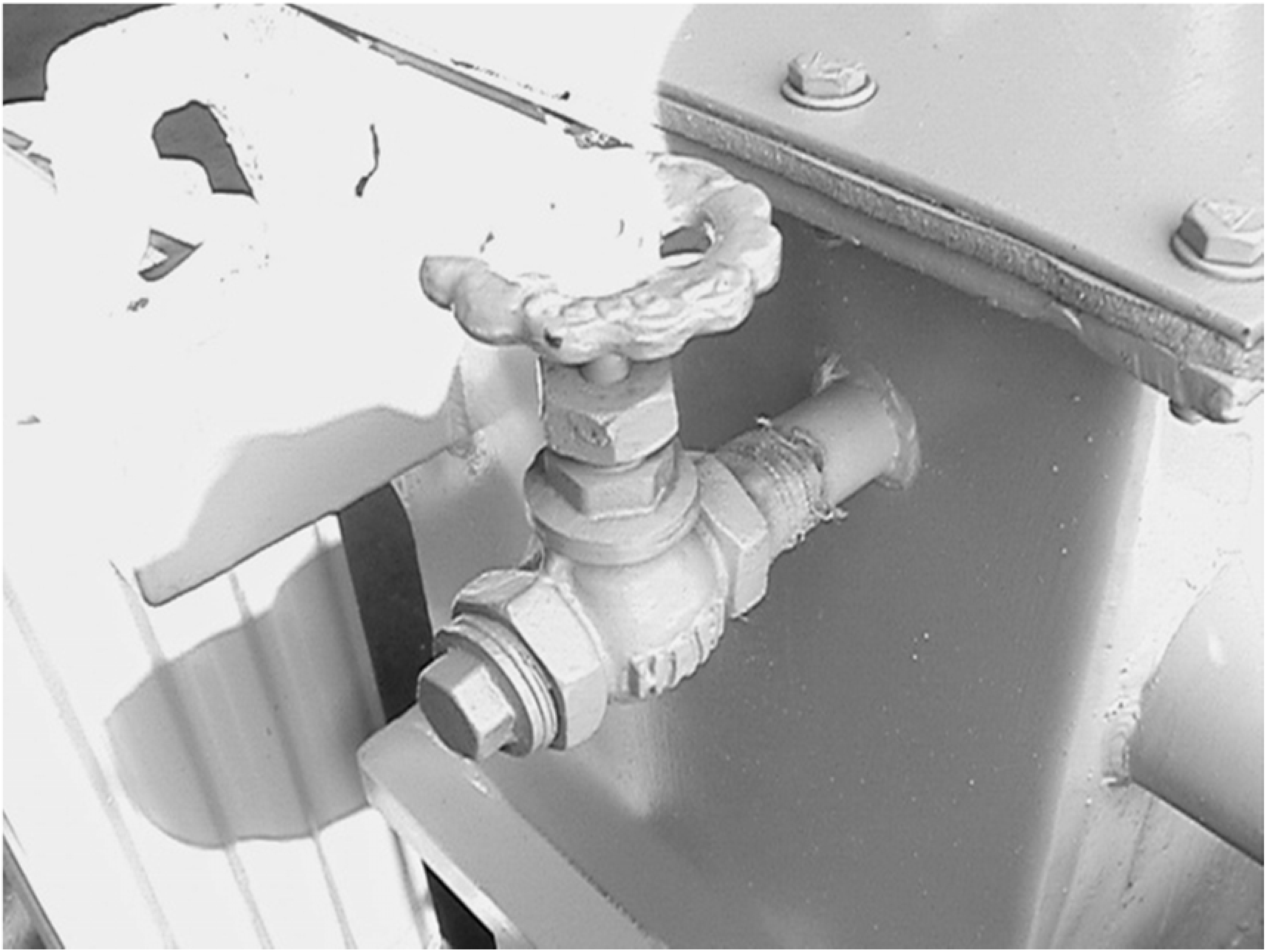


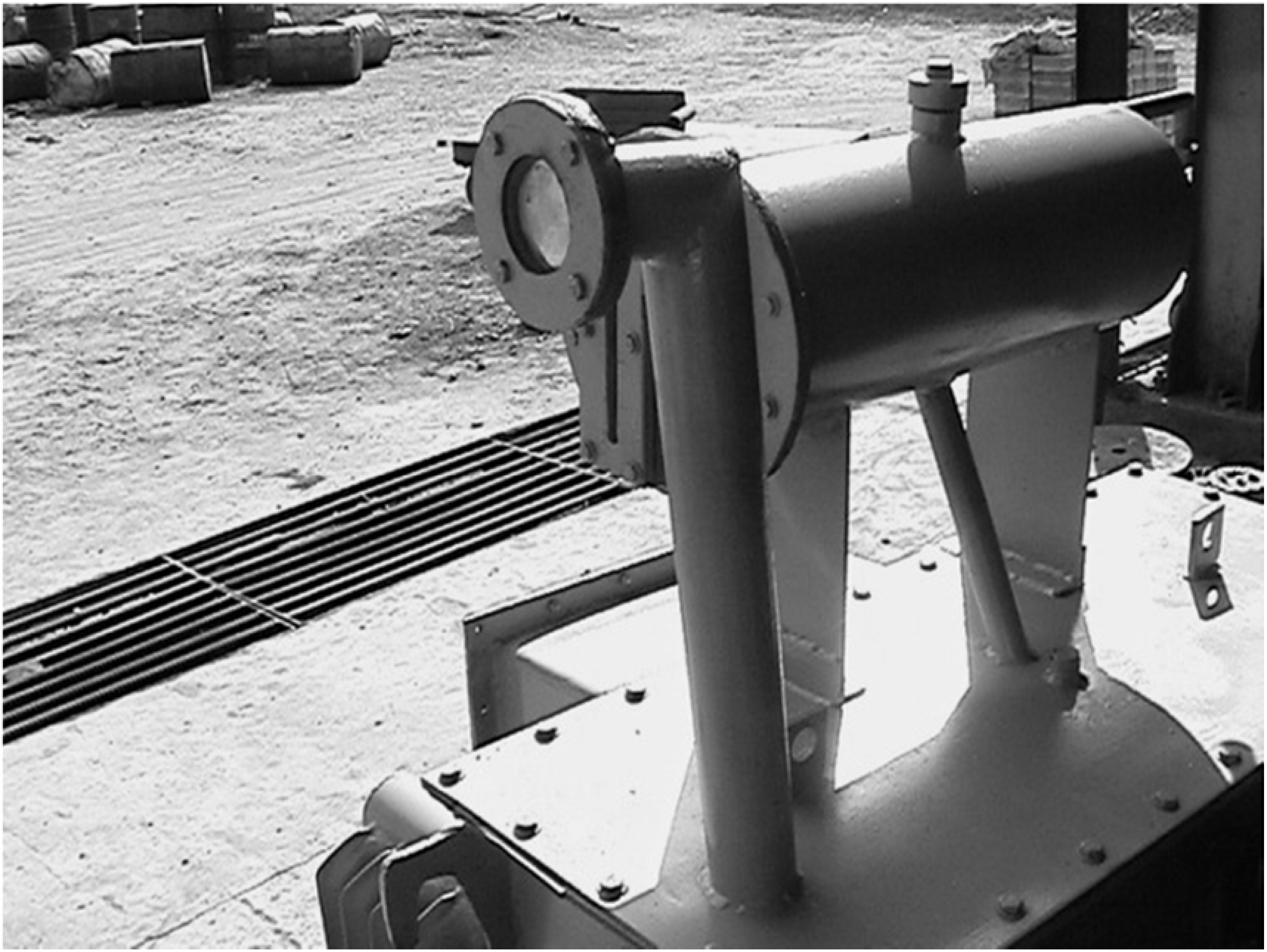
- MAIN TANK
- RADIATORS
- CONSERVATOR
- EXPLOSION VENT
- LIFTING LUGS
- AIR RELEASE PLUG
- OIL LEVEL INDICATOR
- TAP CHANGER
- WHEELS
- HV/LV BUSHINGS
- FILTER VALVES
- OIL FILLING PLUG
- DRAIN PLUG
- CABLE BOX

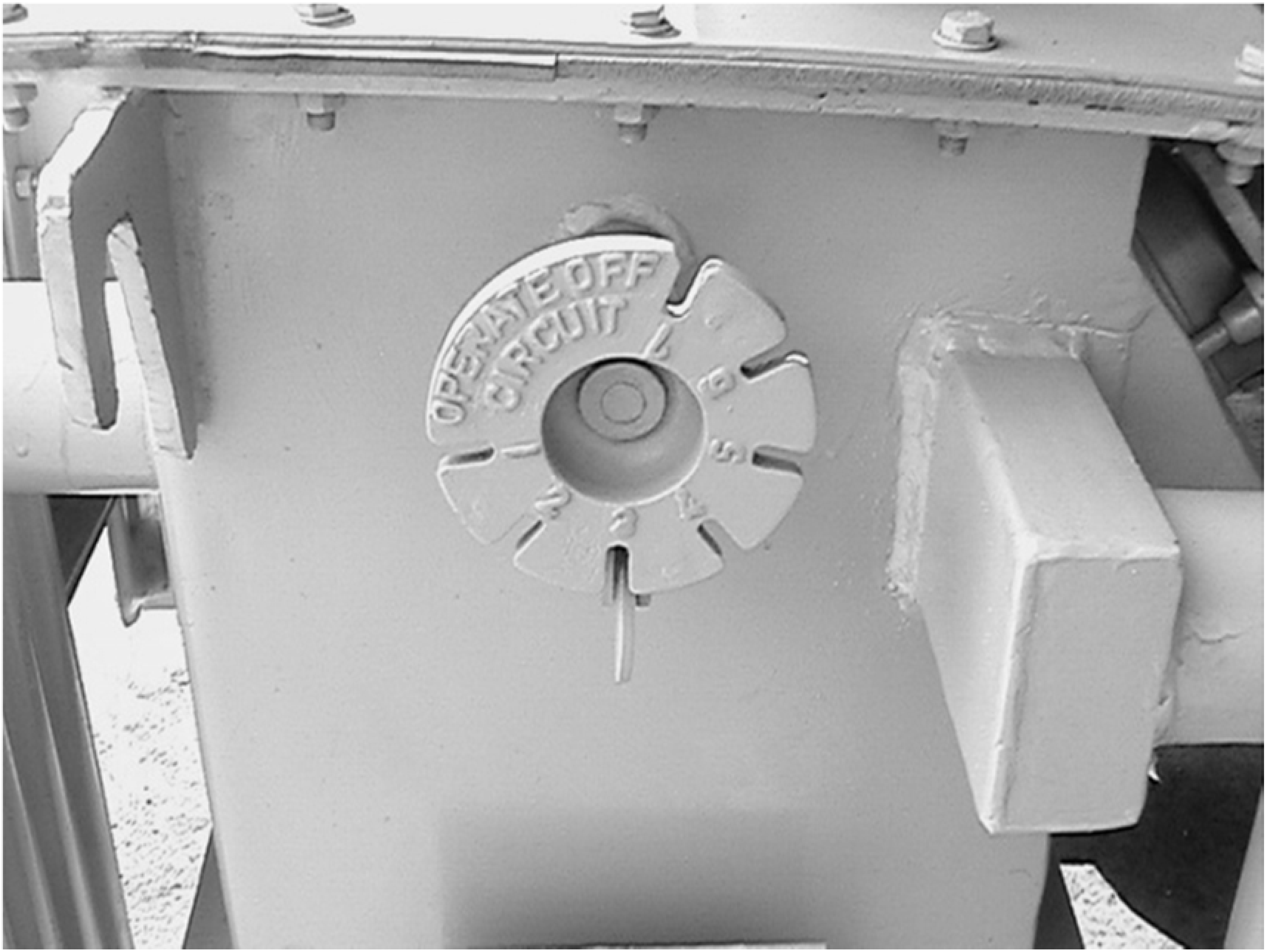


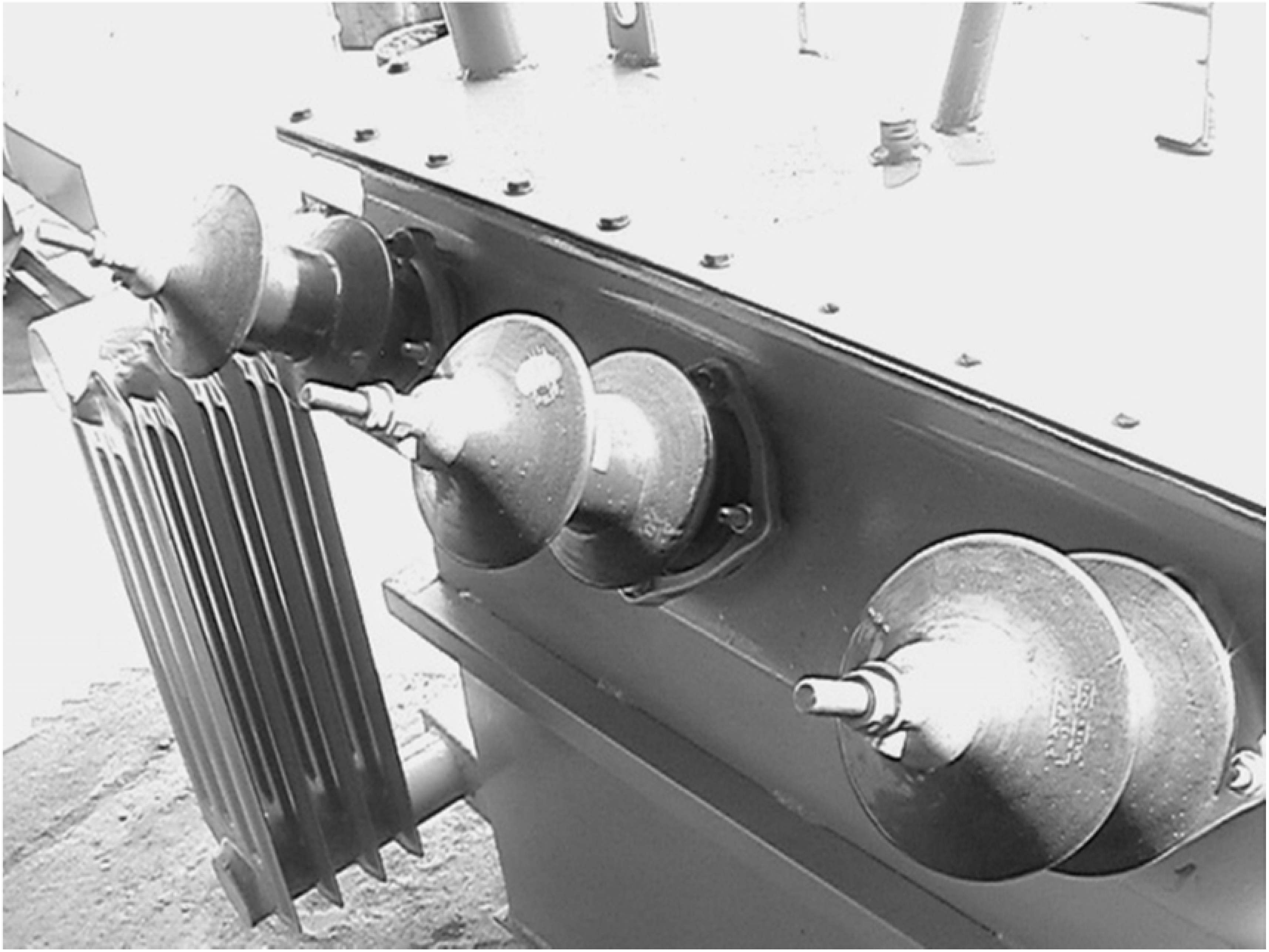


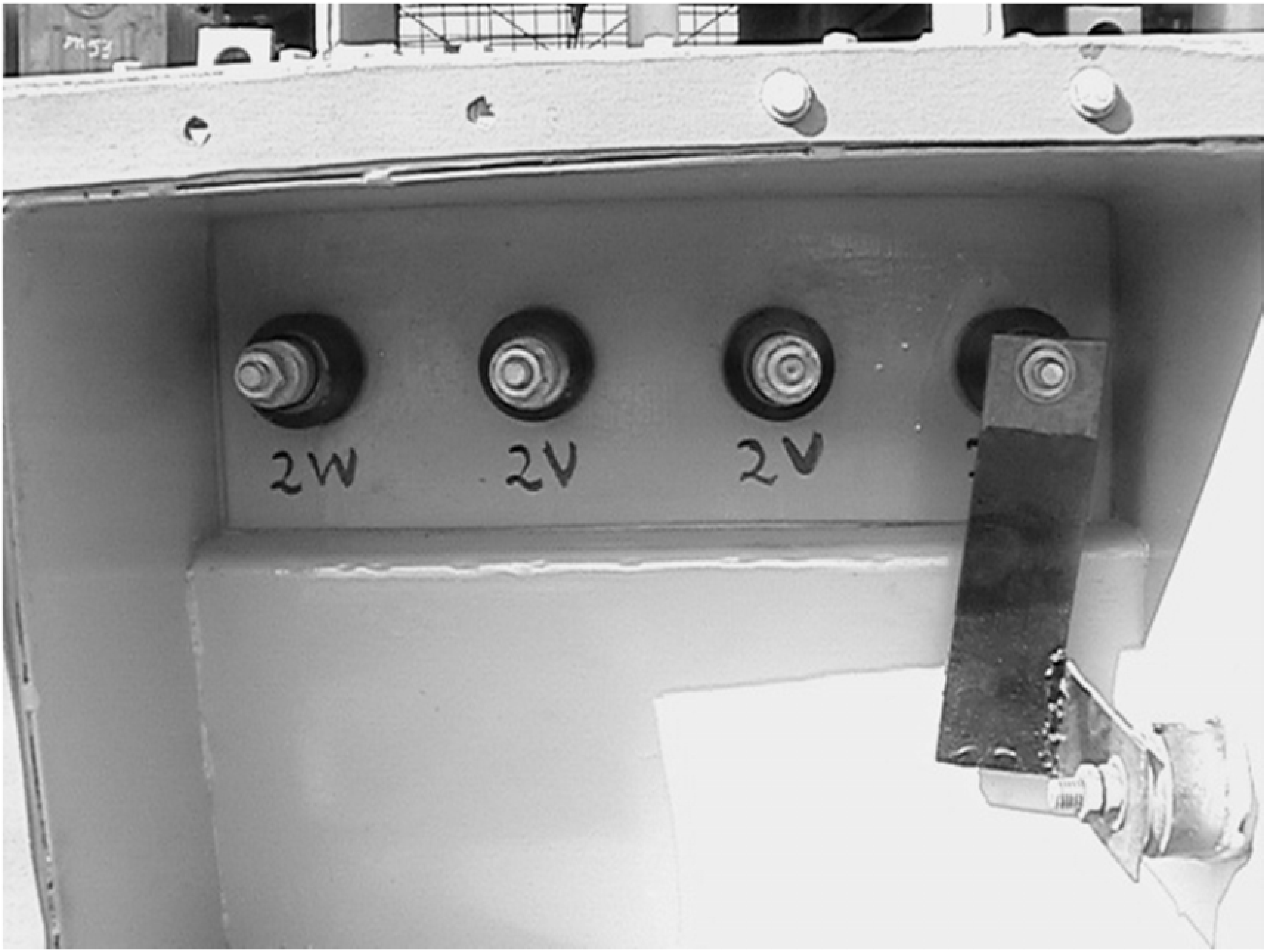


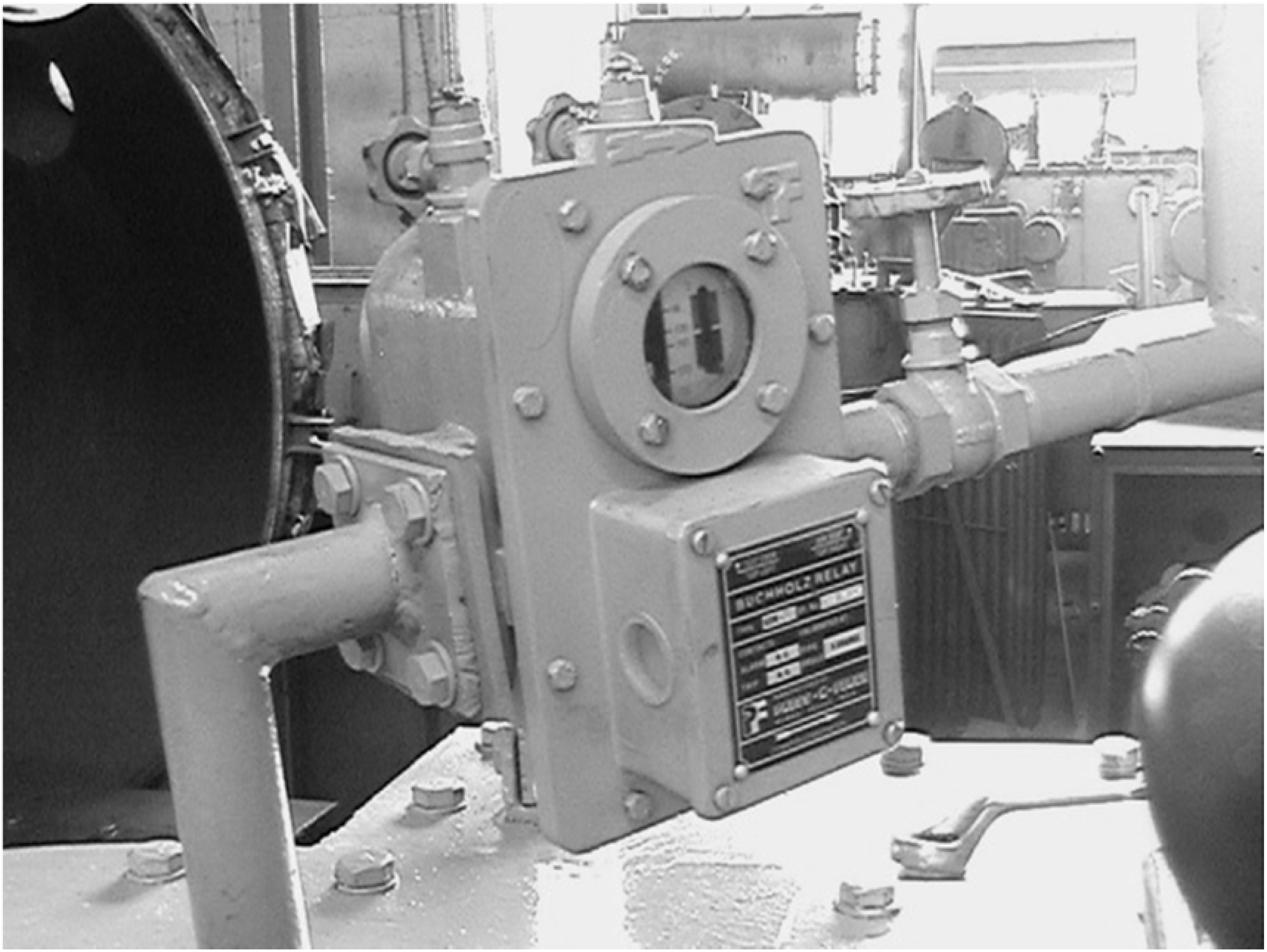





OPERATE OFF CIRCUIT
1
2
3
4
5
6
7




2W
2V
2V


BUCHHOLZ RELAY

TESTING OF TRANSFORMER

- ROUTINE , TYPE TESTS & SPECIAL TESTS

- ROUTINE TESTS (TO BE CARRIED OUT ON EACH JOB)
- 1.Measurement of winding resistance
- 2.Measurement of insulation resistance
- 3.Seperate source voltage withstand test (High Voltage tests on HV & LV)
- 4.Induced Over voltage Withstand test (DVDF test)
- 5.Measurement of voltage ratio
- 6.Measurement of NO LOAD LOSS & current.
- 7.Measurement of LOAD LOSS & IMPEDENCE.(EFFICIENCY & REGULATION)
- 8.Vector Group Verification
- 9.Oil BDV test.
- 10.Tests on OLTC (if Attached)

TYPE TESTS

THESE TESTS ARE CARRIED OUT ONLY ON ONE TRANSFORMER OF THE LOT.

- All routine tests
- Additionally following tests are included in type tests
  1. Lightning Impulse test.
  2. Temperature rise test

SPECIAL TESTS

- Additional Impulse test
- Short circuit test
- Measurement of zero Phase sequence Impedance test.
- Measurement of acoustic noise level.
- Measurement of harmonics of the no load current.
- Magnetic balance test.

MAINTENANCE OF TRANSFORMER

- Transformer is the heart of any power system. Hence preventive maintenance is always cost effective and time saving. Any failure to the transformer can extremely affect the whole functioning of the organization.

MAINTENANCE PROCEDURE

- OIL :

1. Oil level checking. Leakages to be attended.
2. Oil BDV & acidity checking at regular intervals. If acidity is between 0.5 to 1mg KOH, oil should be kept under observation.
3. BDV, Color and smell of oil are indicative.

MAINTENANCE PROCEDURE

1. Sludge, dust, dirt ,moisture can be removed by filtration.
2. Oil when topped up shall be of the same make. It may lead to sludge formation and acidic contents.

- Insulation resistance of the transformer should be checked once in 6 months.
- Megger values along with oil values indicate the condition of transformer.
- Periodic Dissolved Gas Analysis can be carried out.

MAINTENANCE

- BUSHINGS

Bushings should be cleaned and inspected for any cracks.

Dust & dirt deposition, Salt or chemical deposition, cement or acid fumes depositions should be carefully noted and rectified.

MAINTENANCE

- Periodic checking of any loose connections of the terminations of HV & LV side.
- Breather examination. Dehydration of Silica gel if necessary.
- Explosion vent diaphragm examination.
- Conservator to be cleaned from inside after every three years.
- Regular inspection of OIL & WINDING TEMPERATURE METER readings.
- Cleanliness in the Substation yard with all nets, vines, shrubs removed.

PROTECTION OF TRANSFORMERS

- The best way of protecting a transformer is to have good preventive maintenance schedule.
- Oil Temperature Indicators.
- Winding Temperature indicators.
- Buchholz Relay.
- Magnetic Oil level Gauge.
- Explosion Vent.

FAILURES & CAUSES

- Insufficient Oil level.
- Seepage of water in oil.
- Prolonged Over loading.
- Single Phase loading.
- Unbalanced loading.
- Faulty Termination (Improper sized lugs etc)
- Power Theft.
- Prolonged Short Circuit.
- Faulty operation of tap changer switch.
- Lack of installation checks.

FAILURES & CAUSES

- Faulty design
- Poor Workmanship
- Improper formation of core.
- Improper core bolt insulation.
- Burr to the lamination blades
- Improper brazing of joints.
- Burr /sharp edges to the winding conductor.
- Incomplete drying.
- Bad insulation covering.
- Insufficient cooling ducts in the winding.

FAILURES & CAUSES

- Bad Quality of raw material.
- Transit damaged transformers.
- After failure , transformer is removed and replaced with new/repaired one without determining the cause of failure which results in immediate or short time failure.

Understanding Power Concepts

Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- ***Substations***
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

Substations

Fundamental questions (big picture) to ask about **High Voltage Substations**

EHV / HV / MV / LV

Substation Design

- Relay & Control design (One Line Diagram, Schematics, Wiring Diagram, Connection Diagram, SCADA/RTU drawings), Relay setting and coordination
- Review vendor drawings (major equipment, steel drawings,

Procurement Service

- Expedited delivery
- Bid / Evaluate / Award equipment on client's paper or consultants paper

Construction Service

- Construction management / coordination
- Safety
- Document control
- Field verification and engineering
- Record Drawing Set

Environment Service

- CCN for Transmission
- SPCC
- SWPPP

Others

- Coordinate with department of transportation on access road
- Wet Land Permits

Typical Specification

1. Geotech and Survey Spec
2. Major Materials Spec (Transformer, Breaker, Switchgear, Cap Bank, GIS, SVC, Reactor etc.)
3. Material Package Spec
4. Control House and R&C Panel Spec
5. Construction Spec (site spec can be separated)
6. Test & Commission Spec

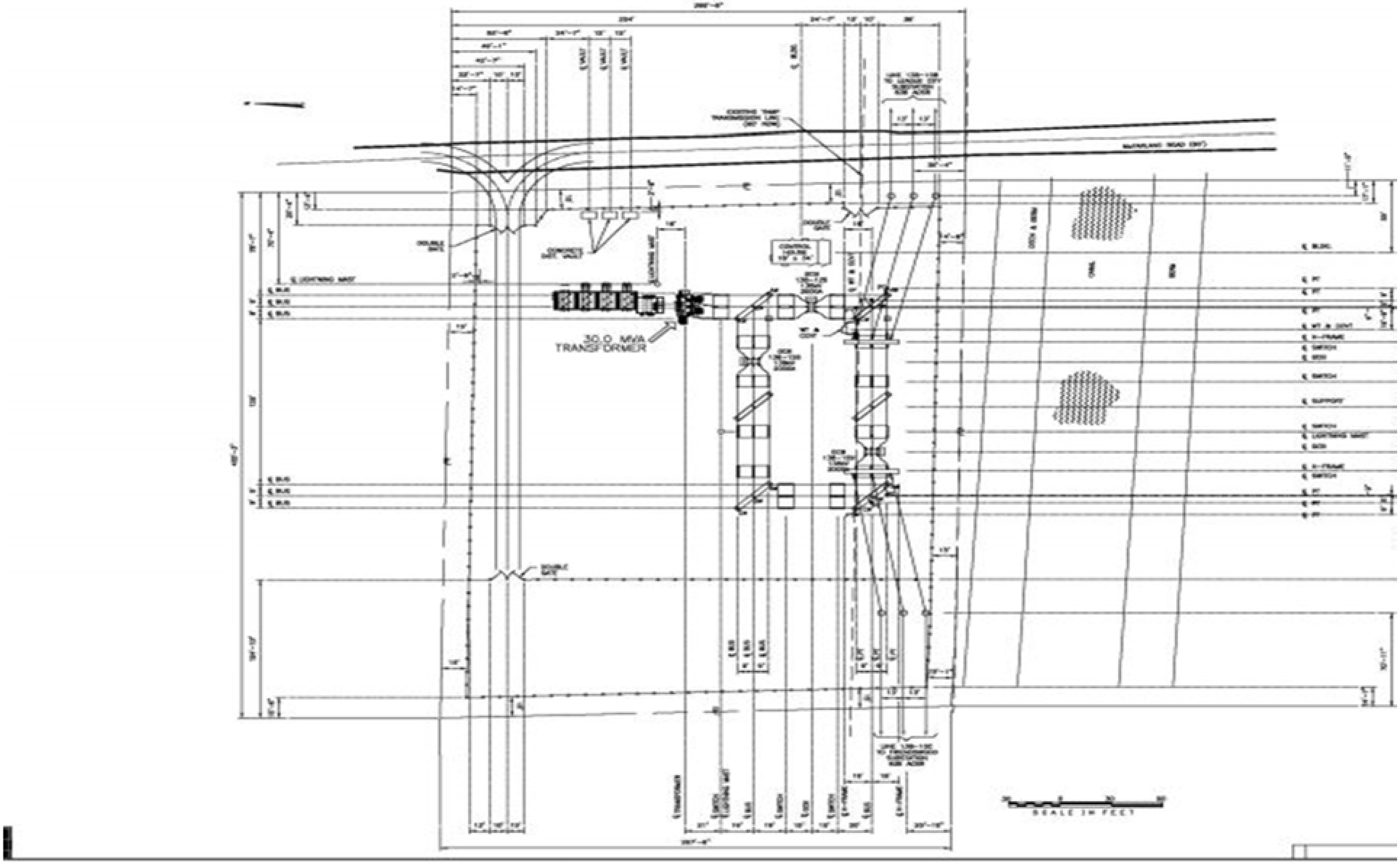
Topics Clients typically perform by themselves

1. System planning to determine the need for substation / transmission
2. Substation Cost Estimate
3. Substation Location Selection and land acquisition
4. Outage Coordination and planning
5. SCADA / Communication Programming
6. Communication Routing Study
7. Operation and Maintenance
8. Distribution line design and routing

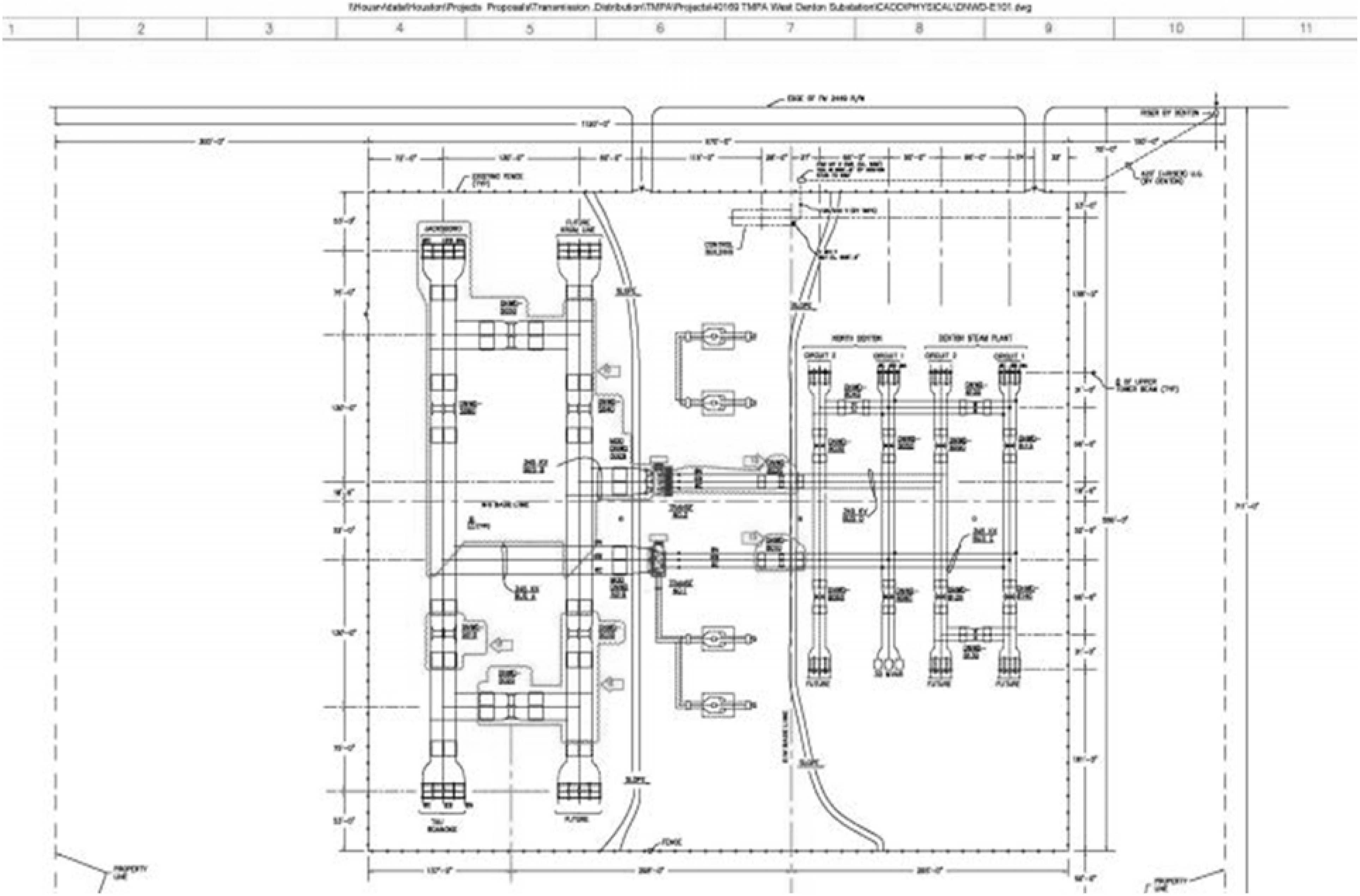
Type of Substations

- Relationship of substation to overall electrical system
- Three type of substations (application)
  - Distribution Substation
  - Transmission Substation
  - Switching Substation
- Two type of substations (insulation)
  - Open air
  - Gas Insulated

Distribution Substation



Transmission Substation



Open Air Substation

COMPACT DESIGN

Compact substation design (55'-6"X 67'-0") with:

a) one dead end tower

b) one disconnect switch

c) one gas circuit breaker

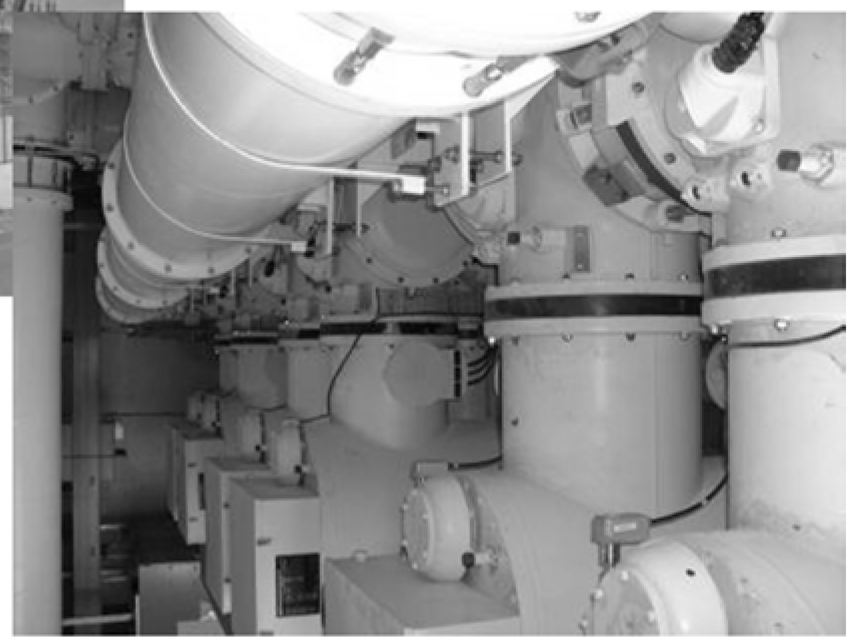
d) one step-down xfmr

e) one ground resistor

f) bus duct in to the PCR bldg

g) one PCR bldg with all electrical equipment inside

GIS Substation



General Design Consideration

- Initial and ultimate requirement
- Location and Siting
  - Location of load
  - Location of power source
  - Right-of-way availability
  - Location of existing distribution line
- Environmental Considerations
  - Appearance
  - Spill Prevention Control & Counter Measurement Plan (SPCC)
  - Storm Water Protection and Prevention Plan (SWPPP)

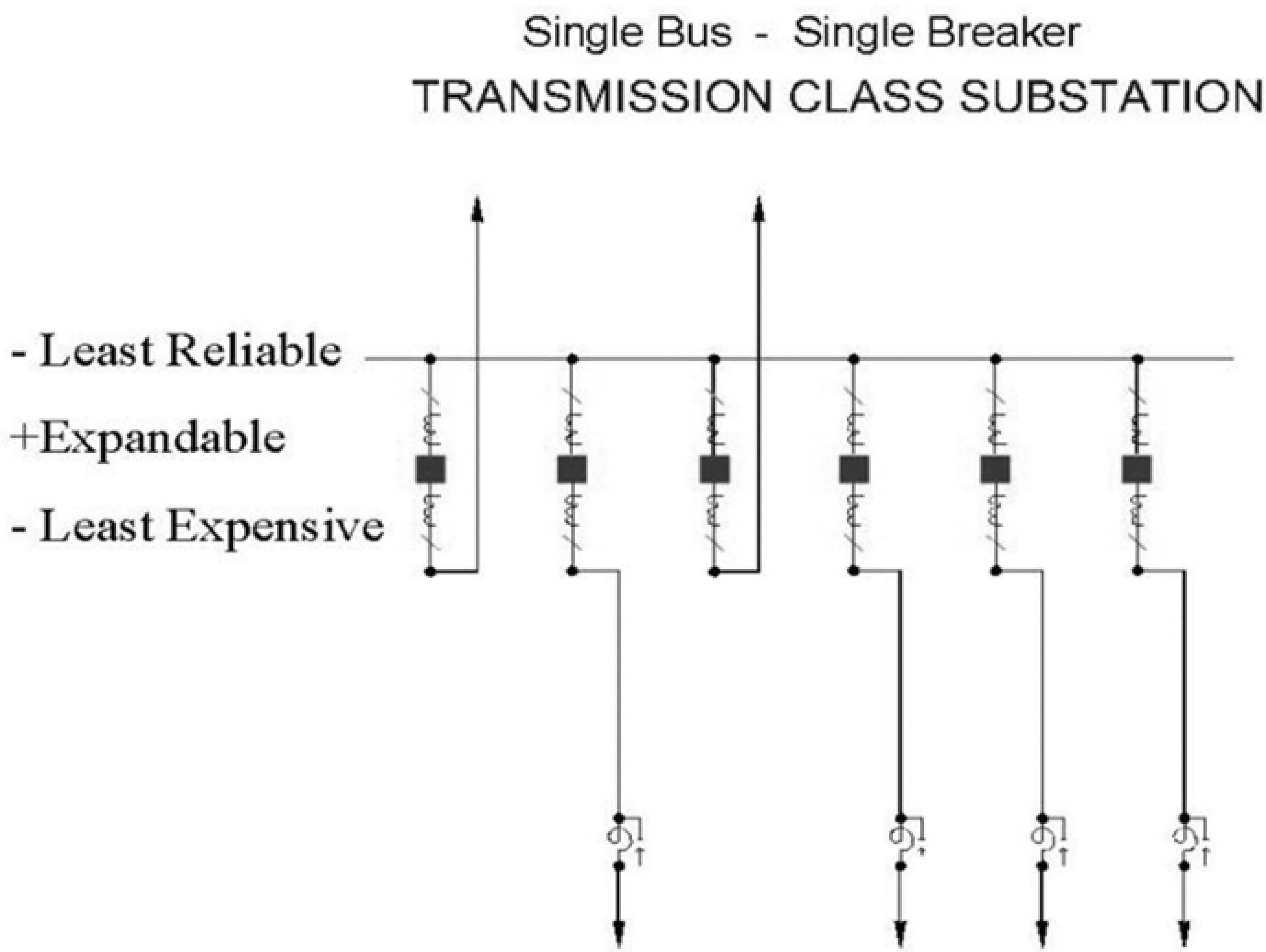
2. General Design Consideration (cont.)

- Weather
  - Wind
  - Ice
  - Temperature
  - Altitude
  - Earthquakes
- Safety Consideration
- Reliability Consideration
- Operational Consideration
- Maintenance Consideration

2. General Design Consideration (cont.)

- Most important drawings
  - Grading Layout
  - Substation Layout (initial and ultimate)
  - Foundation Layout
  - One Line Diagram (Relay & Control, and Communication

Bus Configuration

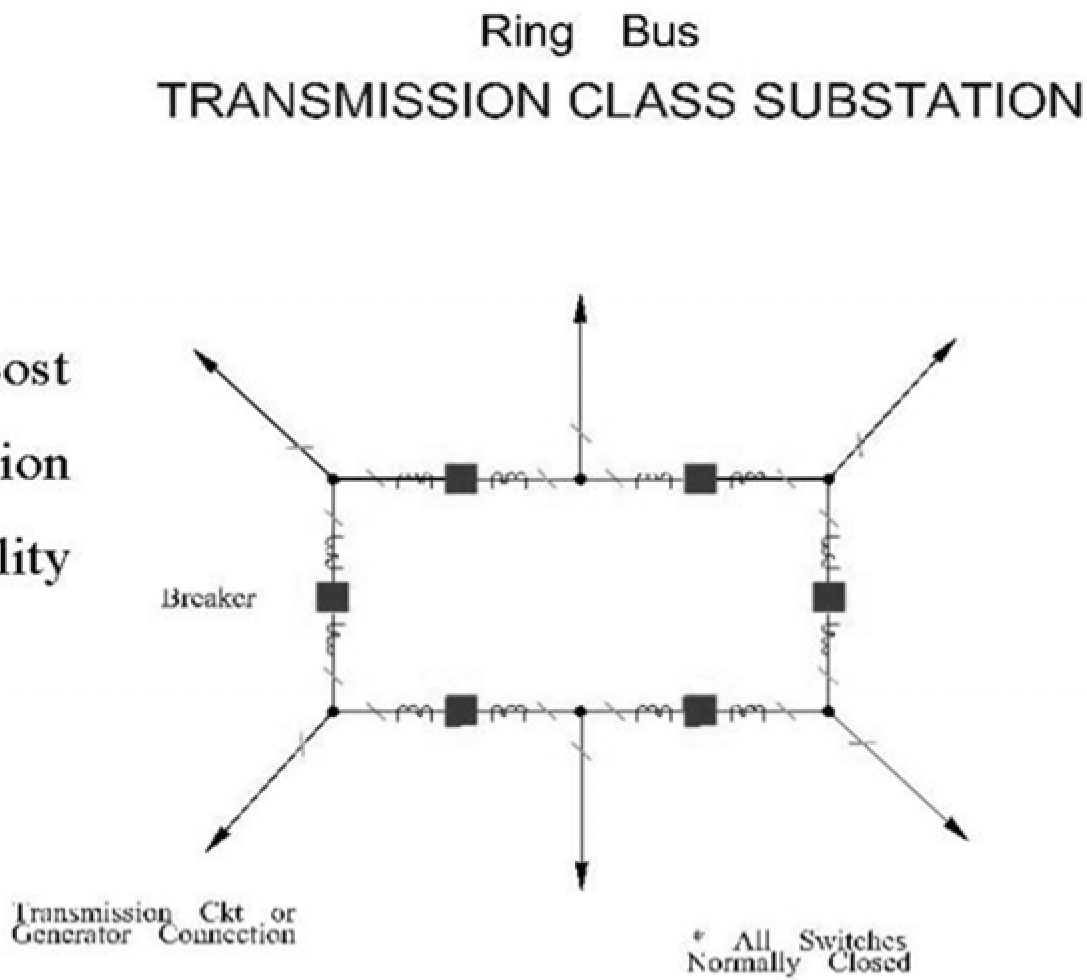


Bus Configuration

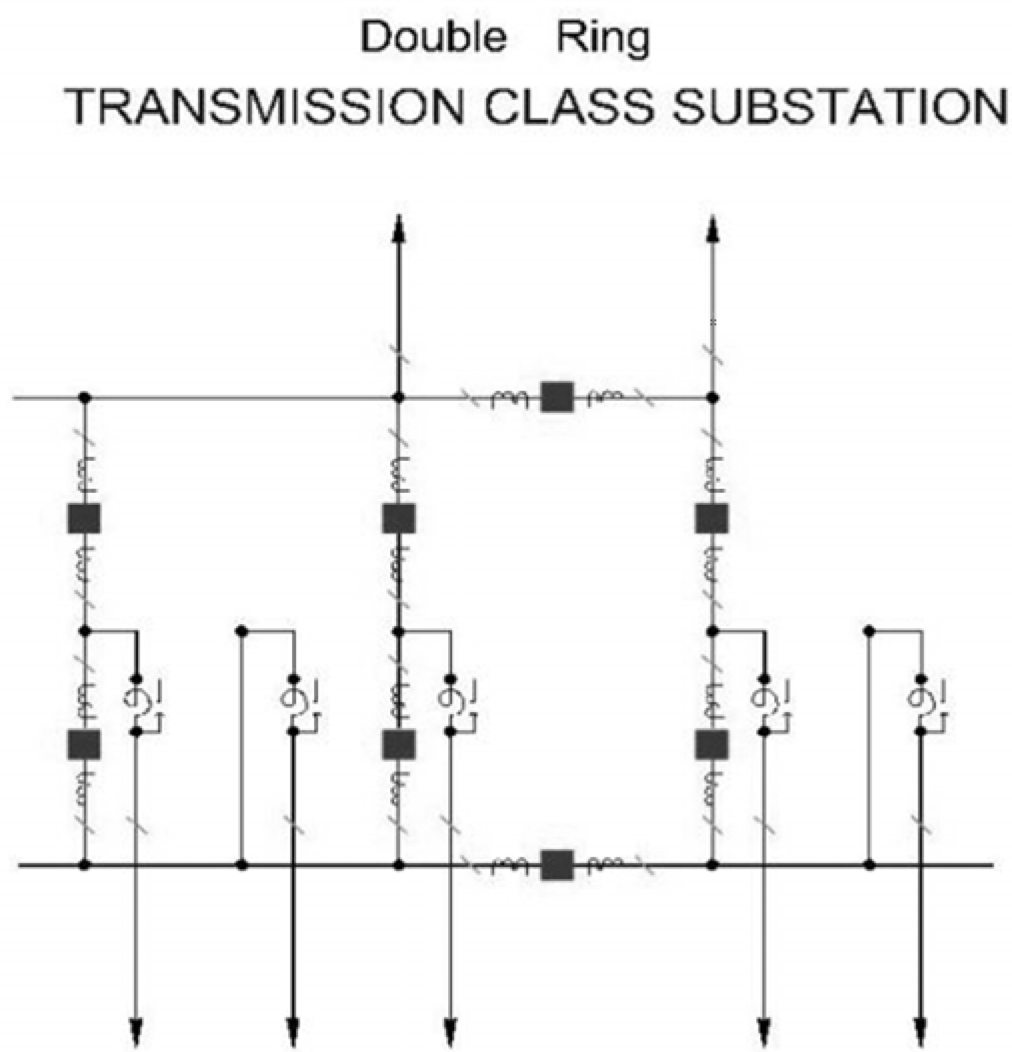
+ Low cost

-Expansion

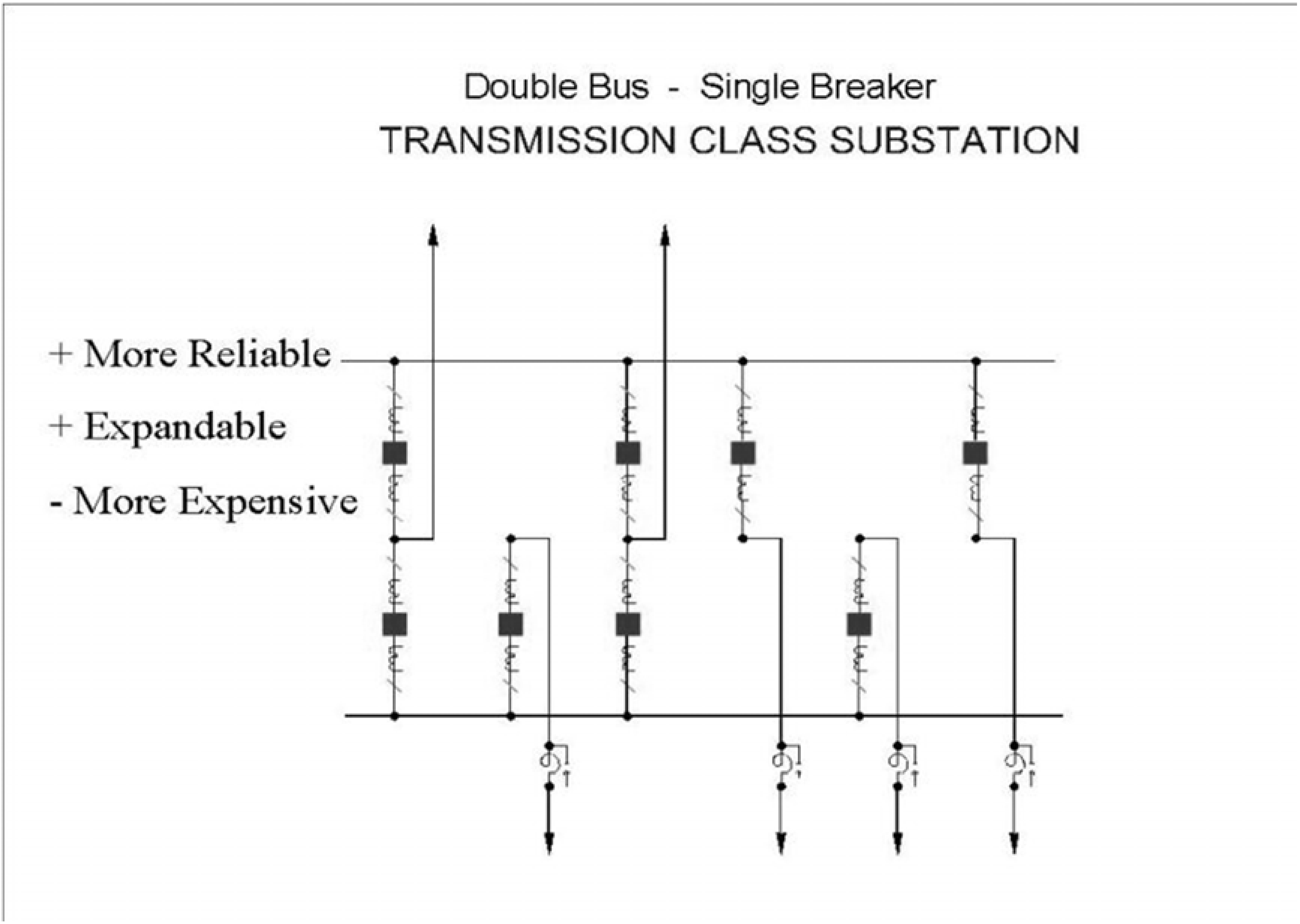
-Reliability



Bus Configuration



Bus Configuration



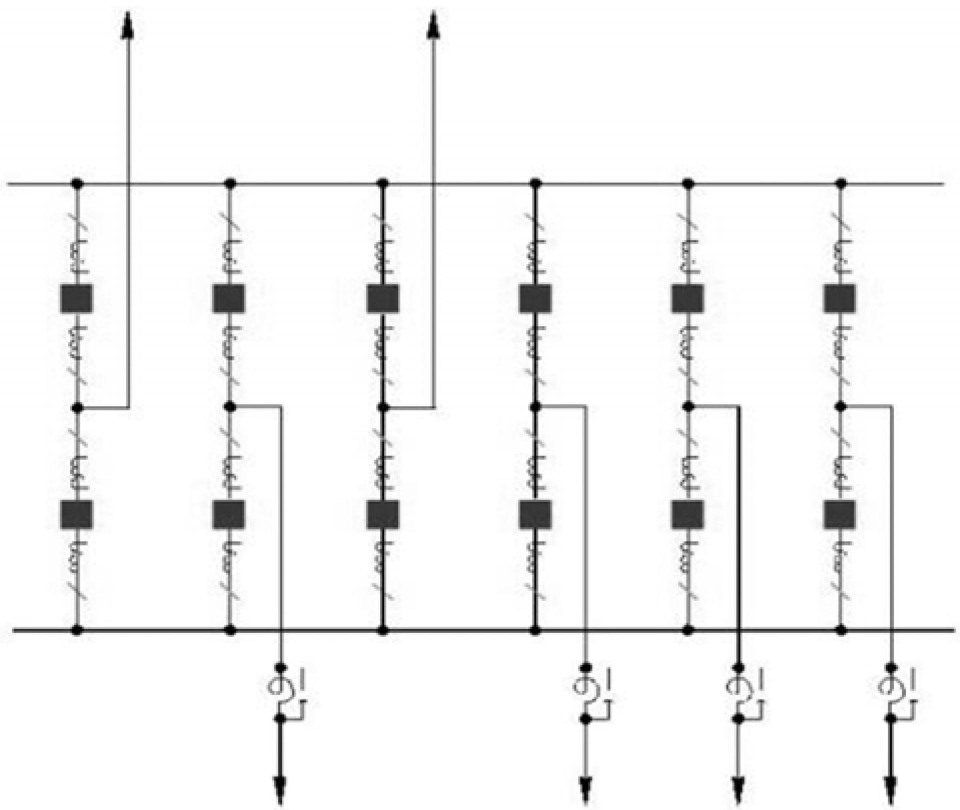
Bus Configuration

Double Bus - Double Breaker
TRANSMISSION CLASS SUBSTATION

+Very Reliable

+Expandable

-Expensive

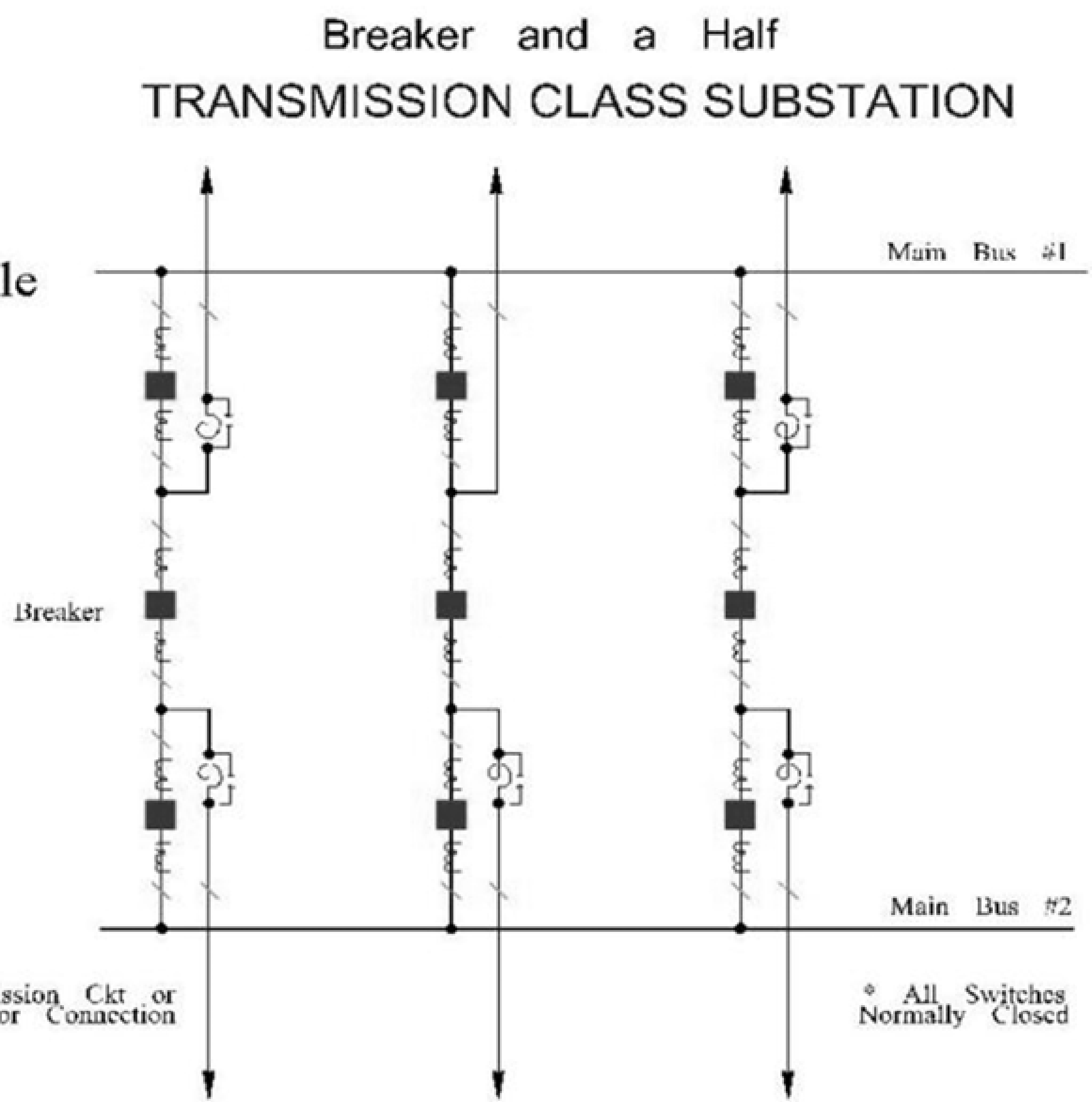


Bus Configuration

+Expandable

+Reliable

+-Average cost



Bus Configuration

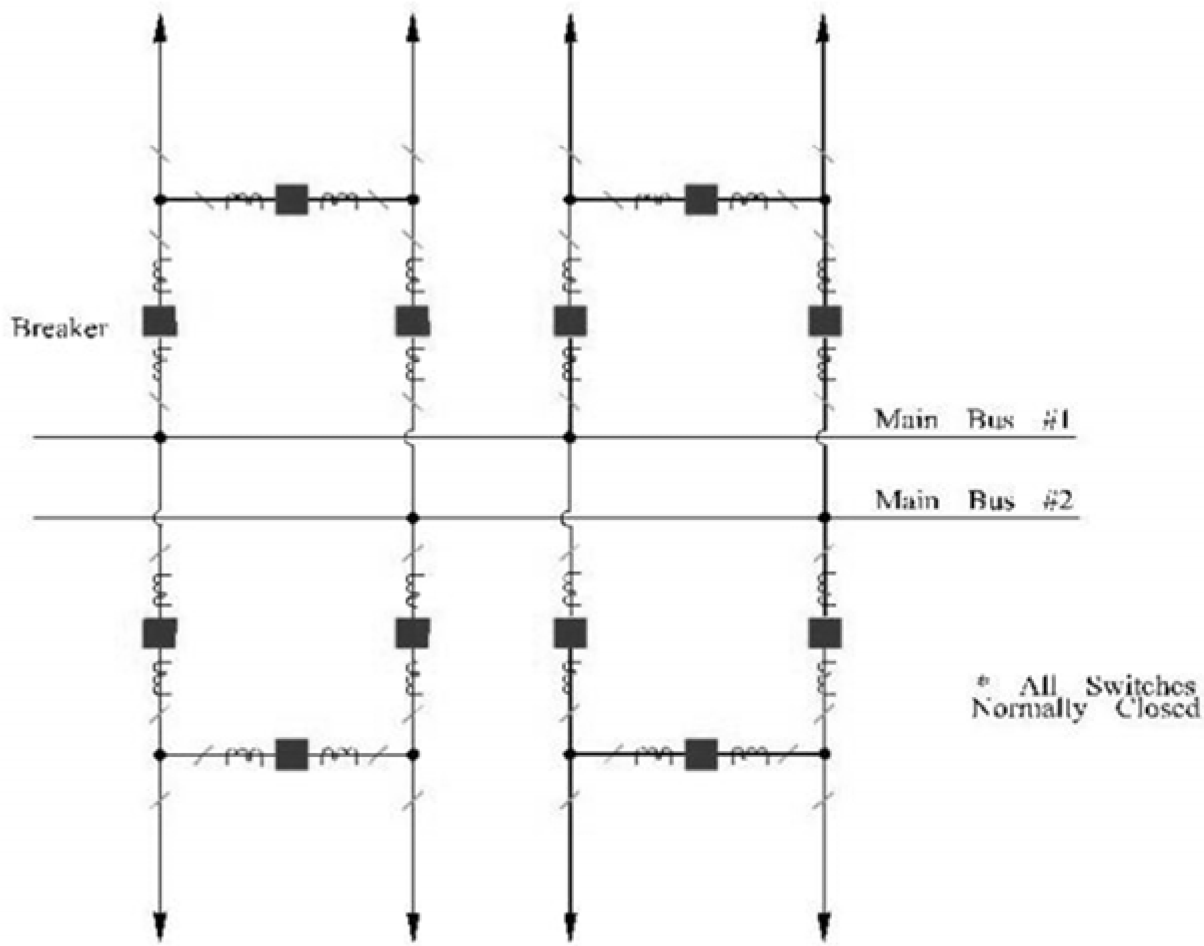
Breaker and a Half
("Inside Main Bus")

TRANSMISSION CLASS SUBSTATION

+Expandable

+Reliable

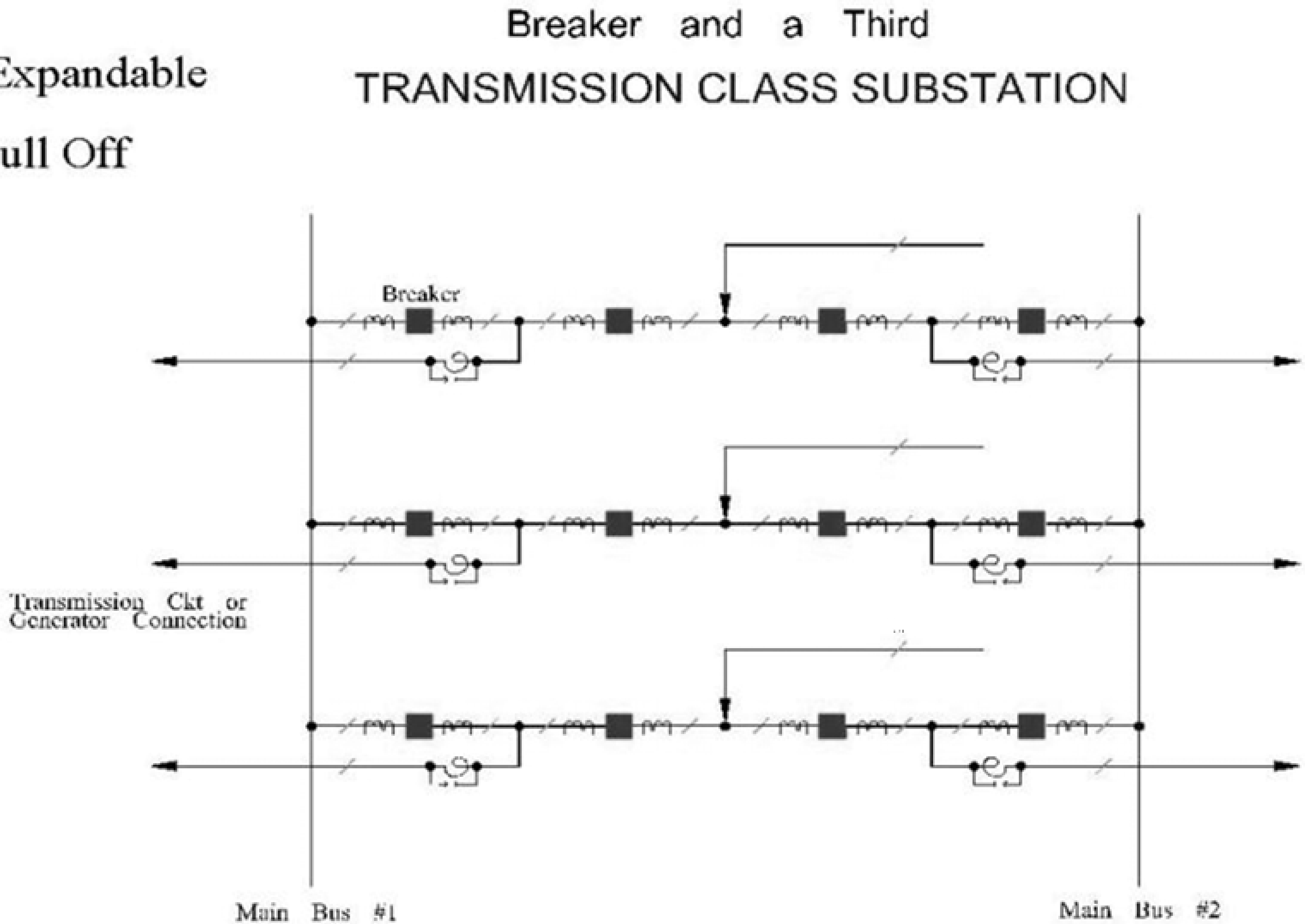
+Pull Off



Bus Configuration

+Expandable

-Pull Off



Substation Insulator

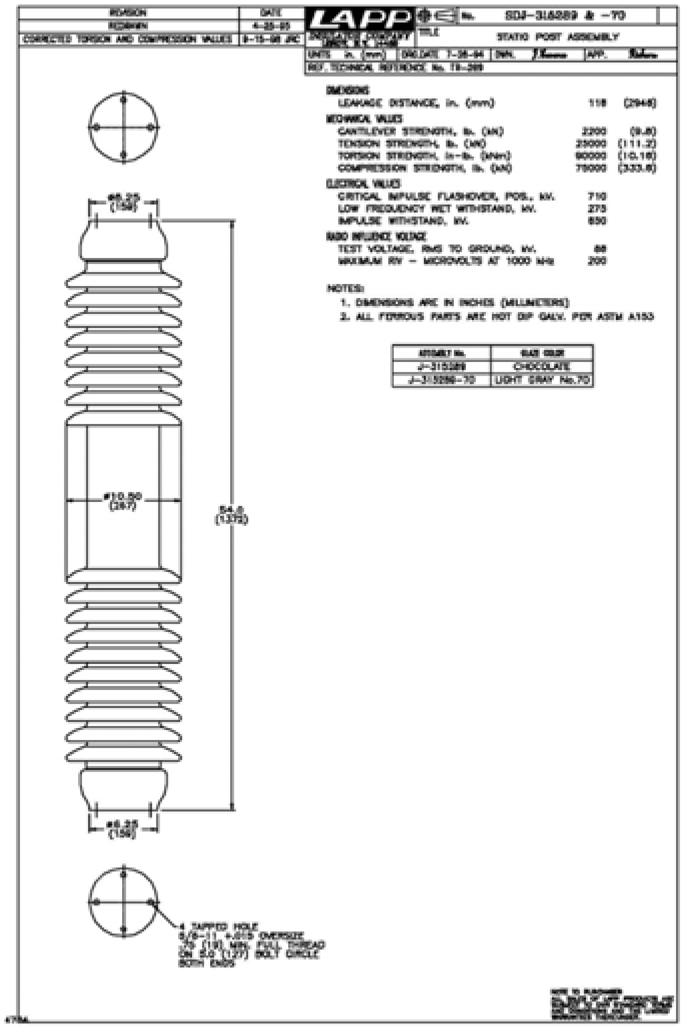
Post Insulator

- Basic Impulse Level (BIL)
- Leakage Distance
- Mechanical Strength

Suspension Insulator

- Electrical Characteristics
- Mechanical strength

Substation Insulator



2

LAPP PORCELAIN SUSPENSION INSULATORS

Design Features

1. **Choice of hardware**
   Both standard and Fog-Pacer suspensions are available for ball-socket or clevis-eye insulator coupling. Caps are ferrous, hot-dip galvanized.
2. **Cement assembly**
   Caps are cemented on the porcelain. This loads the porcelain in a large area, low-intensity compression grip. Lapp uses a Portland cement well-suited for use on porcelain insulator assemblies.
3. **Hardware painting**
   Before cementing, all surfaces of the hardware that will come in contact with the cement are coated. The coating protects the hardware from chemical attack by the cement. It also allows for slight movement between parts to relieve mechanical stress due to thermal variations.
4. **Bonded sand bands**
   Sand bands bonded to the porcelain by glaze provide a rough surface for permanently attaching the hardware and distributing the load evenly through the porcelain. The high-strength compression sand that is used is manufactured by Lapp to match the characteristics of the porcelain body.
5. **Sound porcelain**
   Lapp suspension insulators are made from flint-body porcelain or high-strength alumina-body porcelain, depending on the strength requirements of the unit. Assembled units are subjected to rigorous electrical and mechanical tests before shipment.
6. **Protected leakage**
   The porcelain shell or shed is designed to provide optimum leakage distance in relation to the shell diameter. The sturdy shed design also protects the leakage corrugations from mechanical damage.
7. **Forged steel bolts**
   All strength ratings of Lapp suspension insulators use a forged-steel ball bolt or eye bolt that has been hot-dip galvanized. Most ball-socket units are available with a choice of straight (regular), Corrosion Intercepting Sleeve (CIS), or zinc sleeve ball bolt.
8. **Choice of glazes**
   Lapp porcelain suspension insulators are available in a choice of four glazes: light gray, dark gray, chocolate brown, and royal blue. Consult the tables in this catalog to determine which glazes are available for specific products.

Choice of strength ratings
Lapp porcelain suspension insulators are available in M&E (ultimate) strength ratings of 15,000, 20,000, 25,000, 30,000 and 40,000 lbs. Fog-Pacer suspension insulators are available in 20,000, 30,000 and 36,000 lb. ratings.

Radio and TV interference-free
Lapp porcelain suspension insulators are designed to be free of radio and TV interference. In addition, hardware is smoothly contoured with well-rounded edges to reduce RIV.

Fog-type suspensions
Lapp Fog-Pacer porcelain suspensions provide up to 50% more leakage distance than standard porcelain suspension insulators.

Rigid Bus vs. Strain Bus

Major Physical Equipment

- Power Transformer
- Circuit Breaker
- Circuit Switcher
- M.V. Switchgear (Indoor & Outdoor)
- Air Switches
- Surge Arresters
- Lightning Masts
- Mobile Units
- Capacitor Banks
- Voltage Regulator
- Recloser
- Instrument Transformers (CT, VT/ PT)

Major Physical Equipment

Transformer

Most Expensive item inside substation

Longest Lead item

Technical spec requires

Major Physical Equipment

Dead Tank GCB

Breakers

With live tank circuit breakers, the enclosure that houses the contacts is energized, i.e. "live." Dead tank circuit breaker's contact enclosures are not energized and are connected to the ground grid. Live tank breakers are usually less expensive, but require separate current transformers.

Two types of

Live Tank GCB

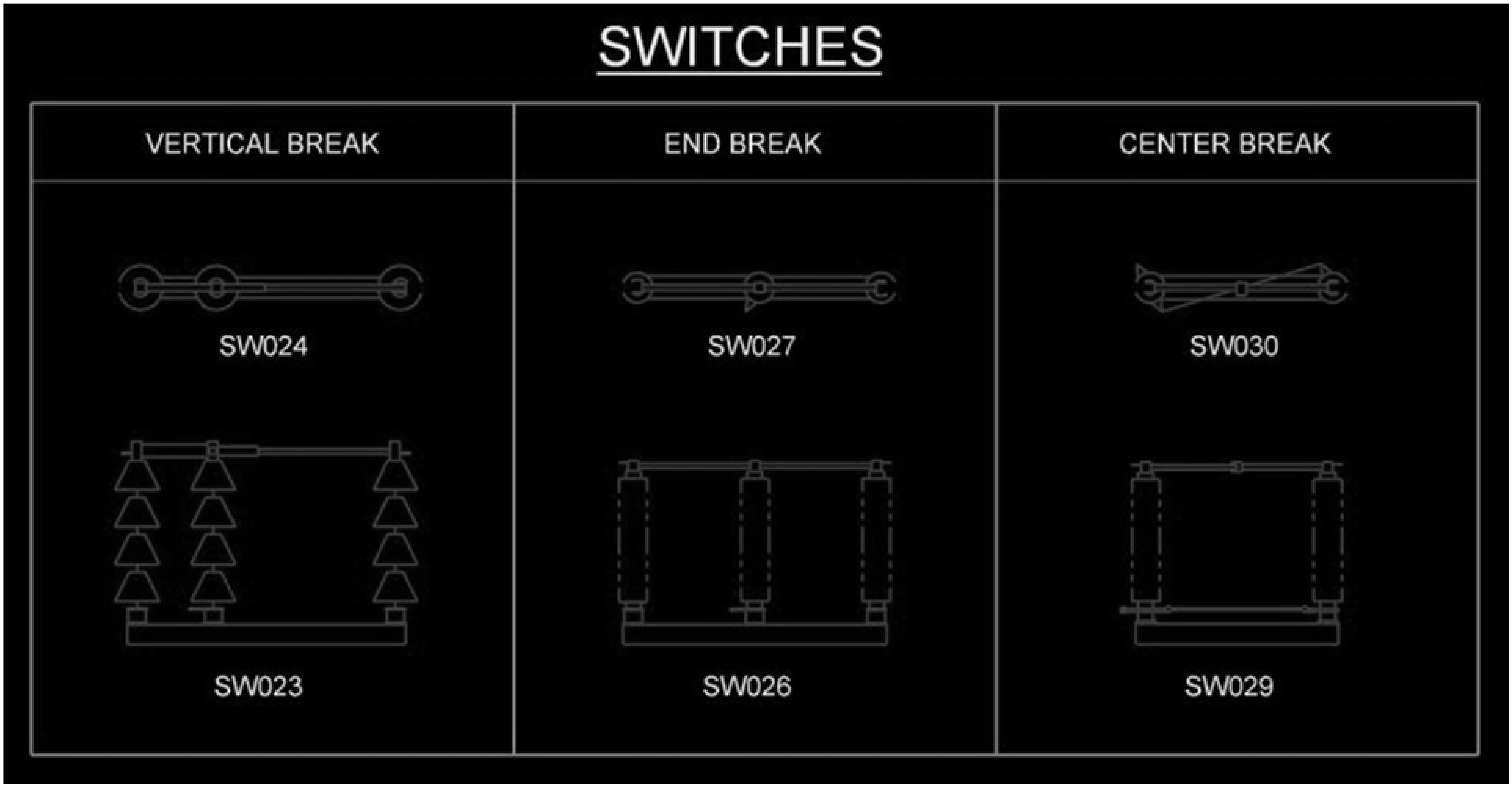
Major Physical Equipment

Capacitor

Circuit Switcher

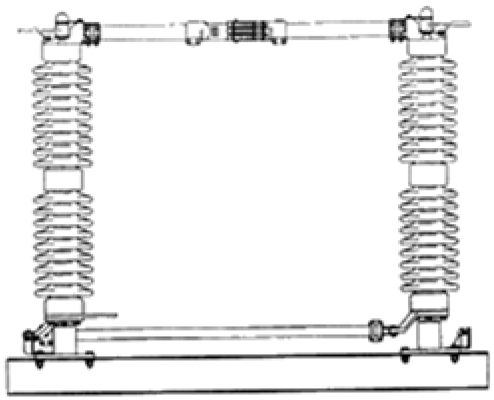
Reactor

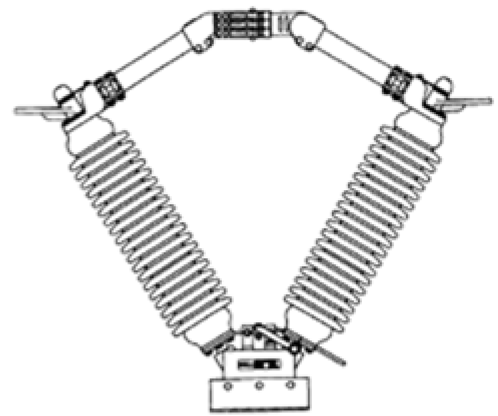
Major Physical Equipment

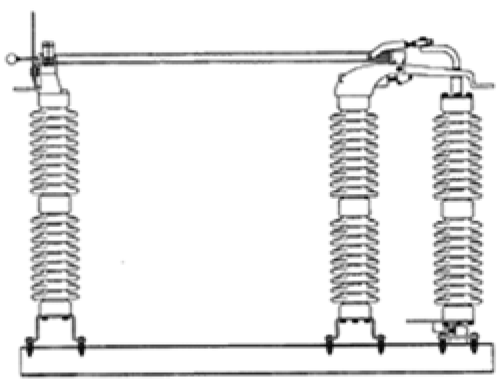


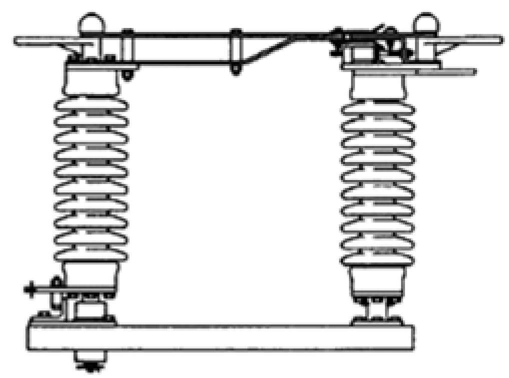
Major Physical Equipment

Switches



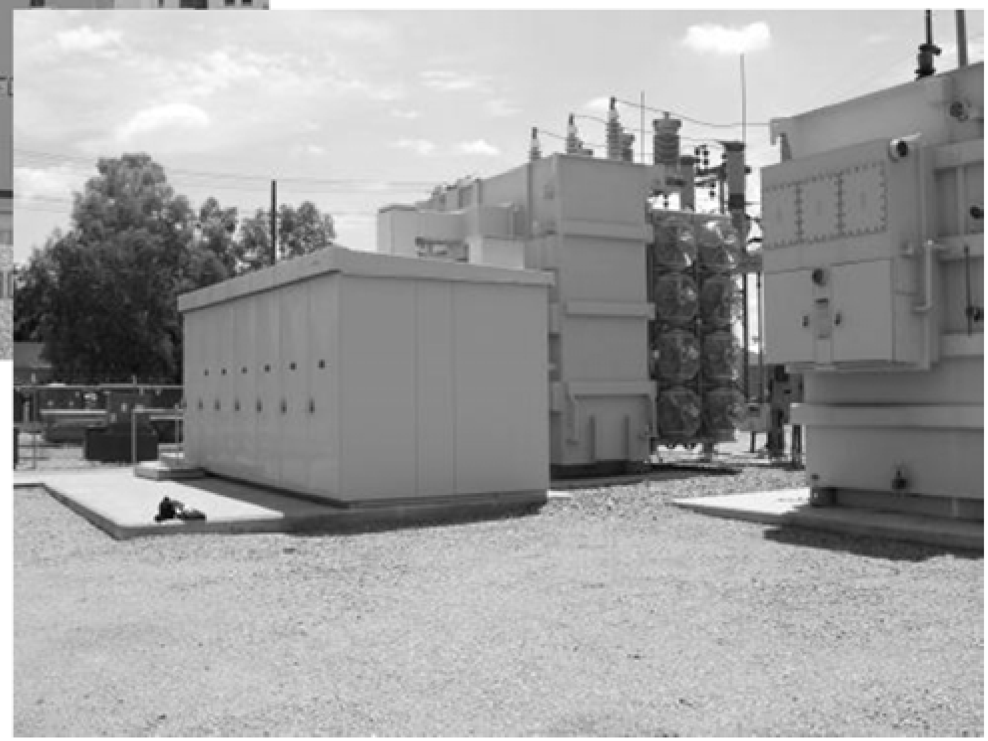






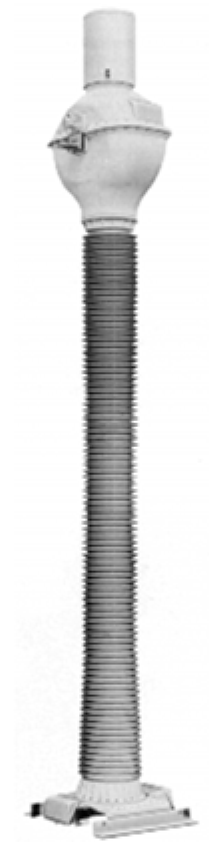
Major Physical Equipment

M.V. Switchgear



Major Physical Equipment

CCVT **PT** **CT** **CT/PT Combo**



Major Physical Equipment

Surge Arrester

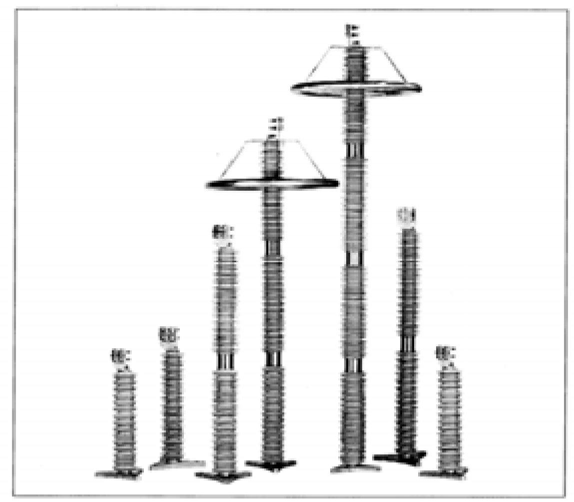
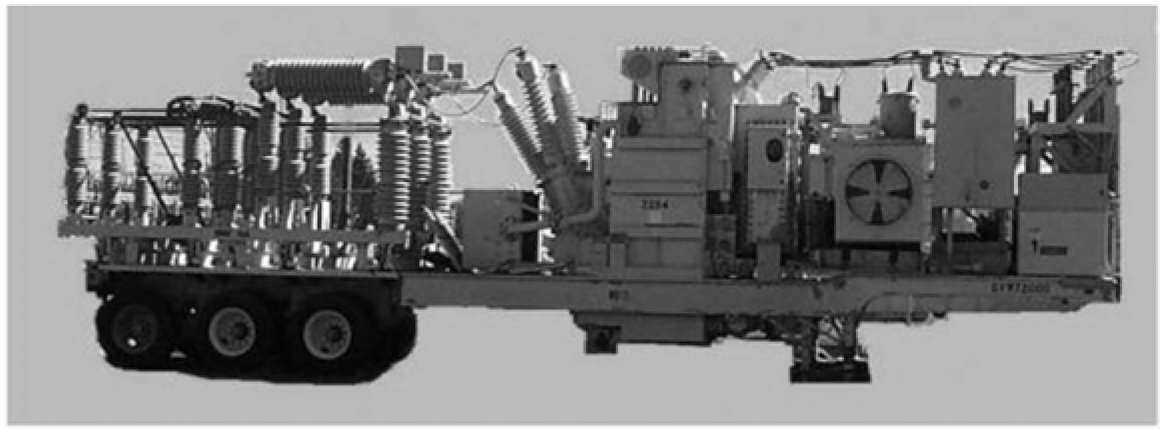


Figure 1.
UltraSIL Housed VariSTAR Class 4 Surge Arrester family.

Major Physical Equipment

Mobile Substation
Portland Gas & Electric
115kV / 15kV
18.5MVA TRF



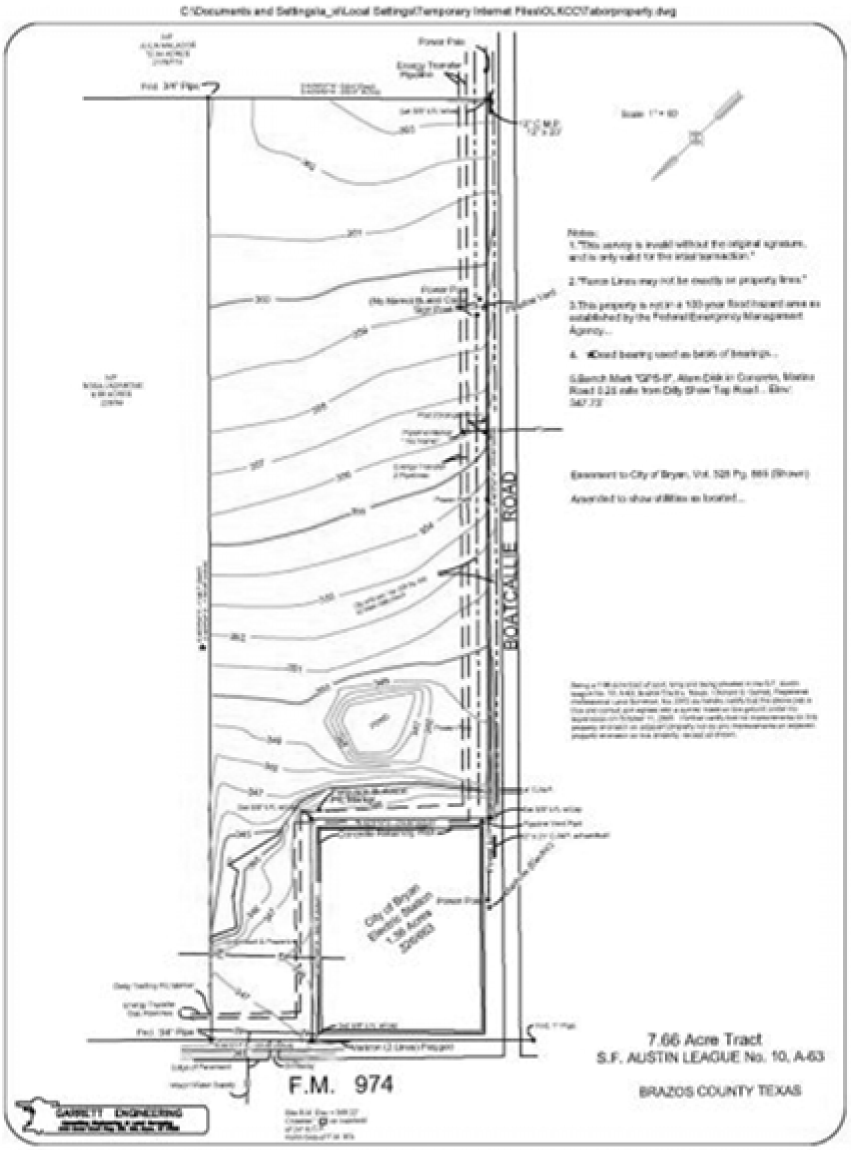
4. Major Physical Equipment

Voltage Regulator

Civil / Structure / Foundation

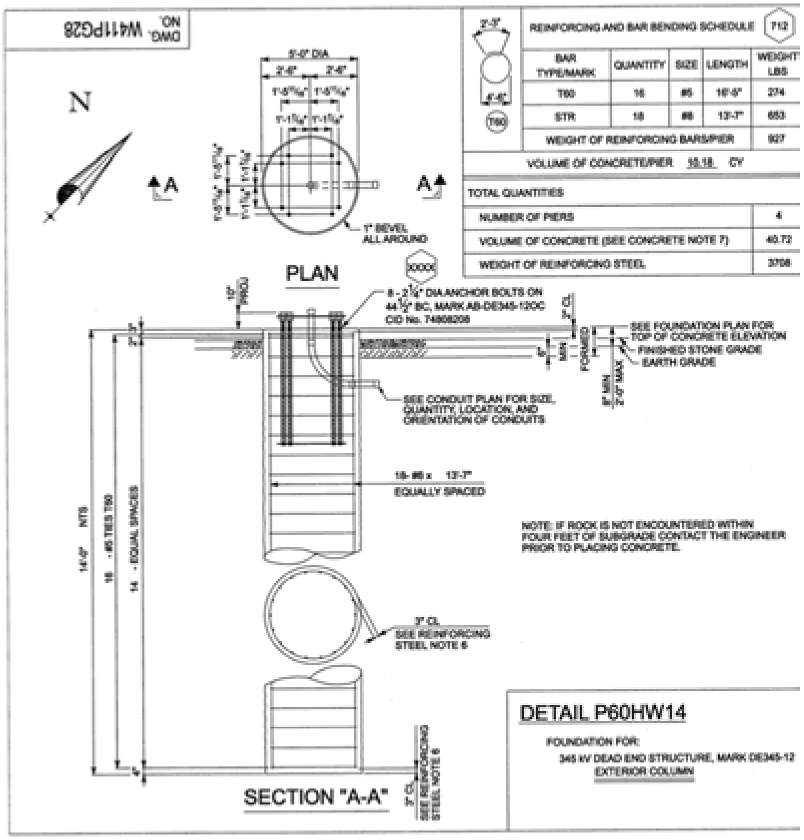
- Site survey
- Geotechnical report
- Grading Design
- Structure Design
- Foundation Design

Civil / Structure / Foundation



Survey:
Specification
Base for Grading

Civil / Structure / Foundation



Foundation Details

Civil / Structure / Foundation

Structure Design

Grounding

- Design per IEEE standard 80-2000 “Guide for Safety in AC Substation Grounding”
- Calculate “Step voltage” and “touch voltage”
- Design consideration:
    - Fault current
    - Split factor
    - Soil condition
    - Ground conductor
    - Grounding area

Grounding

Cable and Raceway

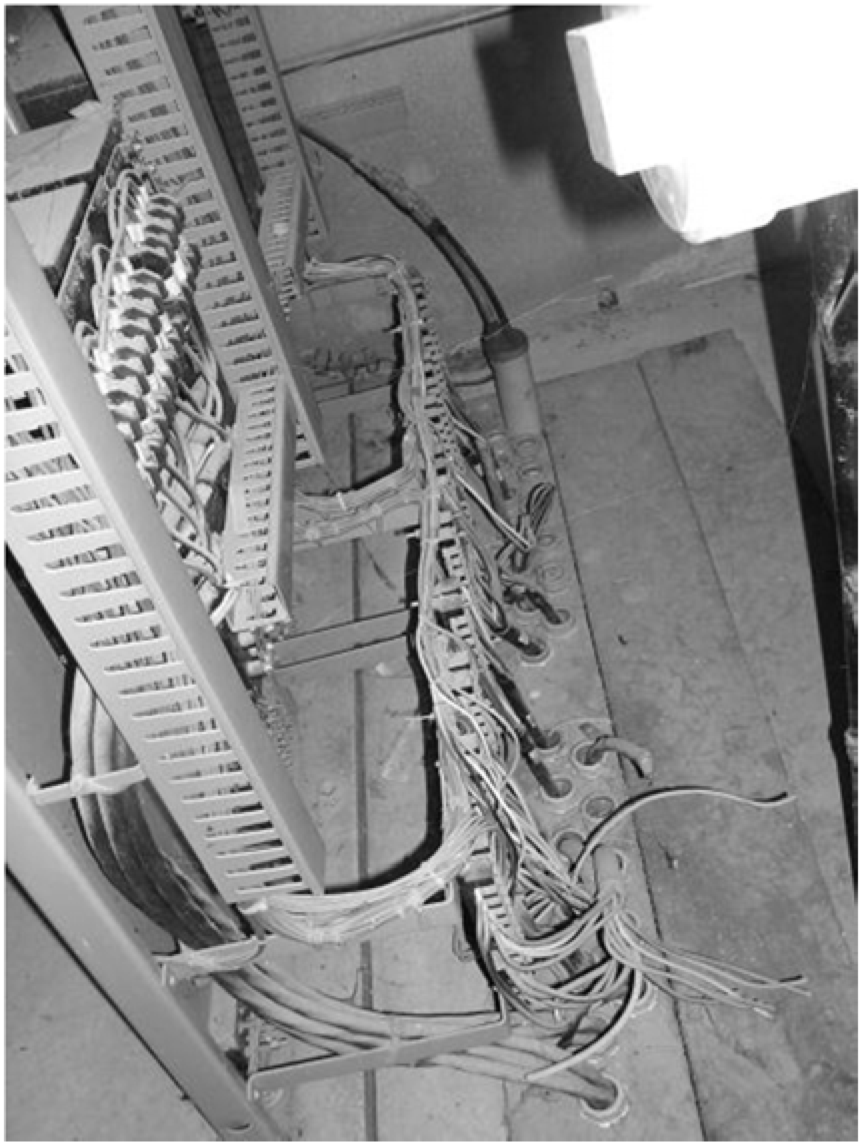
- Cable
  - 600V Control Cable only
  - Cable sizing and voltage drop
  - Color Coding of conductor
  - Shielding
  - Conductor insulation and jackets

Cable and Raceway

- Cable coding
  - K-1, K-2, K-3, K-4, K-5, and K-6
  - K-2 meets NEC requirement. NEC requires white as grounded conductor; and green or green/yellow be grounding conductors
  - K-2 Color coding

Conductor	Base Color	Tracer Color
1	Black	--
2	Red	--
3	Blue	--
4	Orange	--
5	Yellow	--
6	Brown	--
7	Red	Black
8	Blue	Black
9	Orange	Black
10	Yellow	Black
11	Brown	Black
12	Black	Red
13	Blue	Red
14	Orange	Red
…..		

Cable and Raceway



Cable Color Coding

Cable and Raceway

- Cable Shielding
  - 230kV and above requires control cable shielding
  - Grounding of shielding
  - Supervisor cable typically prefer shielding cable
  - ANSI/IEEE std 525 “Guide for Selection and Installation of Control and Low-Voltage Cable Systems in Substation”

Cable and Raceway

- Cable Insulation and Jackets

Material	Oper Temp	Oxy Index	Cost
EPR	90	20	M
PVC	75	28	L
PE	75	18	L
PVC(I)	75	27	M
XLPE	90	18	M
XLPE(I)	90	18	M
FRE	75	27	M

Cable and Raceway

- Raceway
  - Direct Buried Cable
  - Direct Buried Conduit
  - Duct Bank
  - Cable Trench
  - Conductor insulation and jackets
  - Pros and Cons for each application

Cable and Raceway

Cable Trench

Protective Relays

Design Objectives

- Dependability
- Security
- Speed
- Simplicity

Type

- Electromechanical Relays
- Solid State (Static) Relays
- Digital Relays

Protective Relays

Protective Relays

Functions

- Over-voltage / Under-voltage (59/27)
- Over-current (50/51/67)
- Distance (21)
- Differential (87)
- Frequency (81)
- Pressure (63)
- Reclosing (79)
- Synchronizing (25)
- Auxiliary (94 for tripping)
- Device function number per IEEE C37.1989

Protective Relays

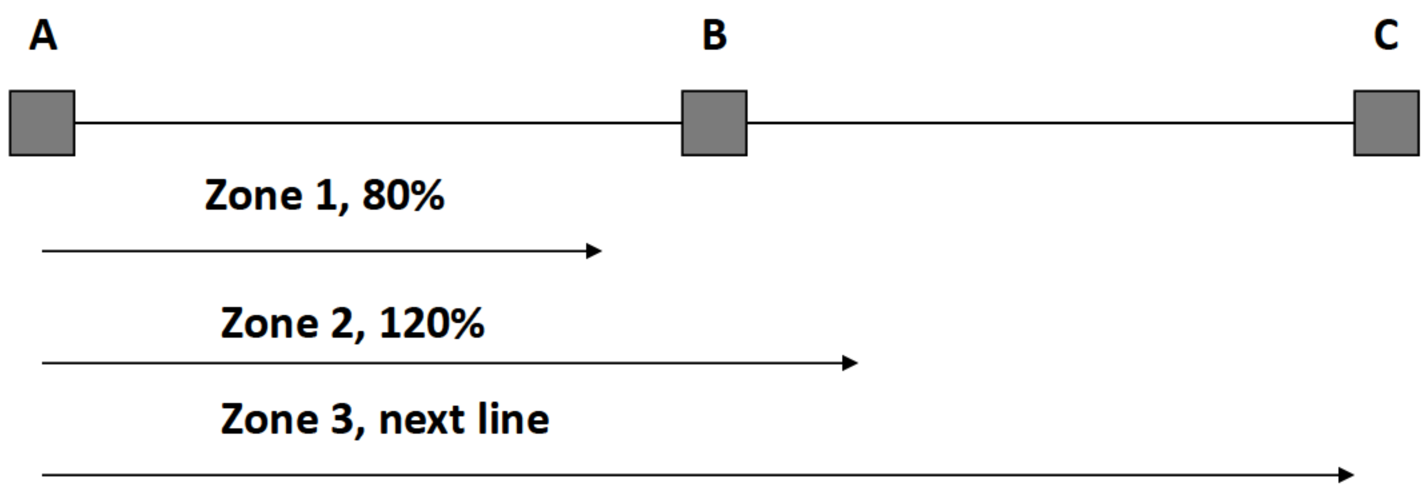
Over-current relay

- Instant Over-current (50)
- Time Delayed Over-current (51)
- Directional Over-current (67)
- Phase Over-current (P) vs. Ground Over-current (G)

Protective Relays

Distance relay

- Zone 1 (80%)
- Zone 2 (120%) with time delay
- Zone 3 (next line) with time delay

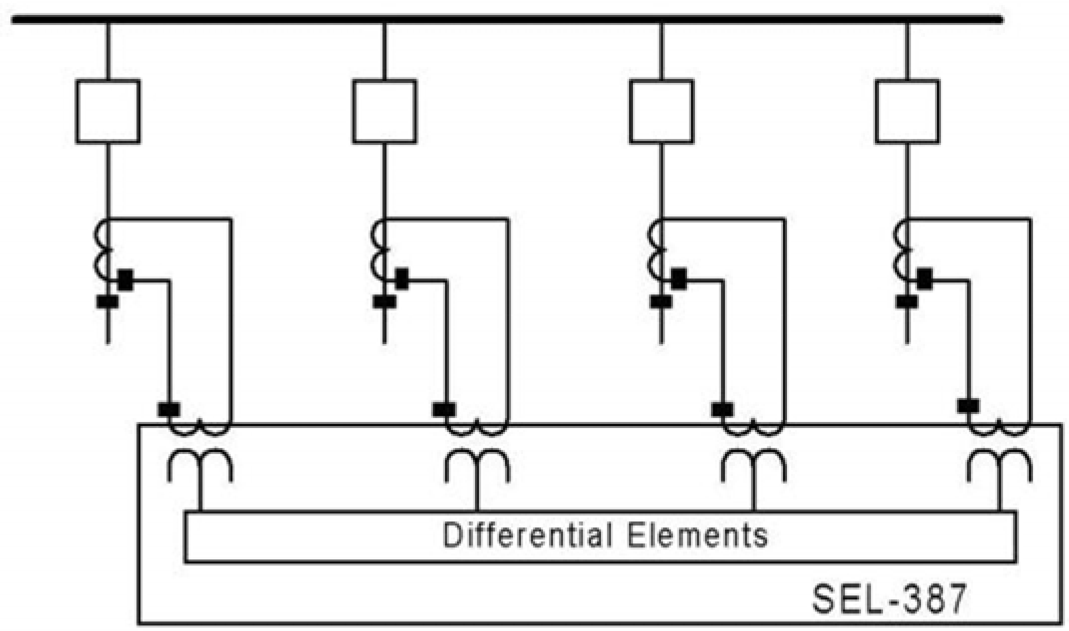


- Even though the transmission line is fully protected with Zone 1 and Zone 2 relays,
- A third forward-reaching zone is often employed.
- This Zone 3 is applied as backup for Zone 2 and may be applied as remote backup for relay or station failures at the remote terminal.

Protective Relays

Differential Relay

- Current Differential
- Bus Differential
- Transformer Differential



Lightning (Surge) Protection

Objective:

- Acceptable low level of service interruptions and transformer failures due to surges
- Minimum cost

Through the application of:

- Direct stroke shielding
- Surge arrestor
- Grounding system

9. Lightning Protection

Lightning (Surge) Protection (Cont.)

9. Lightning Protection

Lightning (Surge) Protection (Cont.)

Transducers and Meters

- Transducers
  - Voltage
  - Current
  - Watt
  - VAR
  - LTC Position

Transducers and Meters

- Meters
  - Voltage
  - Current
  - Watt
  - VAR
  - Display vs. revenue

Control House with AC/DC

- Control House
- AC Supply
- DC Supply

Control House with AC/DC

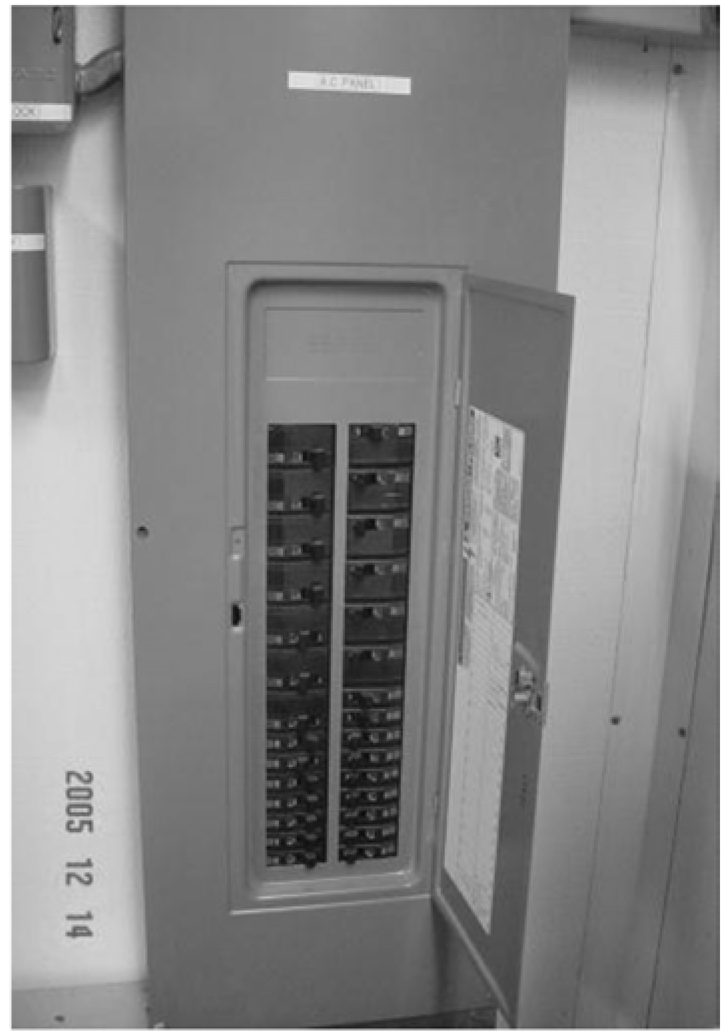
- Control House
  - Pre-fabricated Metal Building
  - Masonry Block Control Building
  - Architecturally-pleasing Masonry Building
  - Materials inside a control house
    - Relay & Control Panels
    - AC/DC Panels
    - Battery and Chargers
    - Cable tray (some)
    - Communication
    - Air Condition (some)
    - Lighting

Control House with AC/DC

Control House

Control House with AC/DC

- AC Supply
  - Station Service Transformer
  - Transfer Switch
  - AC Panel



Control House with AC/DC

- DC Supply
  - Battery (size calc.)
  - Charger
  - DC Panel

Communication & Automation

- Communication
- Automation

Communication & Automation

- Communication
  - Power Line Carrier
  - Leased Telephone Line
  - Microwave (digital / analog)
  - Fiber

Communication & Automation

- Automation
  - Use IED (intelligent electronic device) to monitor, control and protect
  - Share information among IEDs
  - Access information from different channels
  - New technology to replace old technology

Communication & Automation

- Automation benefit
  - Reduce cost (initial and O&M)
  - Avoid future cost
  - Improve quality of service
  - More effective planning
- Status of automation in the industry

Commission and Test

- "The *2003 NETA Acceptance Testing Specifications*" for substation equipment tests

Commission and Test

- INSPECTION AND TEST PROCEDURES
- 7.1 Switchgear and Switchboard Assemblies
- 7.2 Transformers, Liquid-Filled
- 7.3 Cables, Low-Voltage, 600 Volt Maximum
- 7.4 Metal-Enclosed Busways
- 7.5 Switches, Air, Medium- and High-Voltage, Open
- 7.6 Circuit Breakers, Air, Insulated-Case/Molded-Case
- 7.7 Circuit Switchers
- 7.8 Network Protectors, 600 Volt Class
- 7.9 Protective Relays
- 7.10 Instrument Transformers
- 7.11 Metering Devices
- 7.12 Regulating Apparatus, Voltage, Step Voltage Regulators
- 7.13 Grounding Systems
- 7.14 Ground-Fault Protection Systems. Low-Voltage
- 7.15 Rotating Machinery, AC Motors and Generators
- 7.16 Motor Control, Motor Control Centers, Medium-Voltage
- 7.17 Adjustable Speed Drive Systems
- 7.18 Direct-Current Systems, Batteries, Flooded Lead-Acid
- 7.19 Surge Arresters, Medium- and High-Voltage Surge Protection Devices
- 7.20 Capacitors and Reactors, Capacitors
- 7.21 Outdoor Bus Structures
- 7.22 Emergency Systems, Engine Generator
- 7.22 Emergency Systems, Uninterruptible Power Systems
- 7.22 Emergency Systems, Automatic Transfer Switches
- 7.23 Communications - Reserved 155
- 7.24 Automatic Circuit Reclosers and Line Sectionalizers, Automatic Circuit Reclosers, Oil/Vacuum1
- 7.25 Fiber-Optic Cables

Commission and Test

Grounding System TEST PROCEDURES

1. Visual and Mechanical Inspection

- Verify ground system is in compliance with drawings, specifications, and NFPA 70 *National Electrical Code.*
- Inspect physical and mechanical condition.
- Inspect anchorage.

2. Electrical Tests

- Perform fall-of-potential or alternative test in accordance with ANSI/IEEE 81 on the main grounding electrode or system.
- Perform point-to-point tests to determine the resistance between the main grounding system and all major electrical equipment frames, system neutral, and/or derived neutral points.

3. Test Values

- The resistance between the main grounding electrode and ground should be no greater than five ohms for large commercial or industrial systems and 1.0 ohm or less for generating or transmission station grounds unless otherwise specified by the owner. (Reference ANSI/IEEE 142)
- Investigate point-to-point resistance values which exceed 0.5 ohm.

Maintenance

- Periodic Maintenance
- Reliability-centered Maintenance
- Just-in-time maintenance

Maintenance

Periodic Maintenance for DSW

6 months

- Lubricate aux. motors

12 months

- Clean insulators Lubricate & Adjust Mechanical parts
- Clean / replace /align contact
- Tighten connections

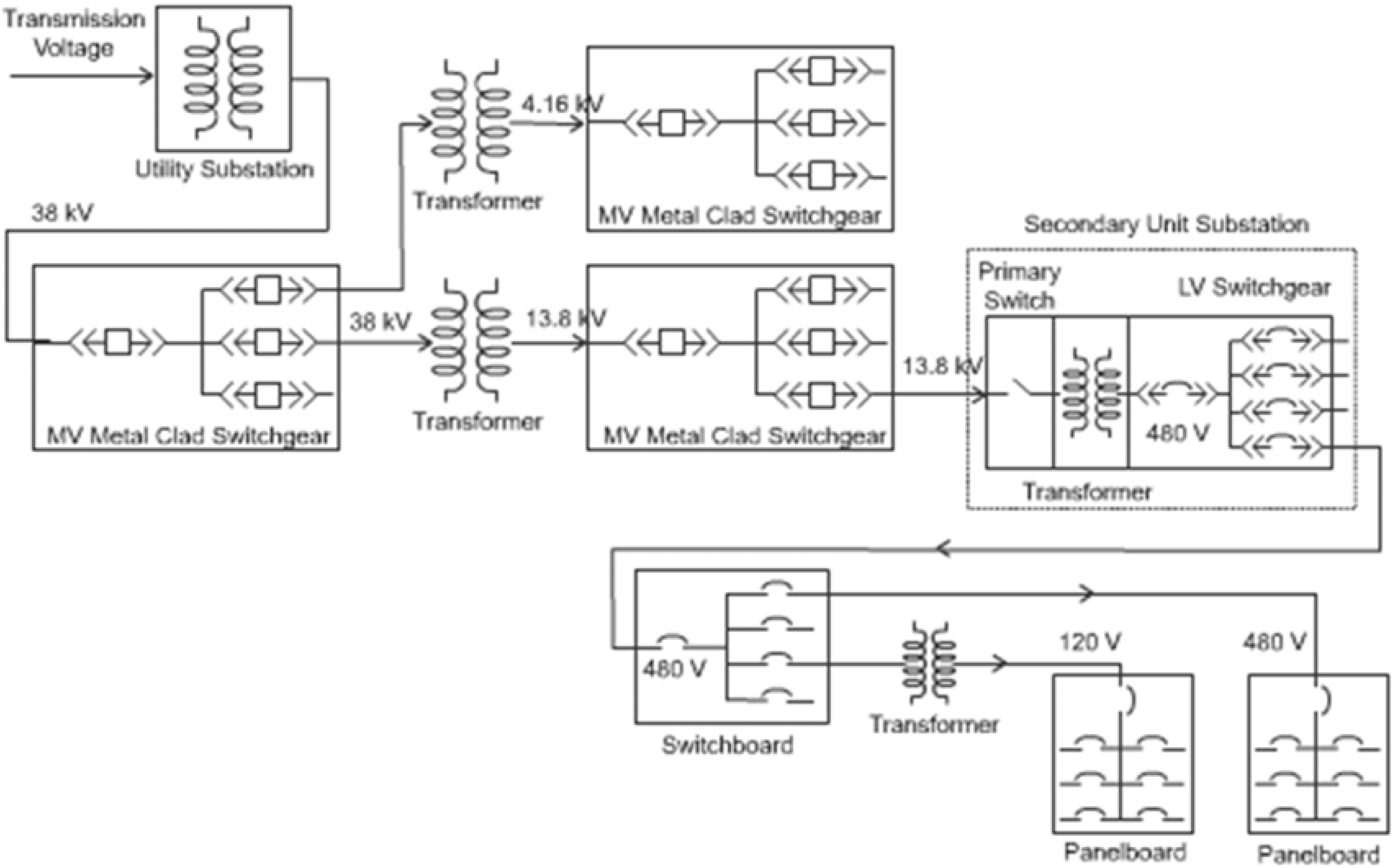
24 months

- Change oil in both gears

Understanding Power Concepts

Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- ***<u>Switchgear</u>***
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems


Transmission Voltage
Utility Substation
38 kV
Transformer
4.16 kV
MV Metal Clad Switchgear
38 kV
Transformer
13.8 kV
MV Metal Clad Switchgear
MV Metal Clad Switchgear
Secondary Unit Substation
Primary Switch
LV Switchgear
13.8 kV
480 V
Transformer
480 V
Switchboard
Transformer
120 V
480 V
Panelboard
Panelboard

METAL-ENCLOSED INTERRUPTER SWITCHGEAR

Featuring:

- Economical Protection
- AC Application thru 35 kv
- Current Ratings thru 4000 A
- Meets All ANSI, NEMA, and IEEE Standards

LISTED

Made In The U.S.A.

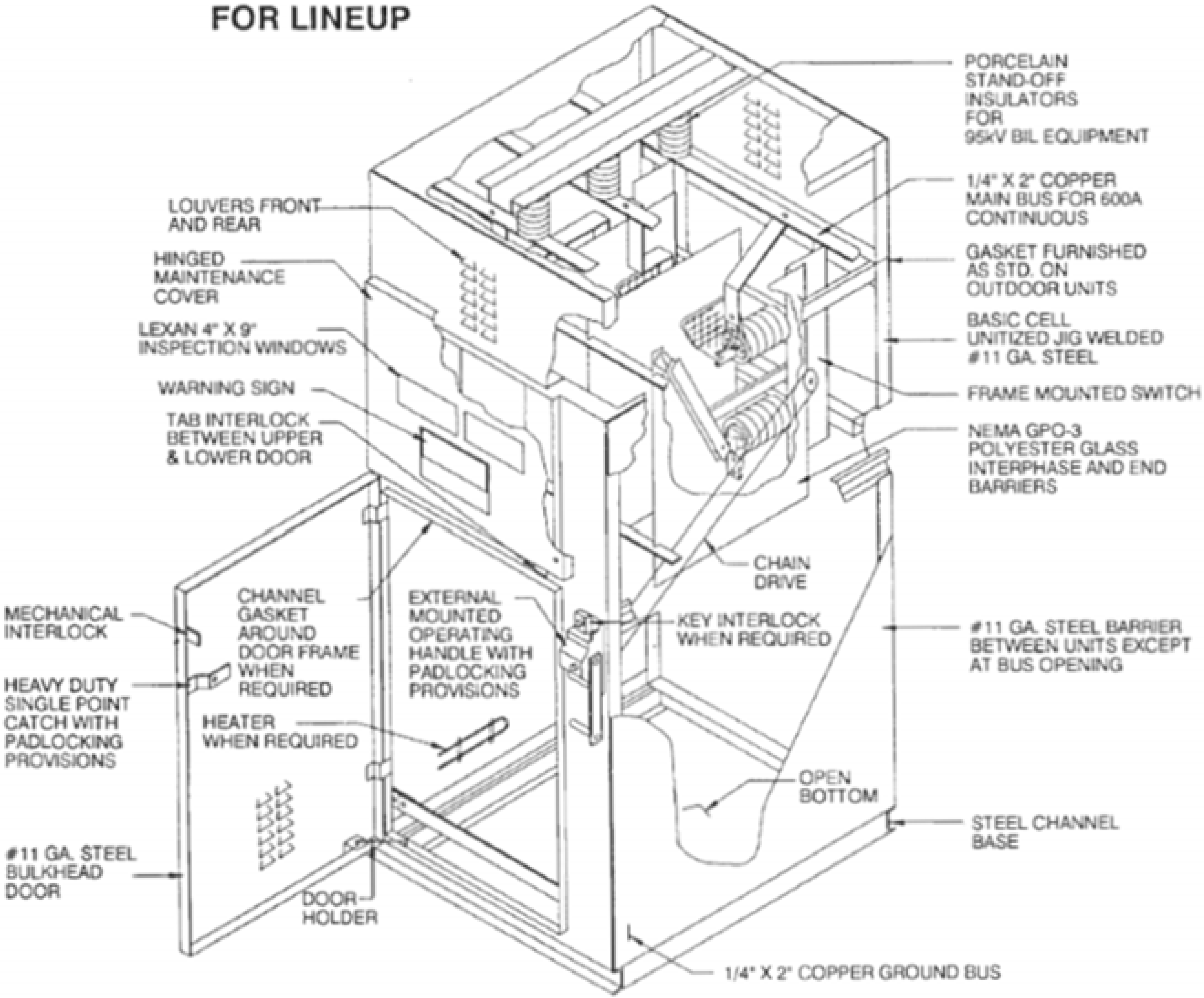
They are capable of switching load currents of 600 and 1200 amperes. Table #1 lists the applicable limits and conditions of switching. These switches are available with either electrical or mechanical operators. When used in conjunction with fuses they will afford overload, short circuit and disconnect services. These are used:

- *On the primary of transformers for their protection and isolation.*
- *For the protection and isolation of single circuit systems.*
- *For the protection and isolation of multi-circuit systems.*
- *For automatic transfer schemes where their ratings are not exceeded.*

Superior Features Provide You With:

- *Unequaled Dependability*
- *Minimum Maintenance and Downtime*
- *Long Interrupting Life*
- *Greater Safety*
- *Simple and Easy to Install and Operate*

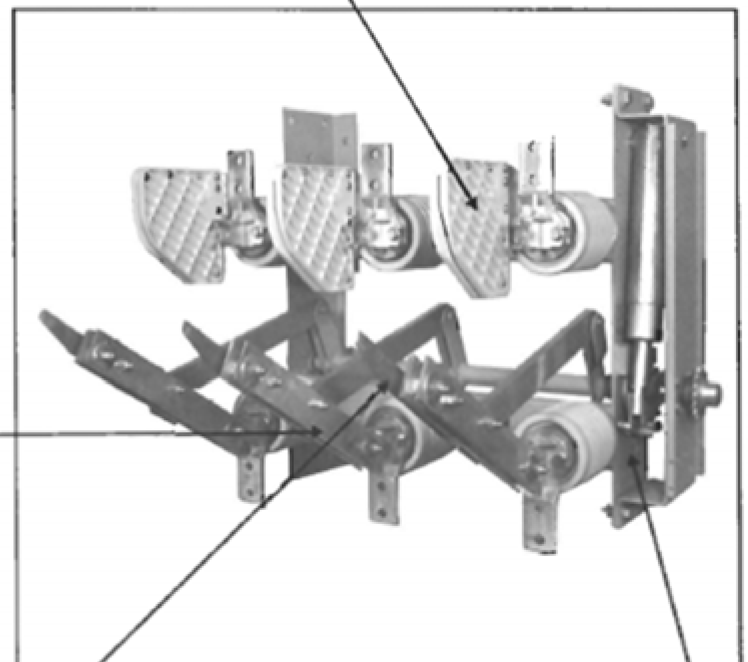
UNFUSED UNIT FOR LINEUP



TYPICAL CONSTRUCTION

- *Unequaled Dependability*
- *Minimum Maintenance*
- *Long Interrupting Life*
- *Great Safety*
- *Simple to Install and Operate*

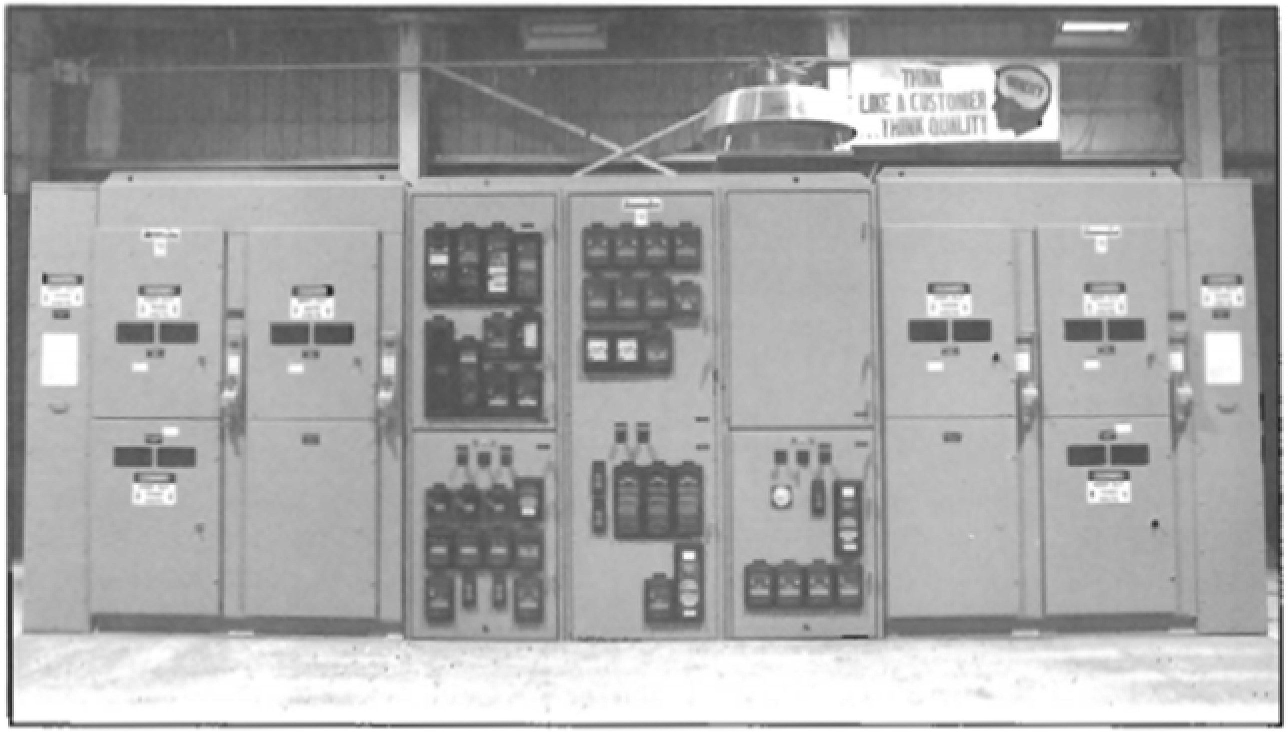
Arcing Chambers - Tungsten material stationary arcing contacts are located inside the arc chutes. They remain at the same potential as the main stationary contact. As the quick break blade is withdrawn from the arc chute it parts with the stationary arcing contacts inside the chute. The chute is made from a specially prepared compound that evolves a gas to quickly extinguish the arc. Clean consistent interruptions result. No appreciable amounts of gas are evolved.

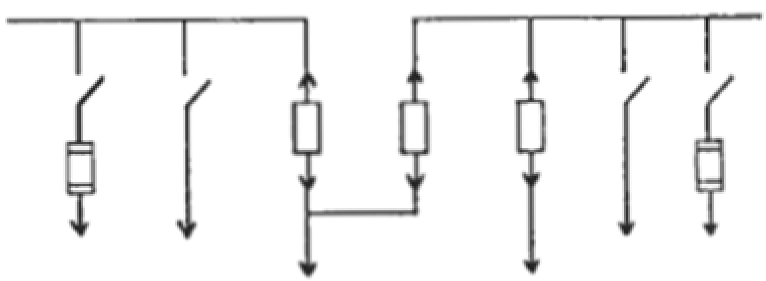


Main Moveable Blades - These blades are made of 99% conductivity hard drawn ETP copper bars and they are heavily silver-plated at the contact points for long dependable operation.

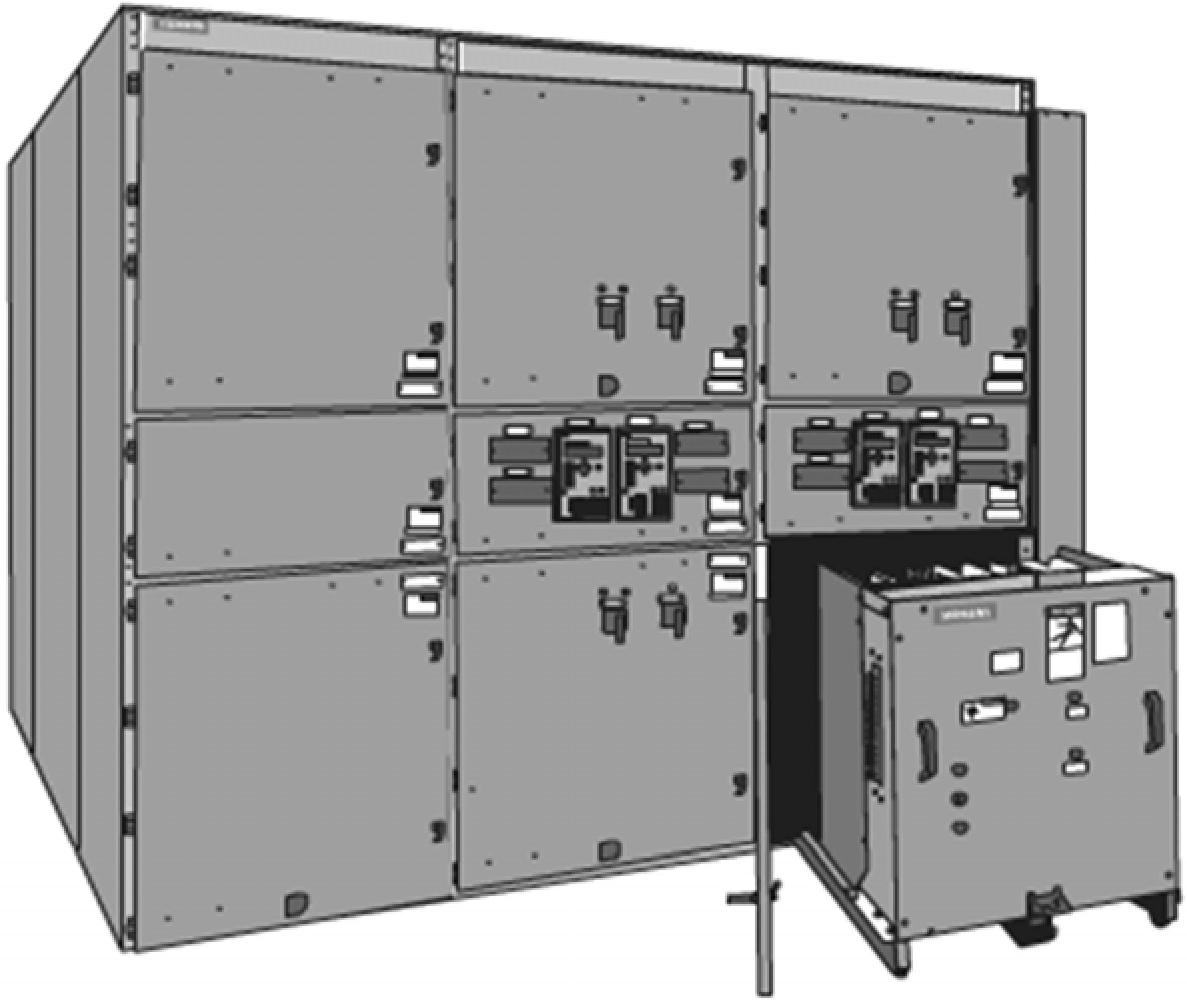
Quick Break Blade - The quick-break arcing blade is made of a special high strength, hi-conductivity material tipped with a tungsten arcing material. A quick-break spring charging mechanism is mounted on the blade that with an assist from the arcing chamber stationary contacts, prevents the opening until after the main contact gap is at the proper clearance spacing.

A Super Structure - Powercon's all welded frame design provides a ruggedness and greater structural strength which is in a class by itself. The jig welded structural member form an assembly to provide a plumb and square switch unit. This assures interchangeability of units and results in a minimum of installation time.

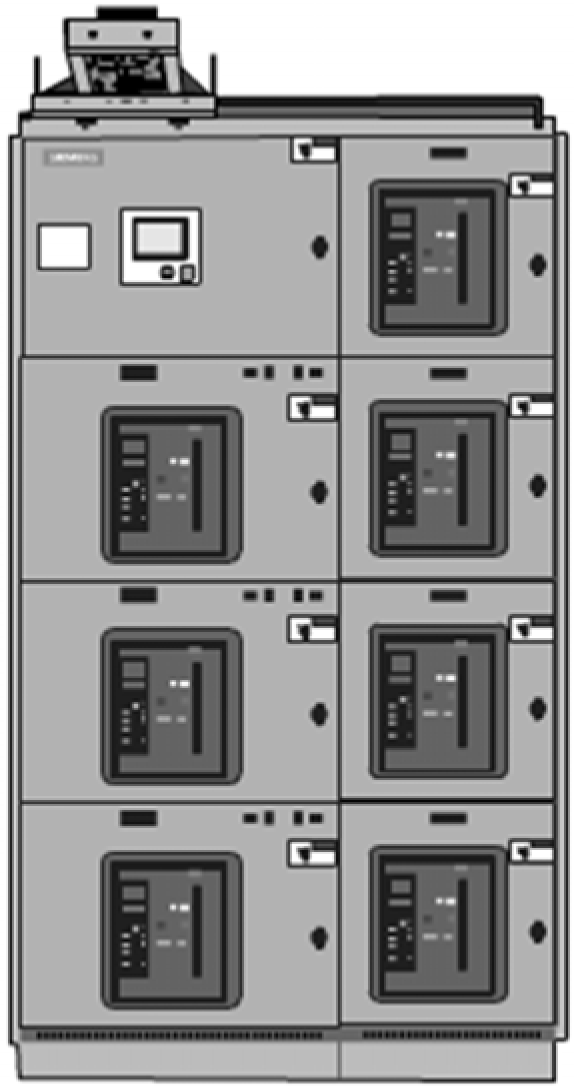


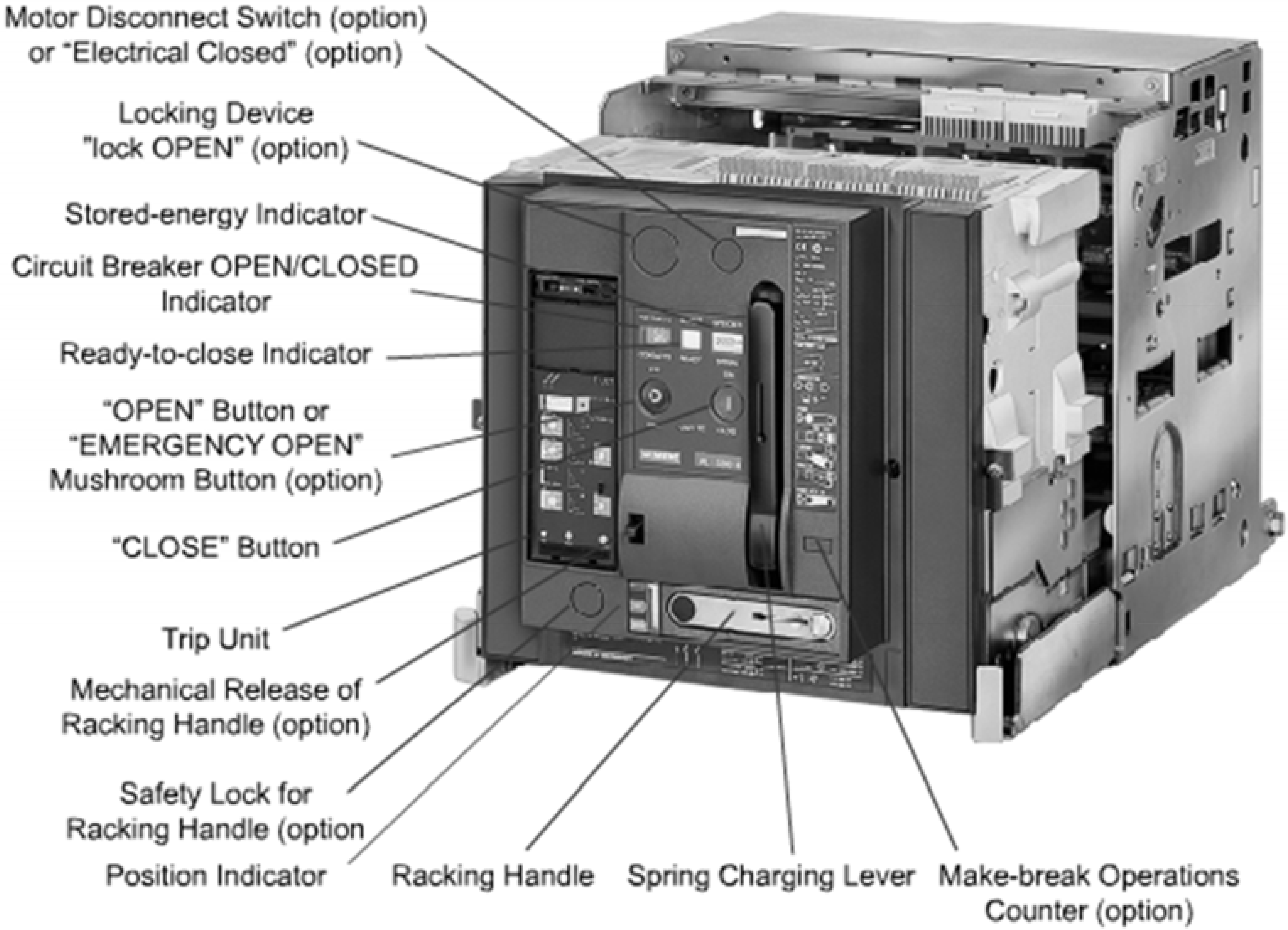


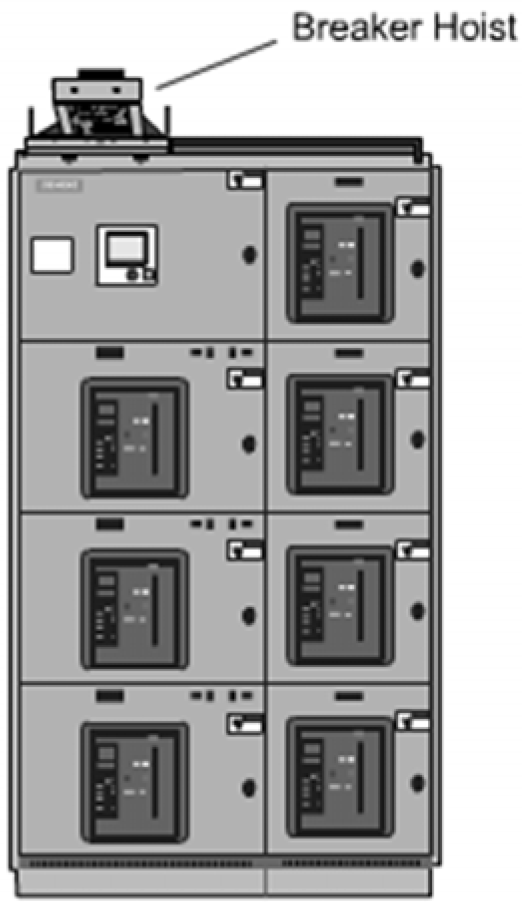
*Metal-Clad
Circuit Breaker
Incoming Line & Load
Interrupter Feeders*



GM-SG Medium Voltage, Air Insulated, Metal-clad Switchgear

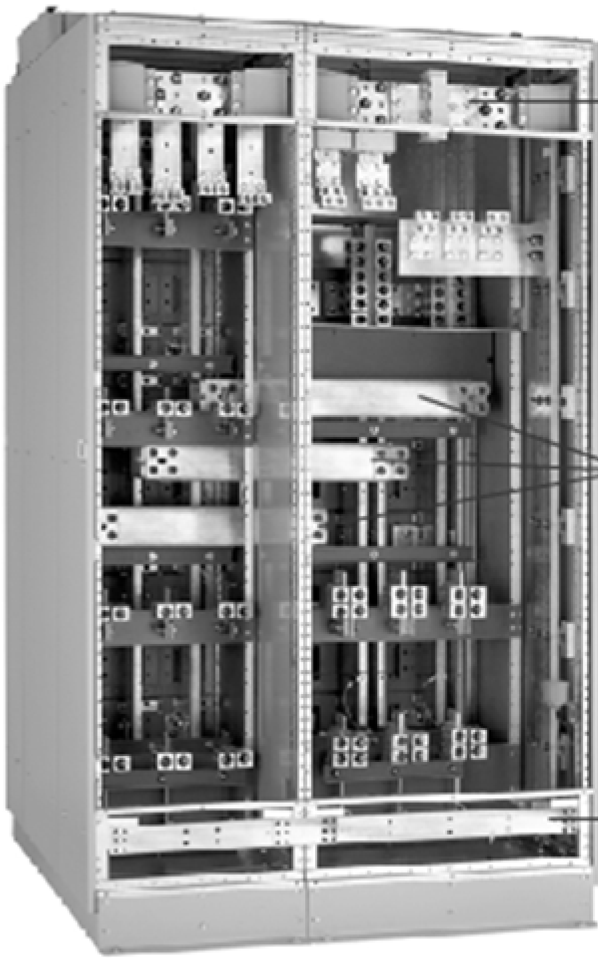



Motor Disconnect Switch (option) or "Electrical Closed" (option)
Locking Device "lock OPEN" (option)
Stored-energy Indicator
Circuit Breaker OPEN/CLOSED Indicator
Ready-to-close Indicator
"OPEN" Button or "EMERGENCY OPEN" Mushroom Button (option)
"CLOSE" Button
Trip Unit
Mechanical Release of Racking Handle (option)
Safety Lock for Racking Handle (option
Position Indicator
Racking Handle
Spring Charging Lever
Make-break Operations Counter (option)

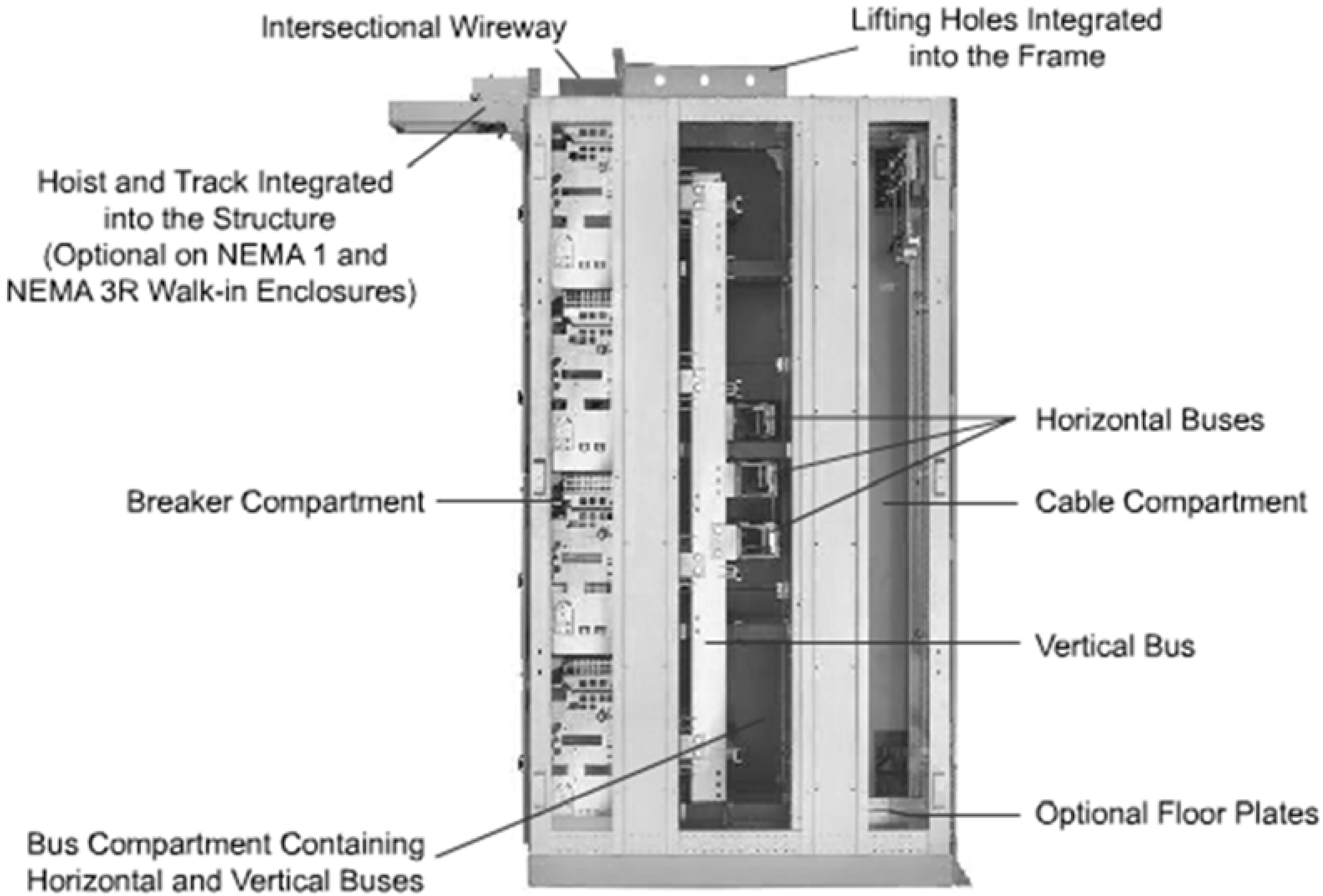


NEMA 1 Enclosure (Front View) with Breaker Hoist (Optional for NEMA 1 Enclosures)

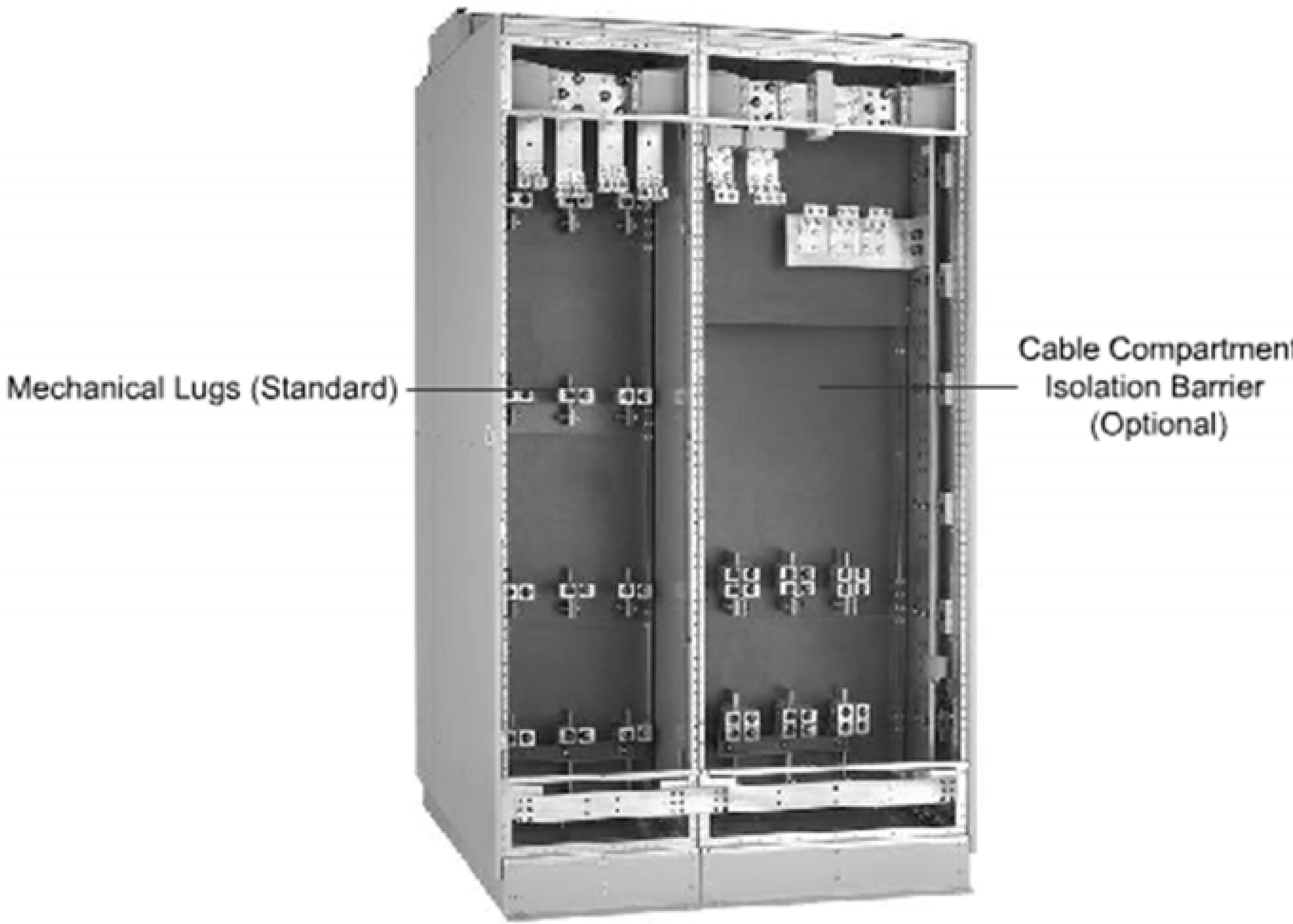
NEMA 1 Enclosure (Rear View) with Standard Ventillation Design and Optional Rear Doors with Quarter-turn Latches and Captive Screws


Unique Channel Shaped Design for Vertical and Horizontal Buses Provides Exceptional Thermal and Short Circuit Withstand Performance
No Heat Sinks on Busbars or Breakers
Three Levels of Bus Through 5000 A
Two Levels of Bus at 6000 A
Neutral Bus
Horizontal Bus Phases
1/4" x 3" Ground Bus

Rear View


Intersectional Wireway
Lifting Holes Integrated into the Frame
Hoist and Track Integrated into the Structure (Optional on NEMA 1 and NEMA 3R Walk-in Enclosures)
Horizontal Buses
Breaker Compartment
Cable Compartment
Vertical Bus
Optional Floor Plates
Bus Compartment Containing Horizontal and Vertical Buses

Side View


Mechanical Lugs (Standard)
Cable Compartment
Isolation Barrier
(Optional)
Rear View

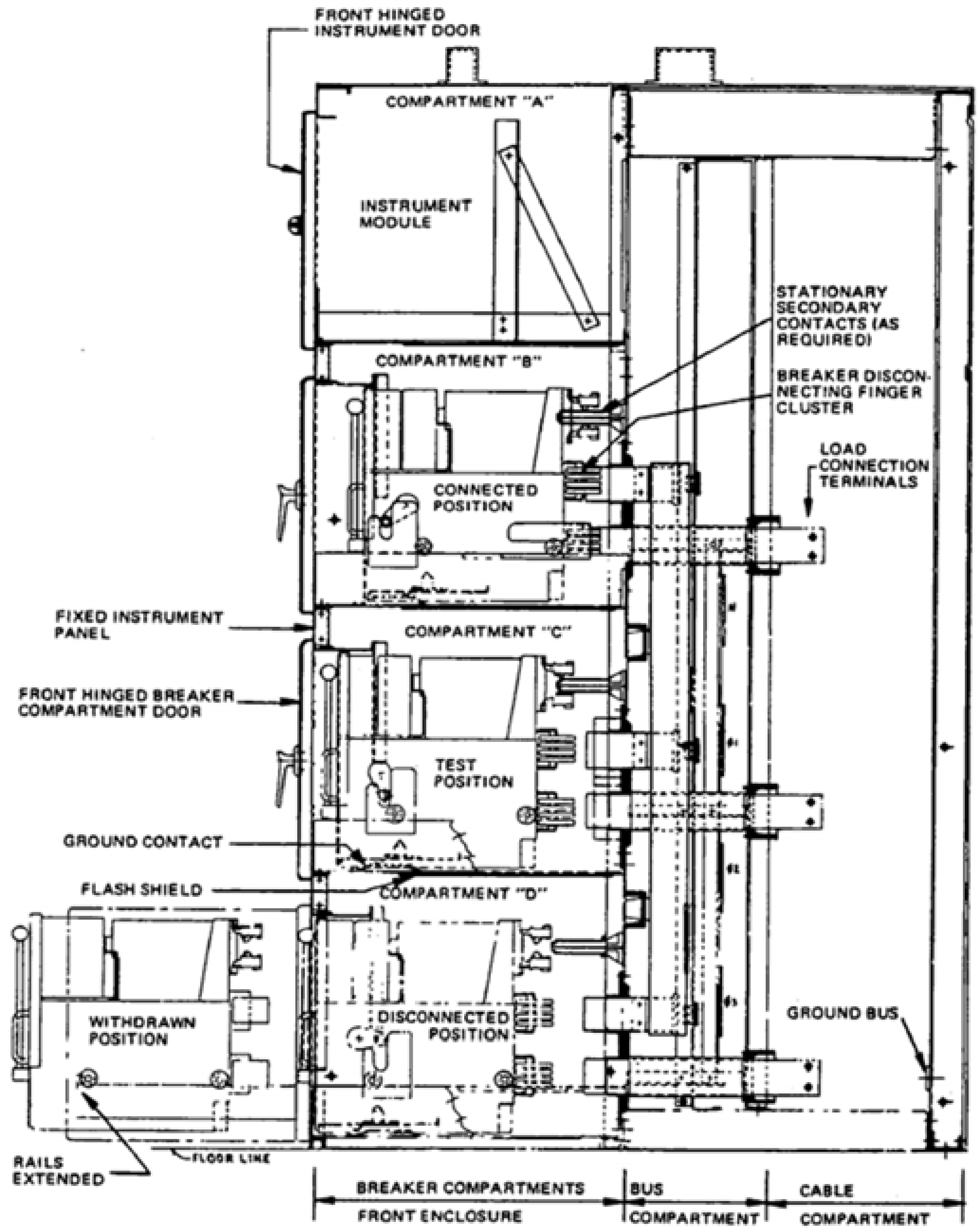
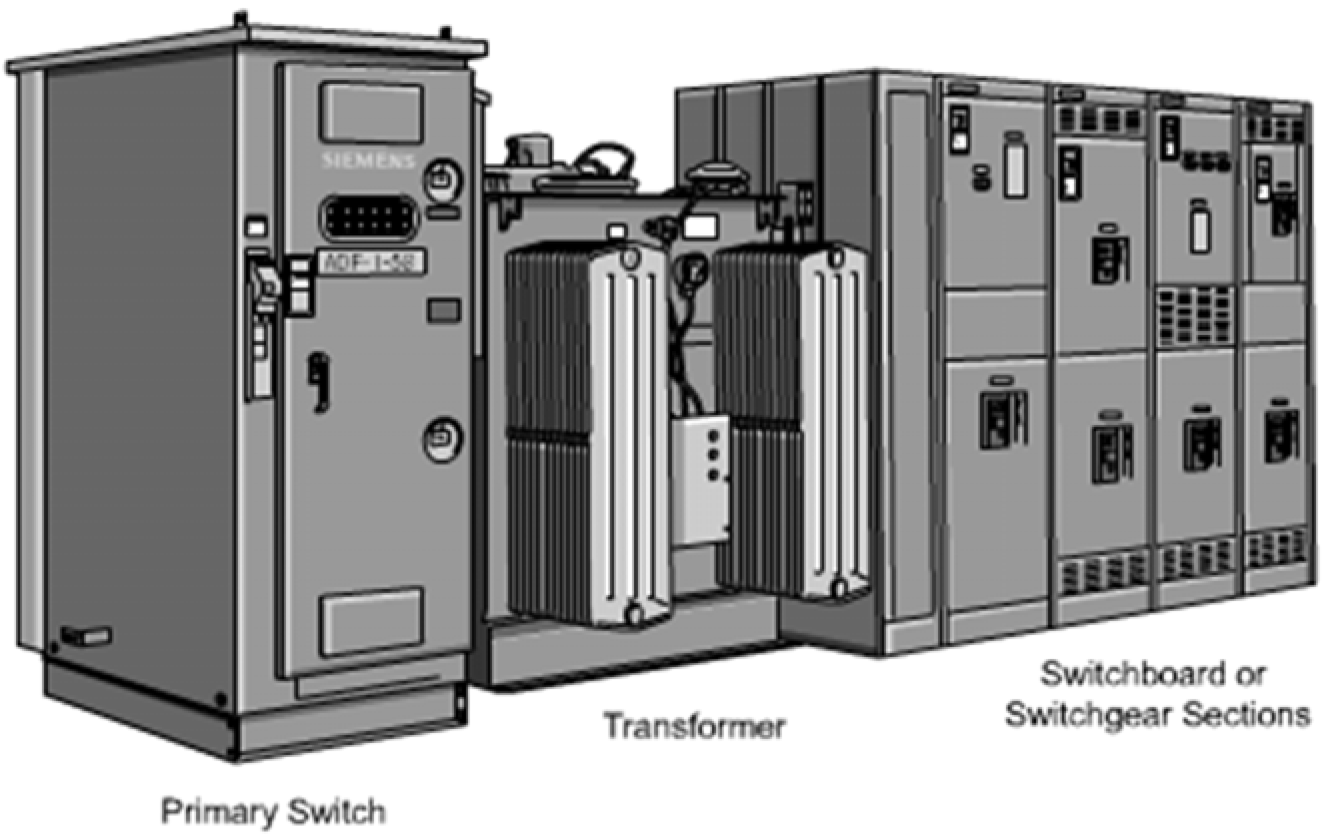
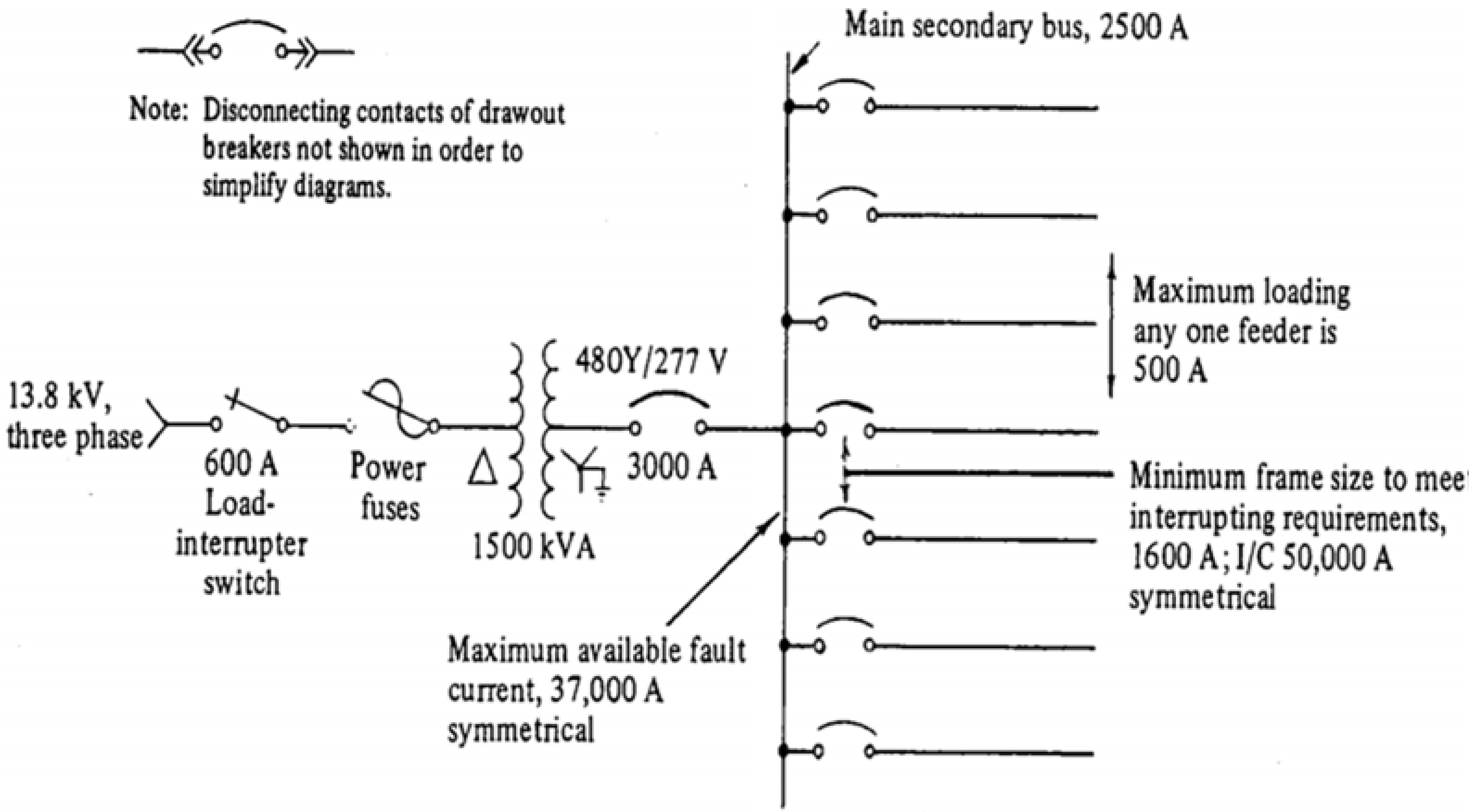


FIGURE 15.7

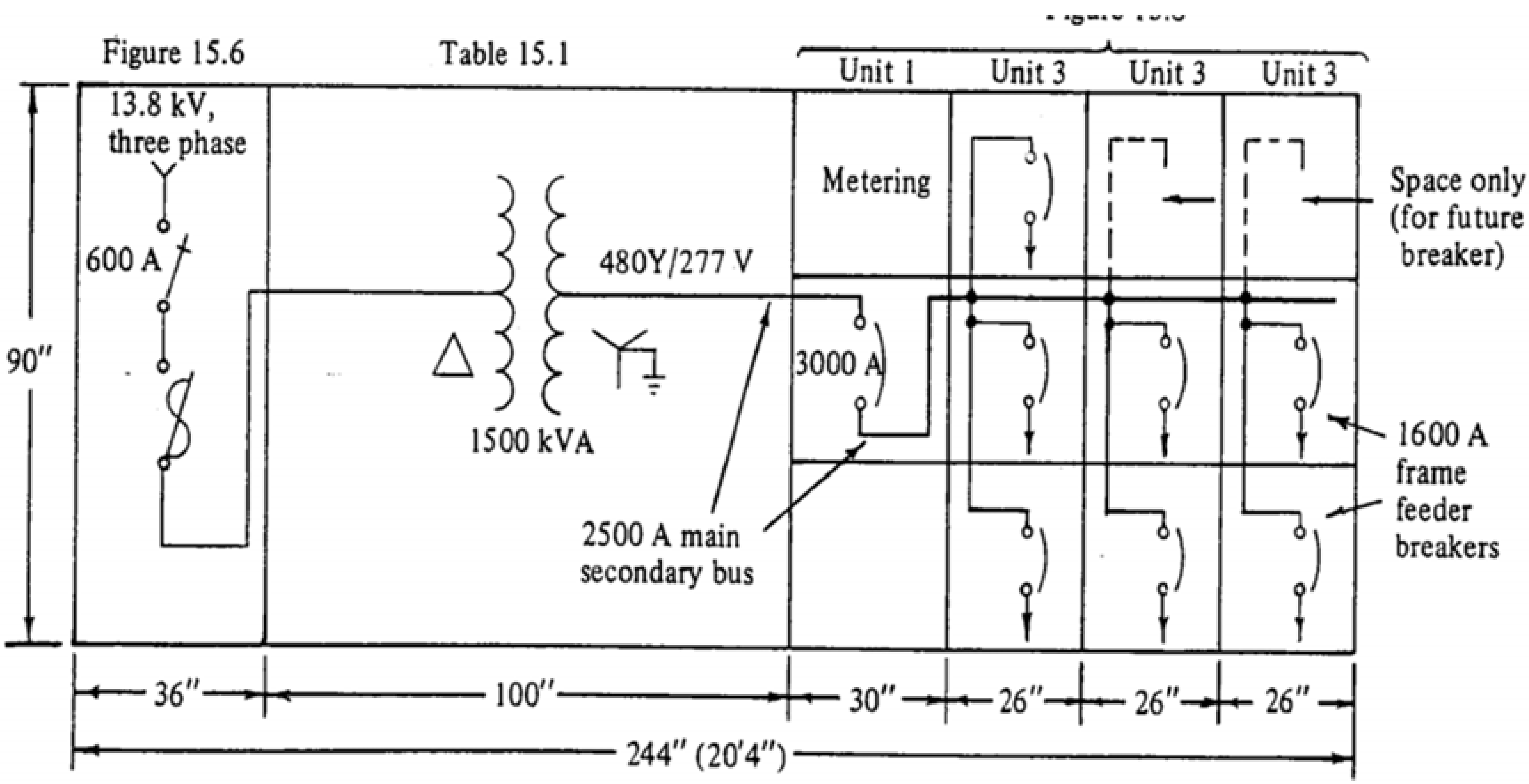
Cross section through typical low-voltage switchboard (refer also to Figure 8.11)



SIEMENS
Switchboard or
Switchgear Sections
Transformer
Primary Switch

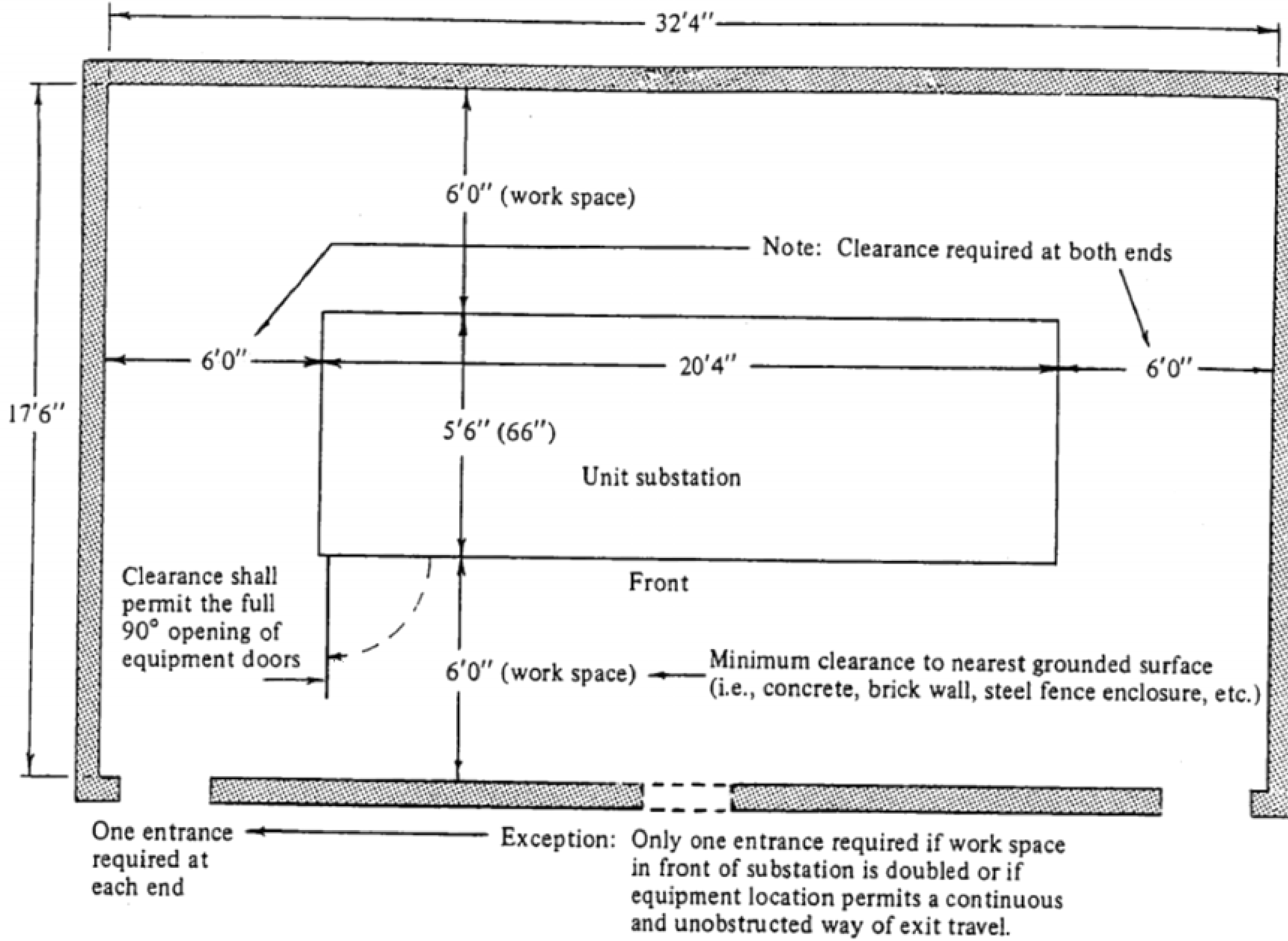


(a) One-line diagram of system



Depth of structure, 66″

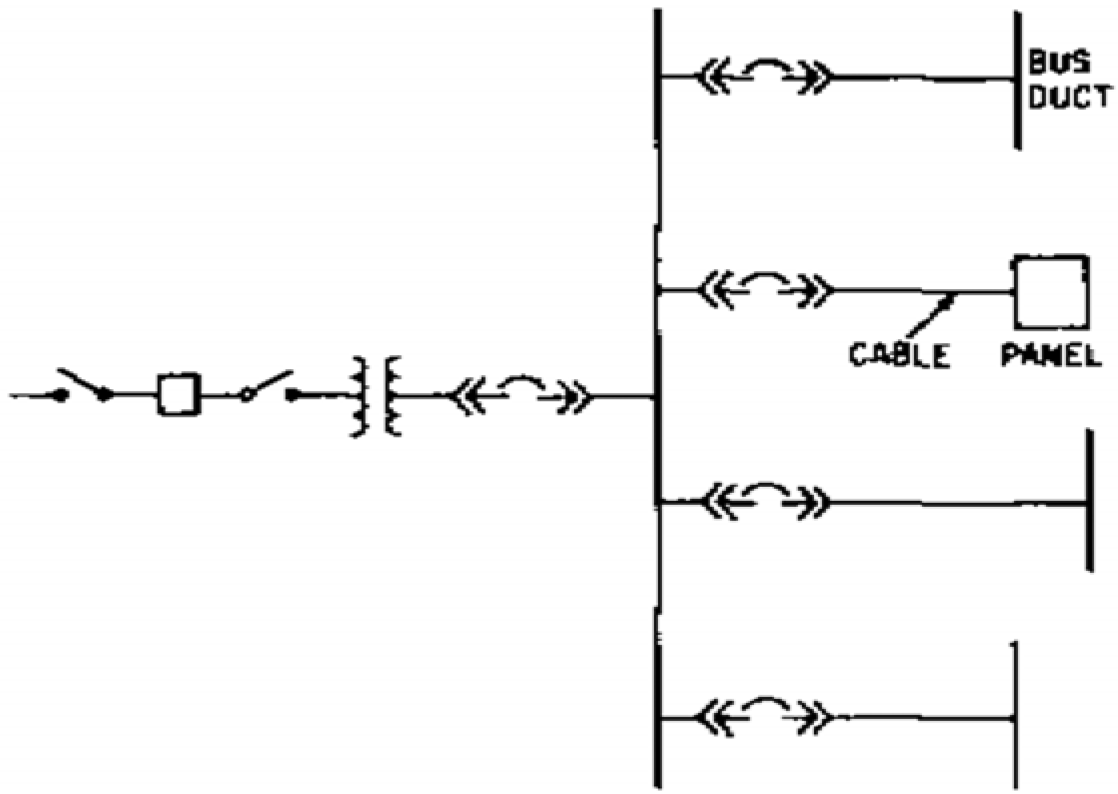
(b) Outline of unit substation


32′4″
17′6″
6′0″ (work space)
Note: Clearance required at both ends
6′0″
20′4″
6′0″
5′6″ (66″)
Unit substation
Front
Clearance shall permit the full 90° opening of equipment doors
6′0″ (work space)
Minimum clearance to nearest grounded surface (i.e., concrete, brick wall, steel fence enclosure, etc.)
One entrance required at each end
Exception: Only one entrance required if work space in front of substation is doubled or if equipment location permits a continuous and unobstructed way of exit travel.

Electrical Distribution Systems

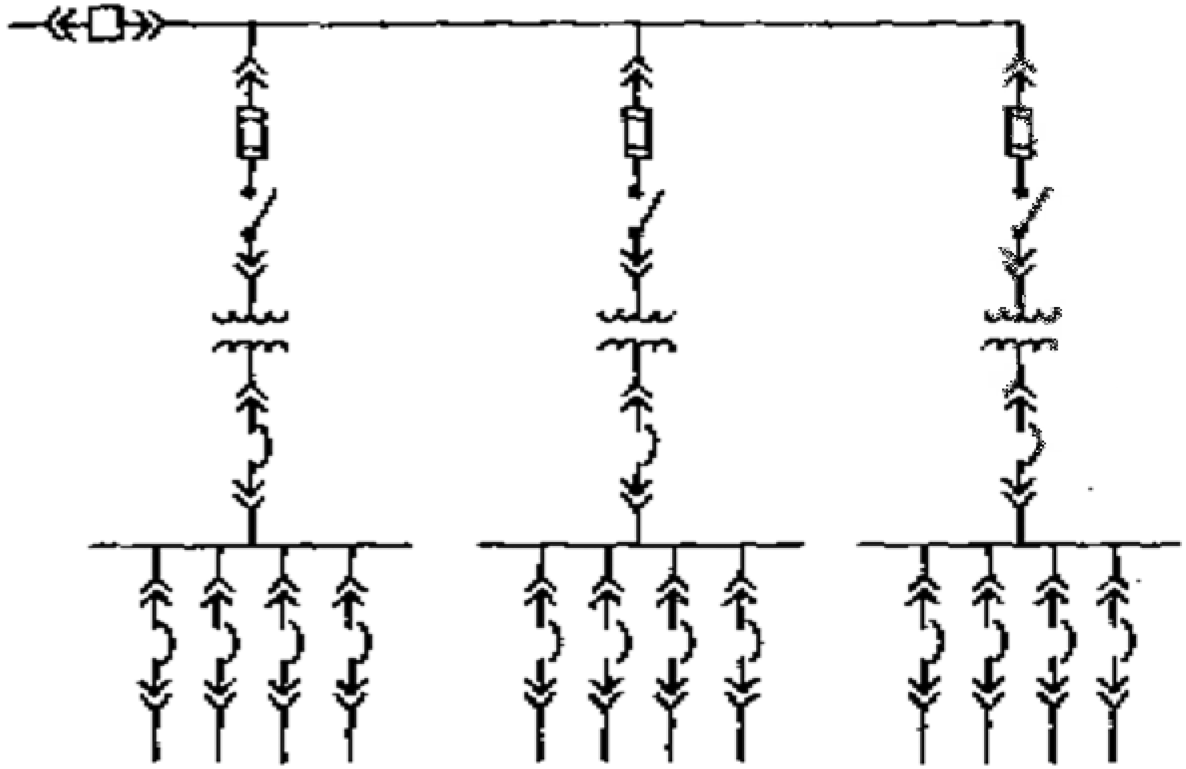
- Typical System Layouts
  - Simple Radial Systems
  - Expanded Radial Systems
  - Primary Selective Systems
  - Primary Loop Systems
  - Secondary Selective Systems
  - Secondary Spot Network Systems
  - Ring Bus Systems

Simple Radial Systems



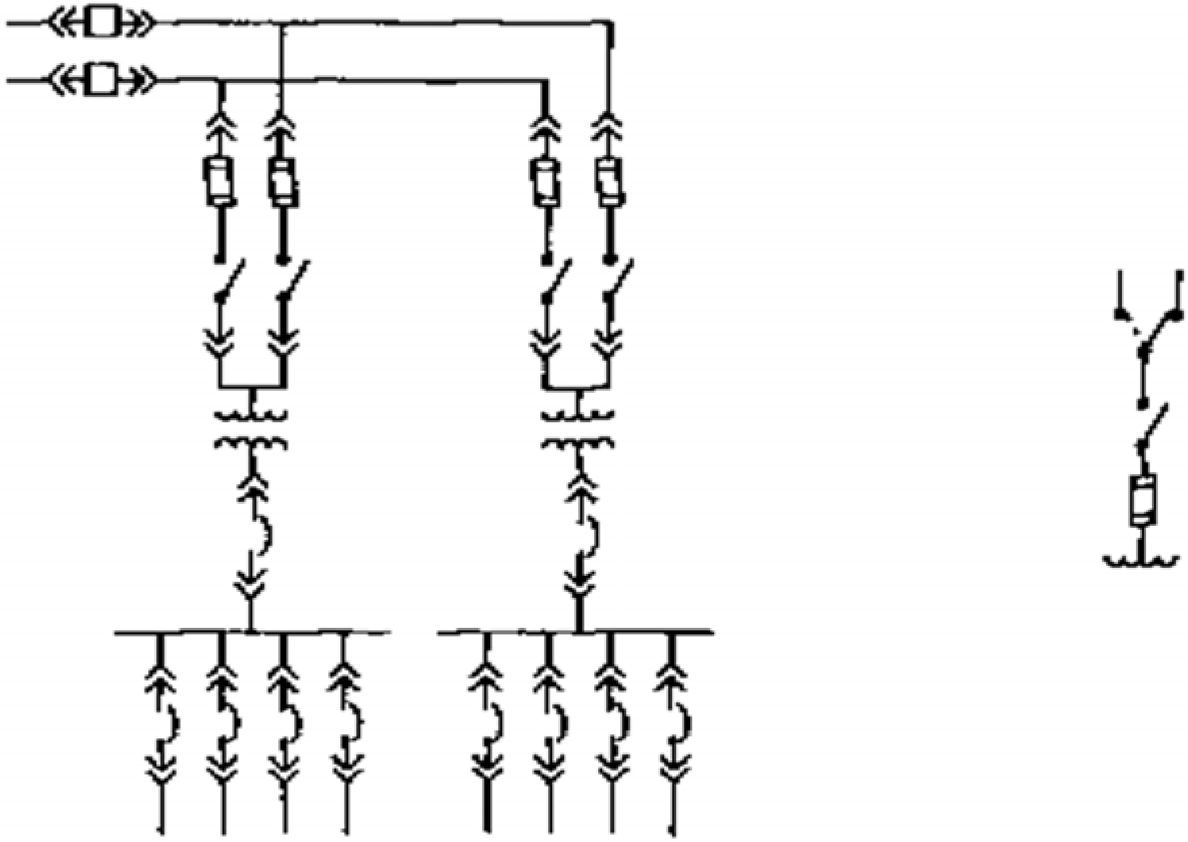
Simple radial system

Expanded Radial Systems



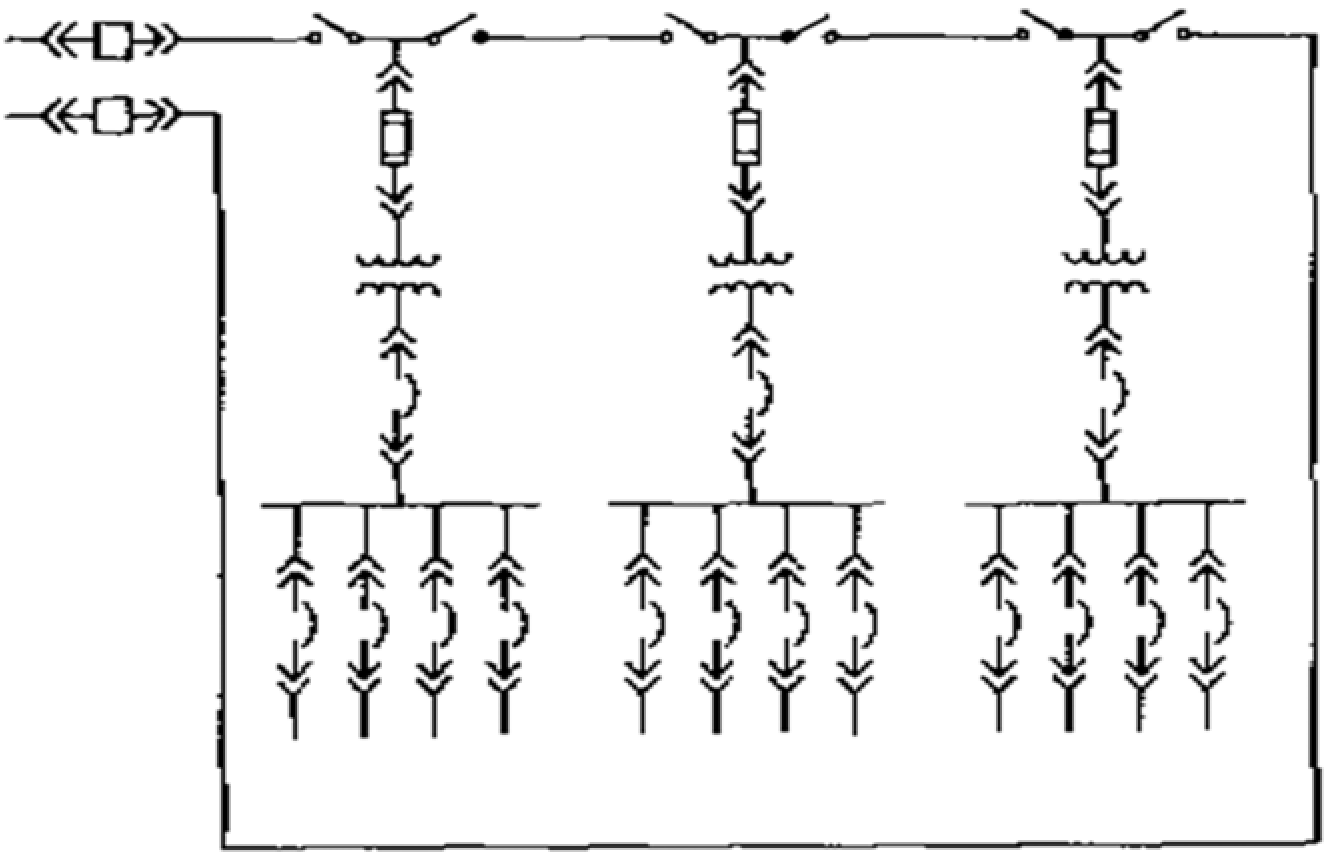
Expanded radial system

Primary Selective Systems



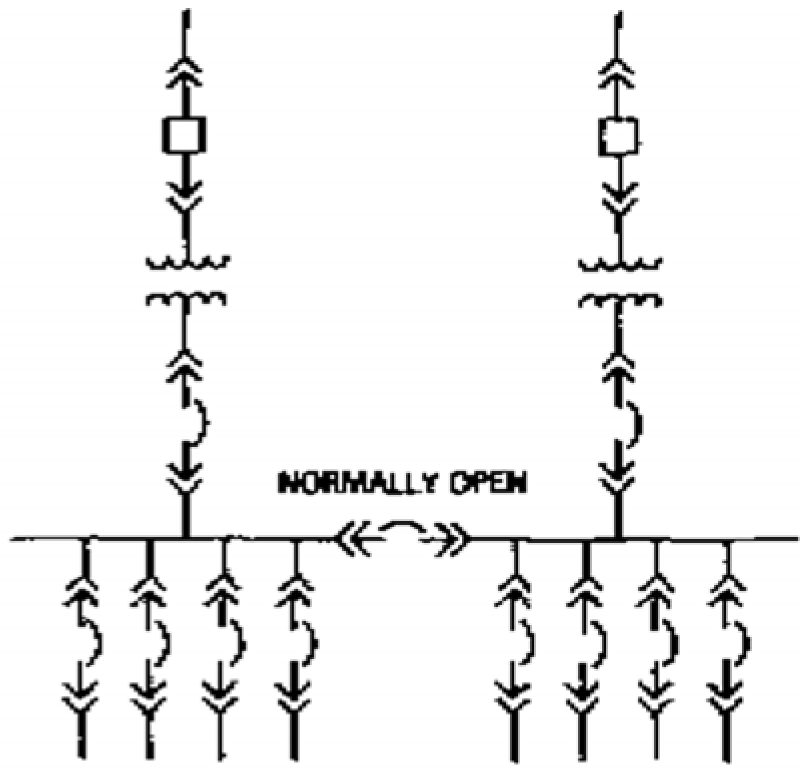
Primary selective system

Primary Loop Systems



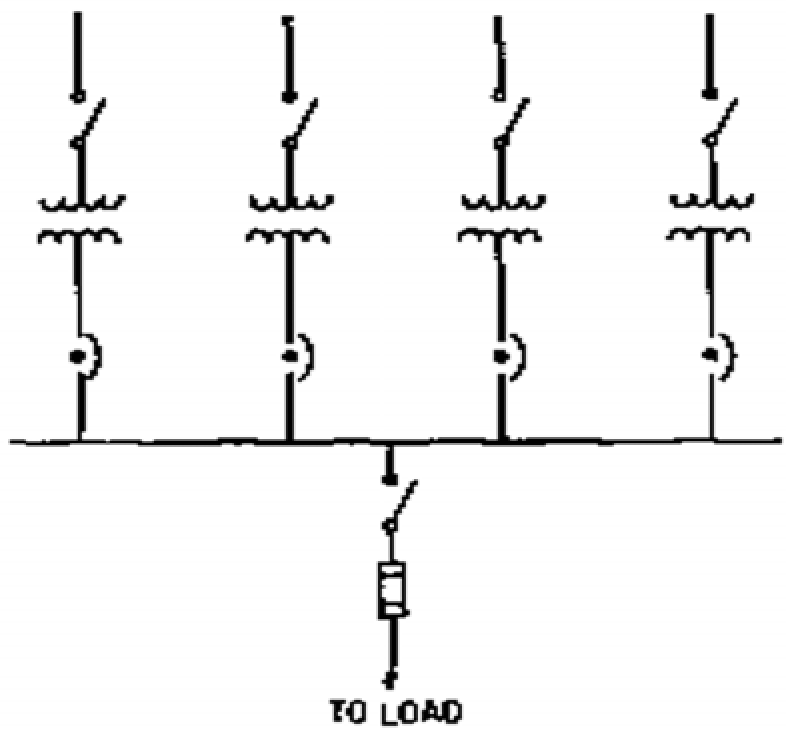
Primary loop system

Secondary Selective Systems



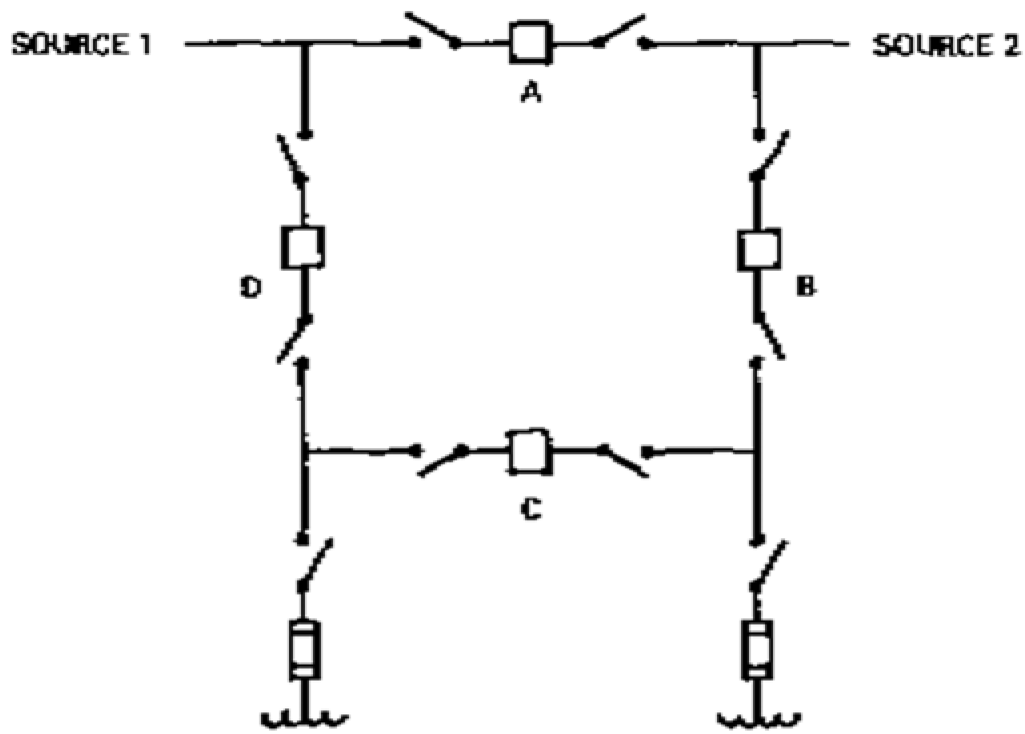
Secondary selective system

Secondary Spot Network Systems



Secondary spot network

Ring Bus Systems



Ring bus system

Electrical Systems

- Electrical distribution is typical of these system layouts.
  - Ring Bus Systems.
  - Primary Loop Systems.
  - Primary Selective Systems.
  - Simple Radial Systems.
  - Expanded Radial Systems
  - Secondary Selective Systems.

Electrical Systems

- Electrical distribution at the has voltage levels at:
  - 138kv - 3 Phase
  - 67kv - 3 Phase
  - 13.2kv - 3 Phase
  - 12.47kv - 3Phase
  - 4.16kv - 3 Phase
  - 480 volt (208 volt) -3 Phase & 1 Phase
  - 120/240 volt - 1 Phase

Switching Equipment

- Switching equipment at the utilize four different interrupting media's:
  - Air
  - Oil
  - SF_6
  - Vacuum

Switching Equipment

- Air break switching is used at all voltage levels within the .
- Air break switches at the 67kv and 138kv levels are <u>NON LOAD BREAK</u>. Switches at this voltage level are for isolation purpose only and are operated only after a circuit breaker has been operated.

Switching Equipment

- Oil and SF_6 are used at the 4.16kv, 13.2kv, 67kv and 138kv levels.
- Before these switches or circuit breakers are operated the following should be verified -
  - Adequate oil level.
  - Adequate SF_6 gas pressure.

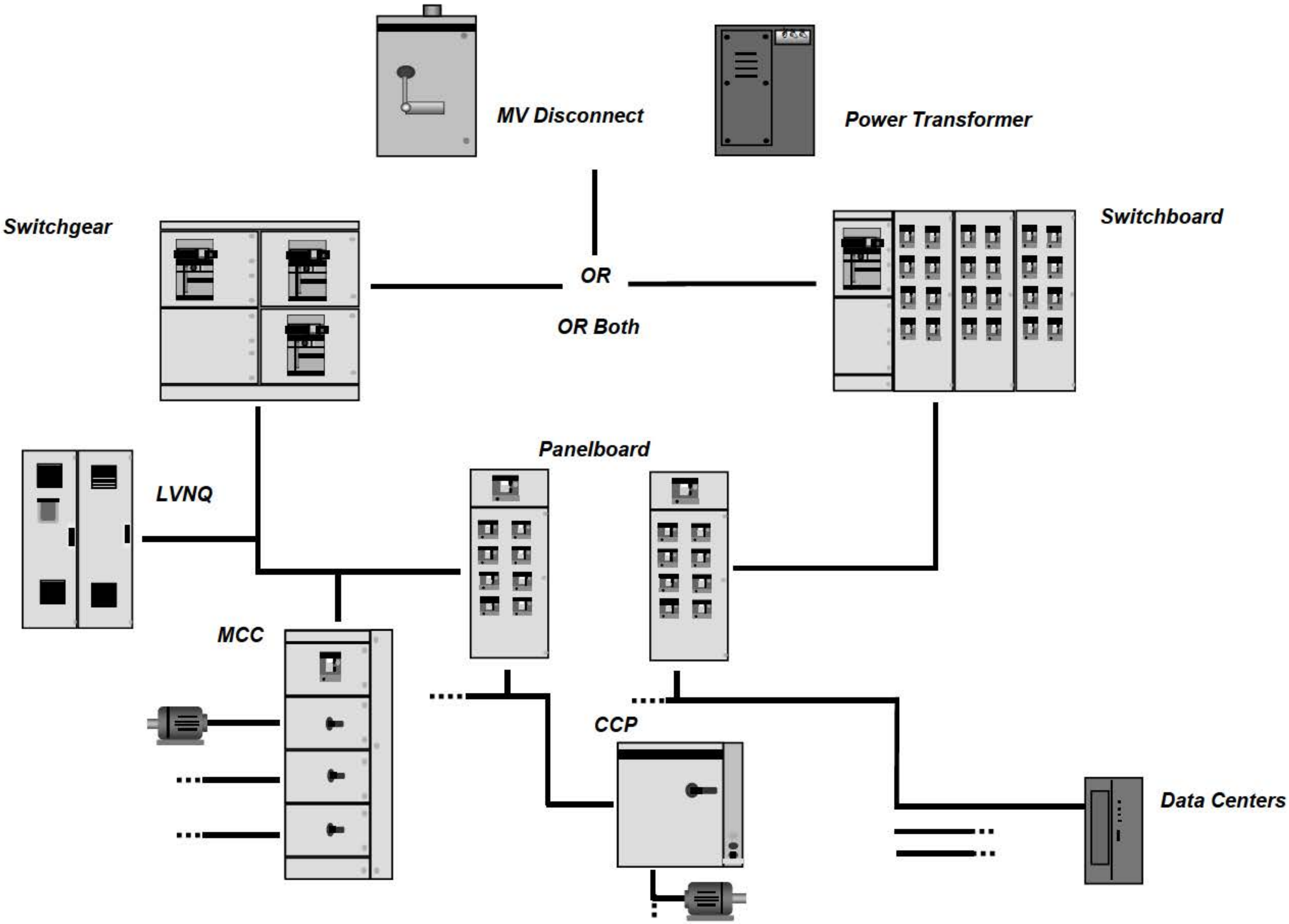
Switching Equipment

- Vacuum is used at the 4.16kv and 13.2kv levels.
- Since there is no practical way to verify that vacuum is present before operation, extreme caution must be taken when operating vacuum devices.

Switching Equipment

- General Safety Precautions
  - Wear appropriate PPE, Flash Suit, HV Gloves, Standard PPE.
  - Do not stand directly in front of a circuit breaker when closing or opening. Stand off to one side.
  - Be aware of the surrounding area, is there a path to escape, are there other people in the area, etc.?

Low Voltage Systems Scenario



Product Overview

- **Definition**
  - **Switchgear** – A switching/interrupting device used in combination with generation, transmission, distribution, and conversion of electrical power for controlling, metering protecting and regulating devices.
  - **Where can they be found?** – Substations (downstream from medium voltage electrical equipment and transformer) and inside electrical equipment rooms such as in hospitals, power plants, and oil and gas refineries.

Product Overview

Description	Value
Rated Main bus current	2000, 3200, and 4000A
Rated Vertical bus	2000A
Rated tested maximum voltage	254Vac, 508Vac, 635Vac
Rated voltage	240Vac, 480Vac, 600Vac
Phases	3 phase 3 wire, 3 phase 4 wire
Neutral	100% rated
Frequency	50/60 Hz
Short circuit current	65 kA, 100 kA
Max peak short circuit current	149.5 kA, 230 kA
Enclosure	NEMA 1 (with Gasket doors), and N3R Walk In

Product Overview

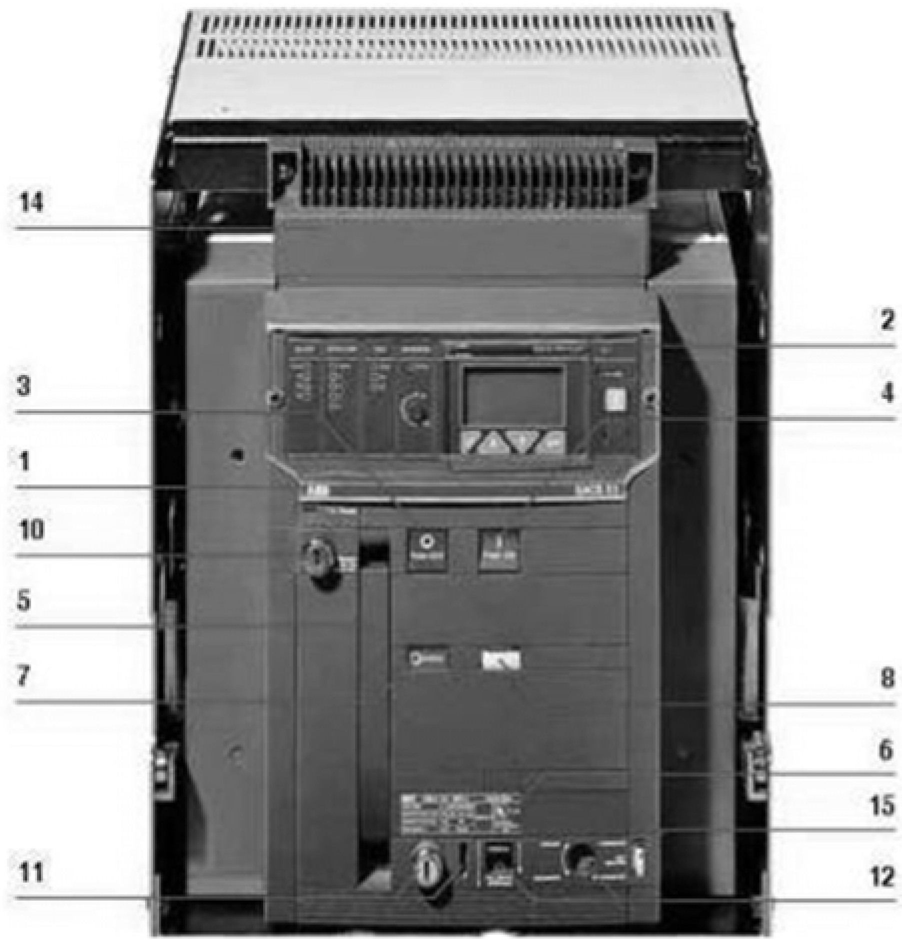
■ Standards

- **SWITCHGEAR**
  - **ANSI C37.20.1** -Metal Enclosed LV Power Circuit Breaker Switchgear
  - **ANSI C37.51** -Testing of Metal Enclosed LV AC Power Circuit Breaker Switchgear
  - **UL 1558** -Switchgear Assemblies
  - **CSA** -Canadian Standard Assemblies
  - **IBC-2006 & CBC-2007** - Seismic Qualification
- **CIRCUIT BREAKER**
  - **ANSI C37.13** – LV AC Power Circuit Breakers Used in Equipment
  - **ANSI C37.16** – Preferred Rating, Related Requirement, Application Recommendations For LV Power Circuit Breakers and AC Power Circuit Protectors
  - **ANSI C37.50** – Testing of Low Voltage AC Power Circuit Breakers
  - **UL 1066** – Low Voltage Power Circuit Breakers

Key Features and Benefits

Power Circuit Breakers –

1. Trademark, size of CB
2. Trip unit
3. PB for manual opening
4. PB for manual closing
5. Lever to manually charge closing spring
6. Label with electrical characteristics
7. Mechanical device to signal CB open “O” and Closed “I”
8. Signal for springs charged or discharged
9. Mechanical indication of trip
10. Key lock in open position
11. Key lock and padlock in racking-in, racking-out position
12. Racking-in, racking-out device
13. Terminal box
14. Sliding contacts
15. CB position indicator



Key Features and Benefits

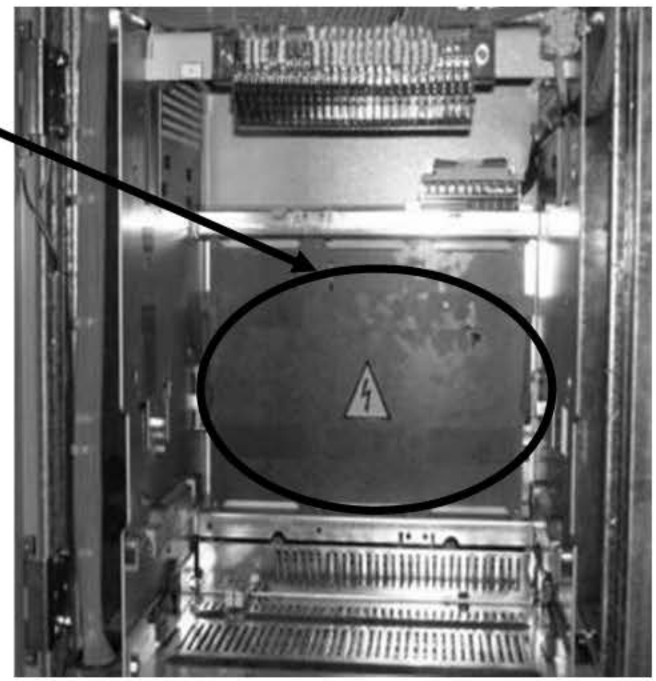
Three Trip Units

- PR121
  - Protection Features Only
- PR122
  - Protection Features
  - LCD Display
  - Current Measurement
  - Contact Wear
  - Communications option
- PR123
  - PR122 Features
  - Harmonic Measurements
  - Communications option

Key Features and Benefits

Safety Features

- **Safety shutters (standard)**



Key Features and Benefits

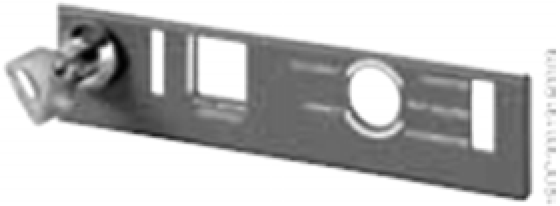
Safety Features

– Breaker compartment keyed cells

Key Features and Benefits

Safety Features

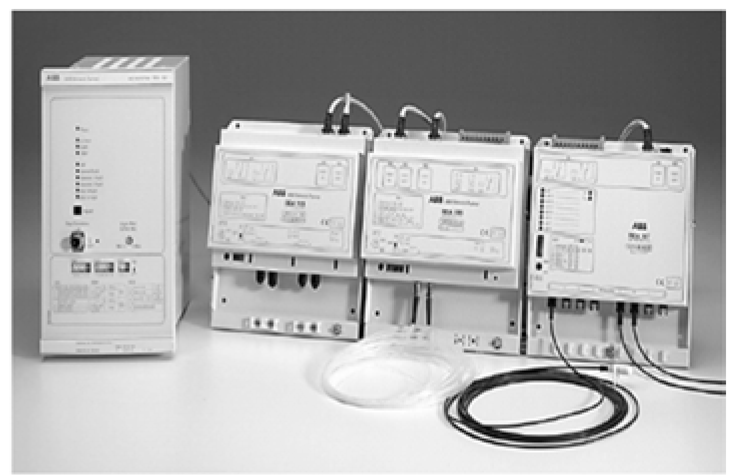
- Padlocking provisions
  - Anti-insertion lock
  - Disconnect, connect, and test position



Key Features and Benefits

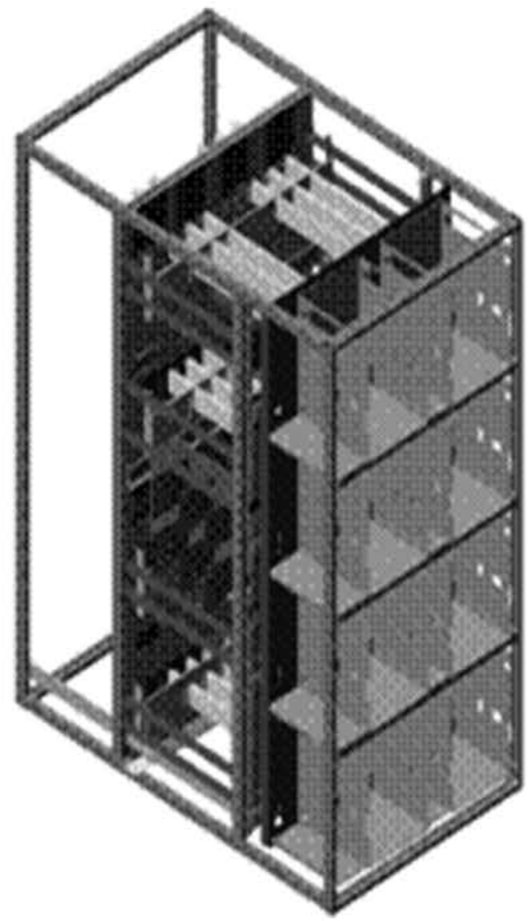
- Maintenance Switch Option
  - Provides option to dial down to a lower instantaneous setting on trip unit for performing instantaneous

- REA Relay Arc Flash System
  - Detects an arc anywhere in the bus compartment and cable compartment utilizing long-fiber sensor system, tripping upstream main breaker in order to provide minimal damage to equipment



Construction

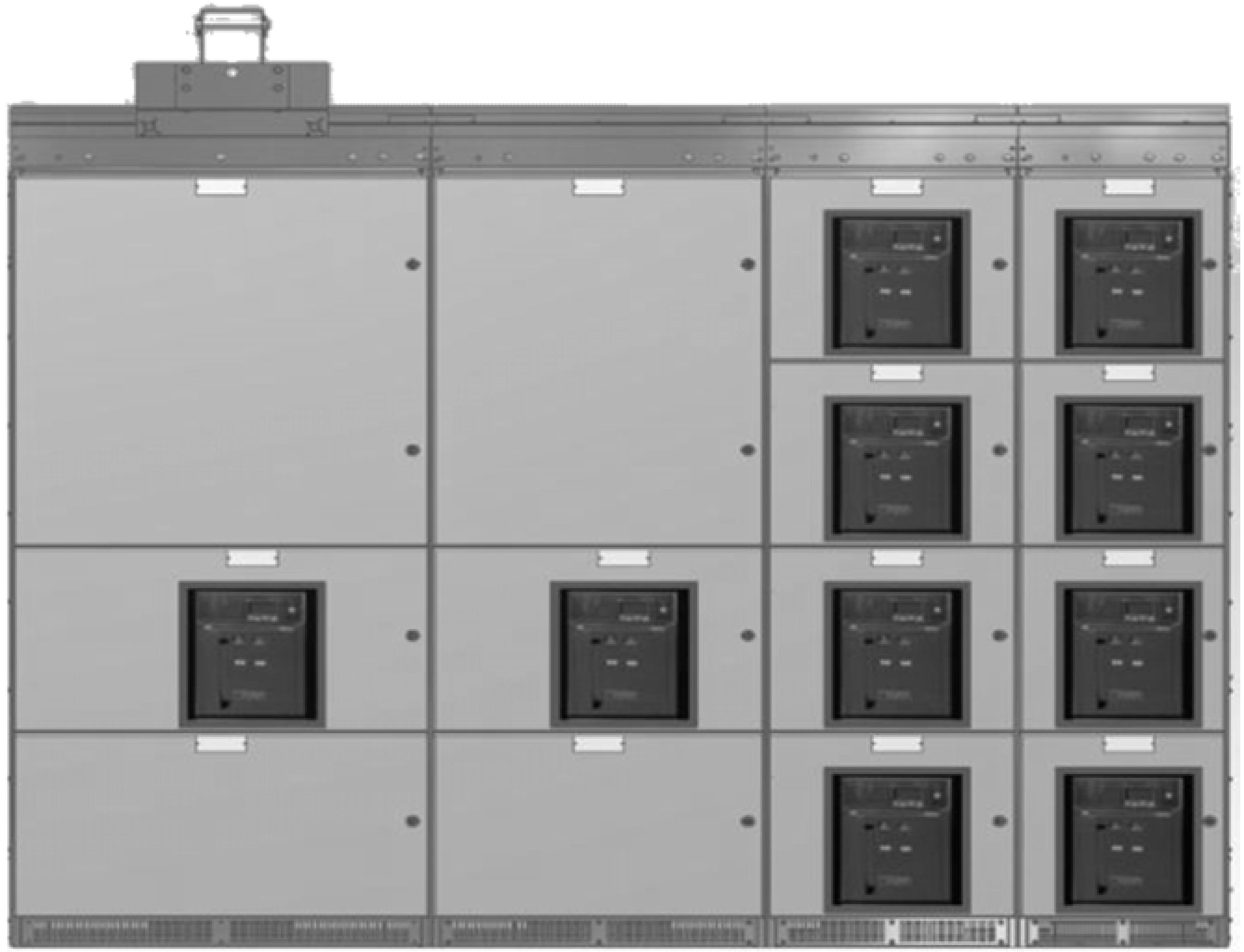
Front doors, rear doors, left and right side panels, rear panels (Carbon)	14 GA
Internal Sheet Metal (Galvanized) (Instrument compartment, breaker compartment, protection panel, truck rail, overhead lift device, riser support)	11 GA
Shipping Frame (Galvanized)	12 GA



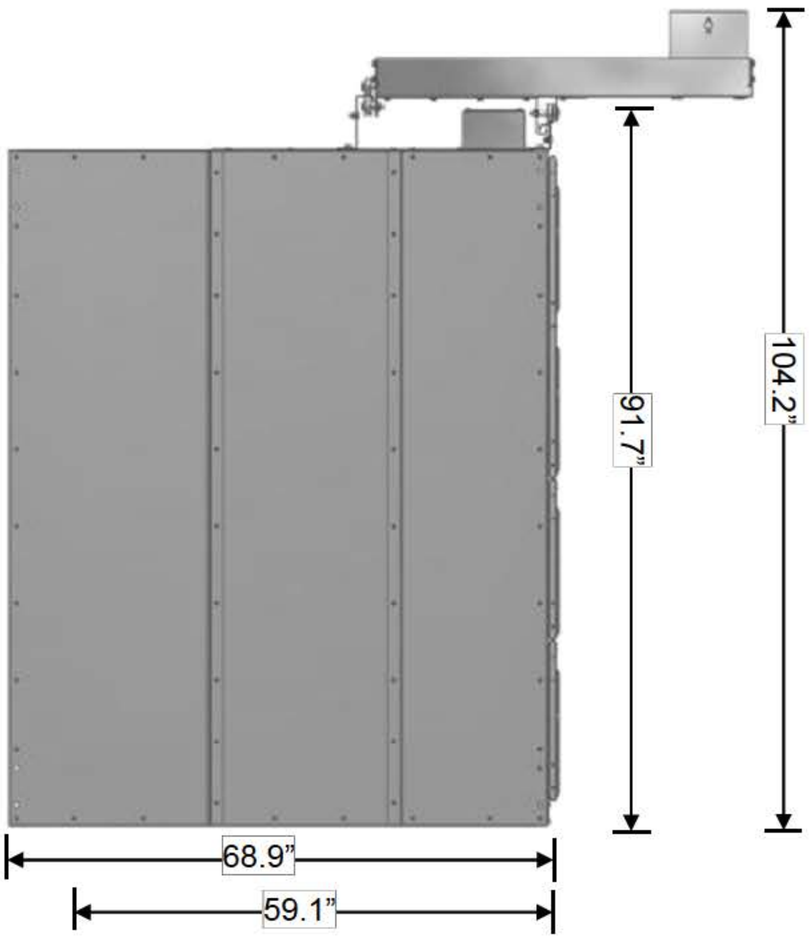
Construction

Available Widths

E6 4000 Amp	E2/E3 800 – 2000 E4 3200 Amp (65 & 100 kA)	E2/E3 800 – 2000 (65 & 100 kA)	E2 800 - 1600A (65 kA)
39.4”	**31.5”**	**23.6”**	**19.7”**



Construction



- **Depth**
  - Standard – 68.9"
  - Optional 59.1"

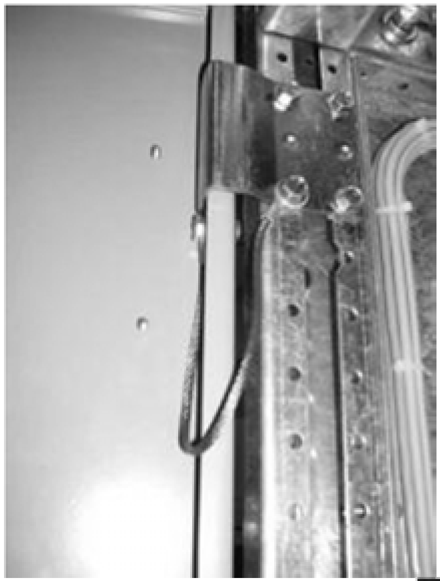
Height

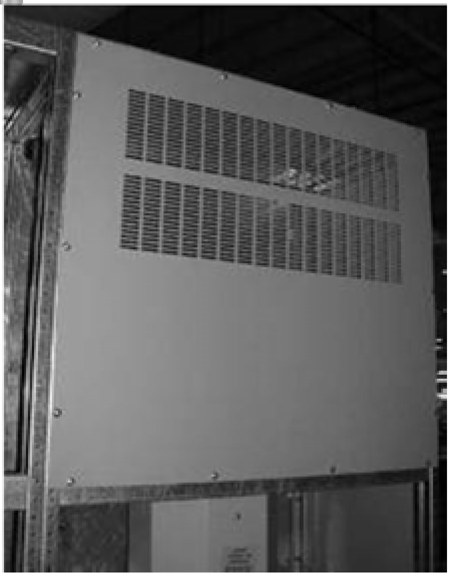
91.7" without overhead lifting device

104.2" with overhead lift device

Construction

- Doors:
  - Front doors - Semi-concealed hinges
  - Rear doors – Bolted, optional hinge, Pad-locking handles available
  - Infrared Windows (Optional)

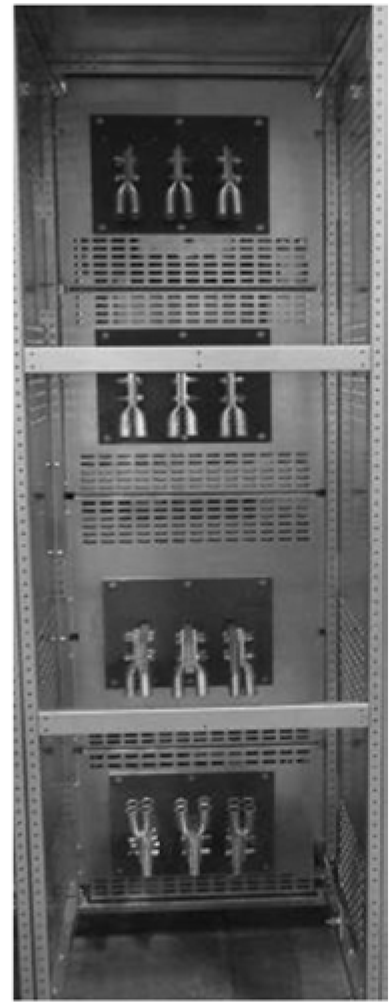




- Paint
  - ANSI 61 Electro static powder coat (standard)
  - ANSI 70 (Optional)

Construction

- **Rear cable area**
  - Mechanical Lugs (standard)
  - Compression Lugs (optional**)**
  - Main Bus Barriers separating bus compartment from cable compartment (Standard)
  - Vertical Steel Barriers between sections in cable compartments (Optional)



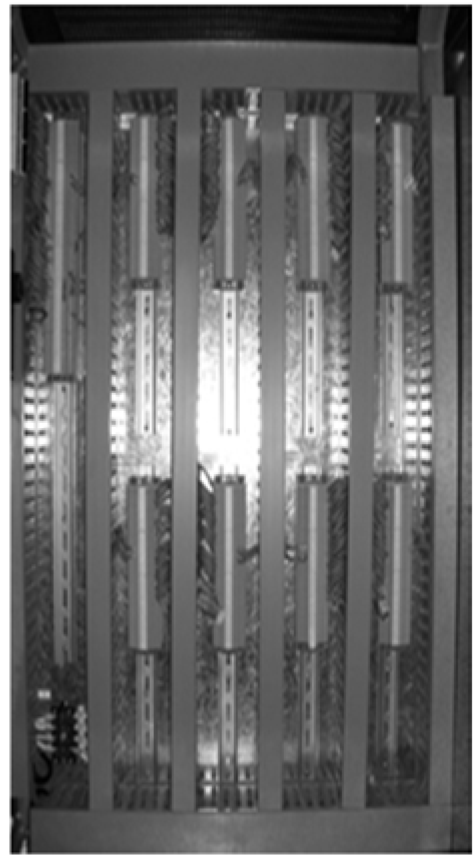
Construction

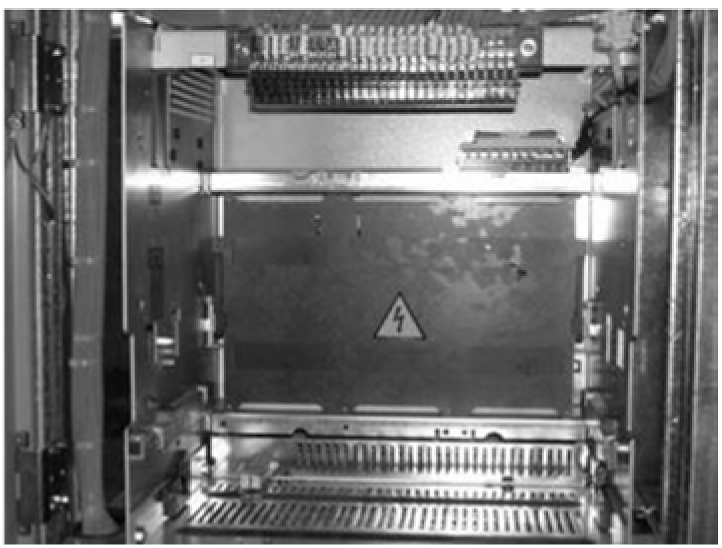
- **Bus Design**
  - Standard temperature rise Max 65ºC over 40ºC ambient
  - Main bus amperages include: 2000A, 3200A, and 4000A with bus bracing at 65kA or 100kA.
  - Vertical bus riser amperages include: 2000A for feeder sections and up to 5000A for Tie sections with bus bracing at 65kA or 100kA.
  - Non-insulated silver plating bussing is standard; optional tin-plating is available.
  - Optional insulated bussing consist of: thermal-contractile flame resistant non-hydroscopic tubing and boots on main horizontal and cable compartment runback bussing.

Construction

Control Wiring

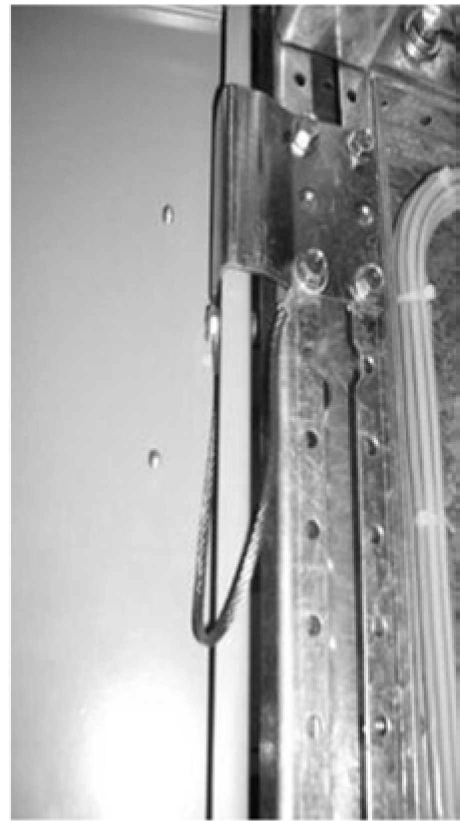
- Inter-cubical wiring made easy
  - Terminal strips
  - Located in wire way on top of enclosure



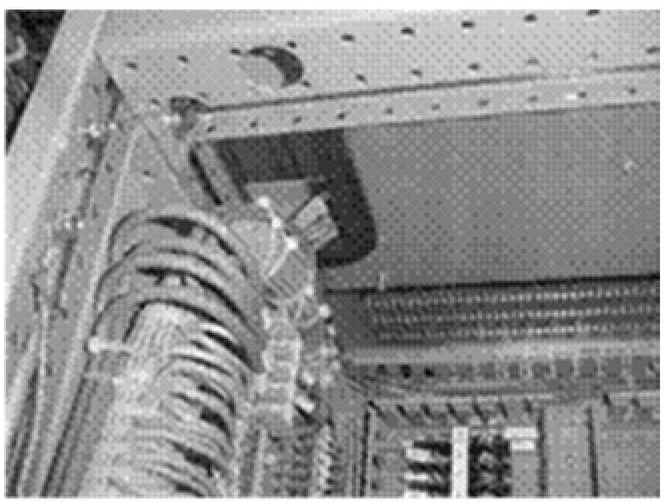


Construction

Front door grounding

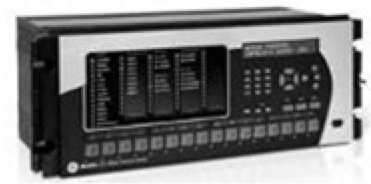


Inter-cubicle wiring made easy



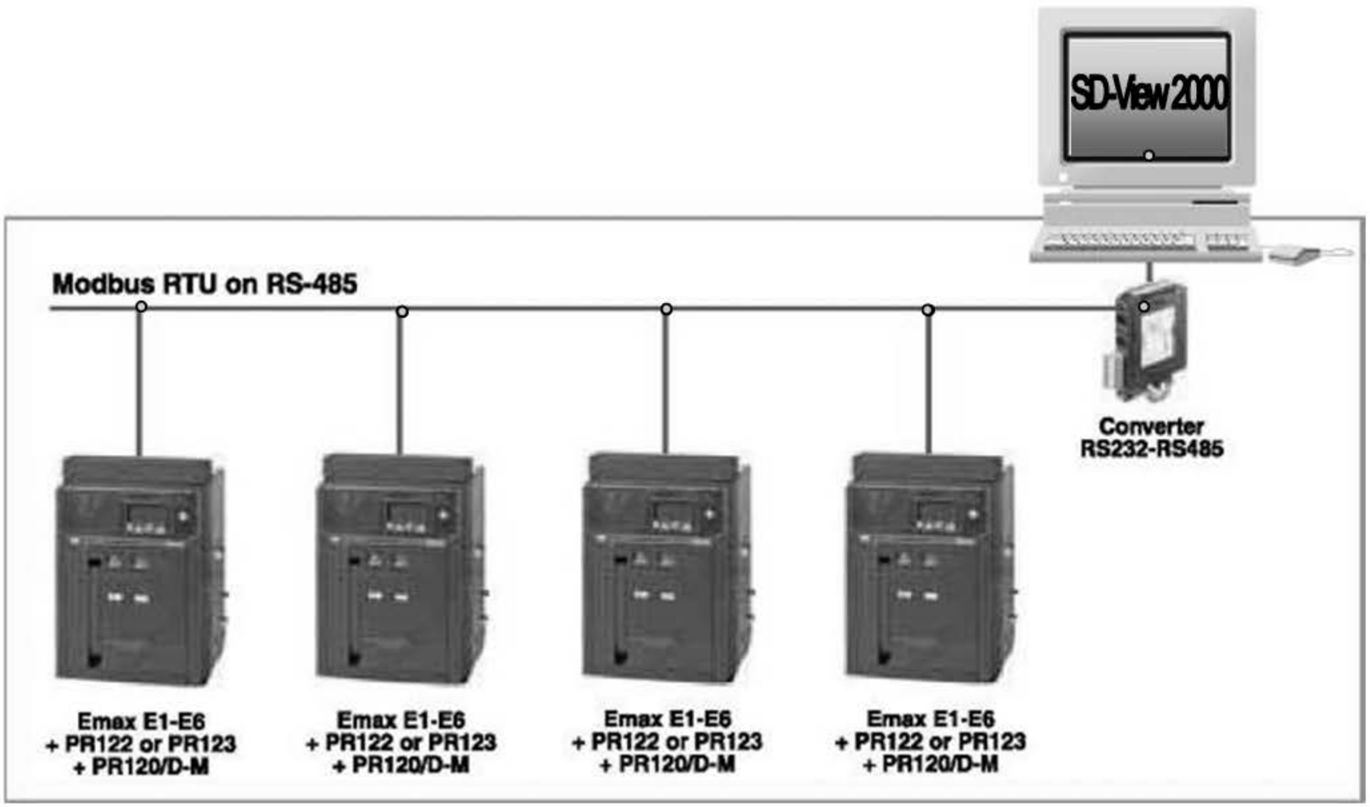
Instrumentation

- **Breaker door mounted lights, meters and control**
  - ABB Indicating Lights
  - Volt, amp, and watt meters
  - Electroswitch Series 20 and 24 control switch
  - Multifunction Metering
    - Electro Industries
    - Others
  - Relays
    - ABB (provided standard when required)
    - GE Multilin (Optional)
    - Basler, Schweitzer, Others (Optional)
  - Surge Protectors
    - ABB TVSS (Standard)
    - Others (Optional)



Applications

Communications
- DCS monitored
  - Modbus (Standard)
  - Profibus
  - DeviceNet
  - Ethernet



Understanding Power Concepts

Part 3

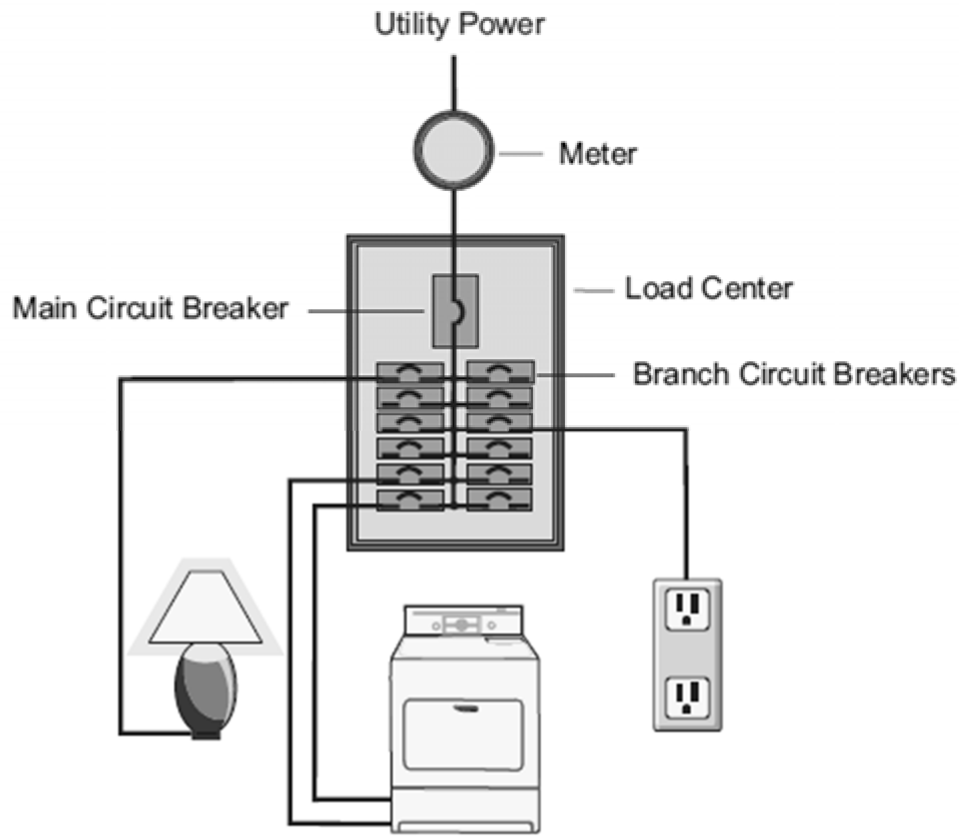
- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- ***<u>Panels (Lighting and Power)</u>***
- MCC
- DC/UPS Systems

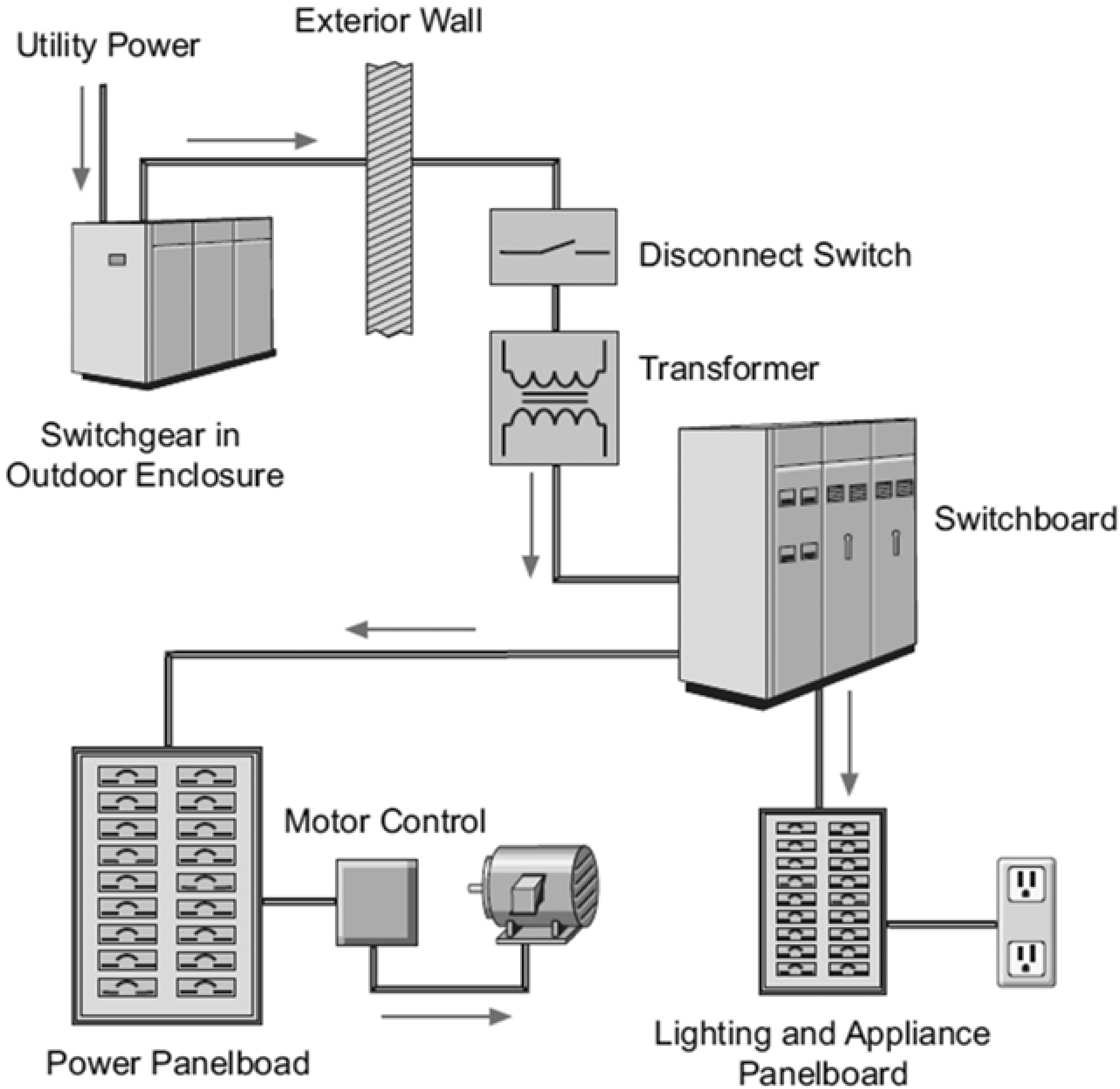
Panel Boards

- NEC Article 384-14 defines a lighting and appliance branch circuit panel board as a panel board that has more than 10 percent of its overcurrent devices rated 30 amperes or less, for which neutral connections are provided.

- *Note: Lighting and appliance panel boards are often just referred to as lighting panel boards.*

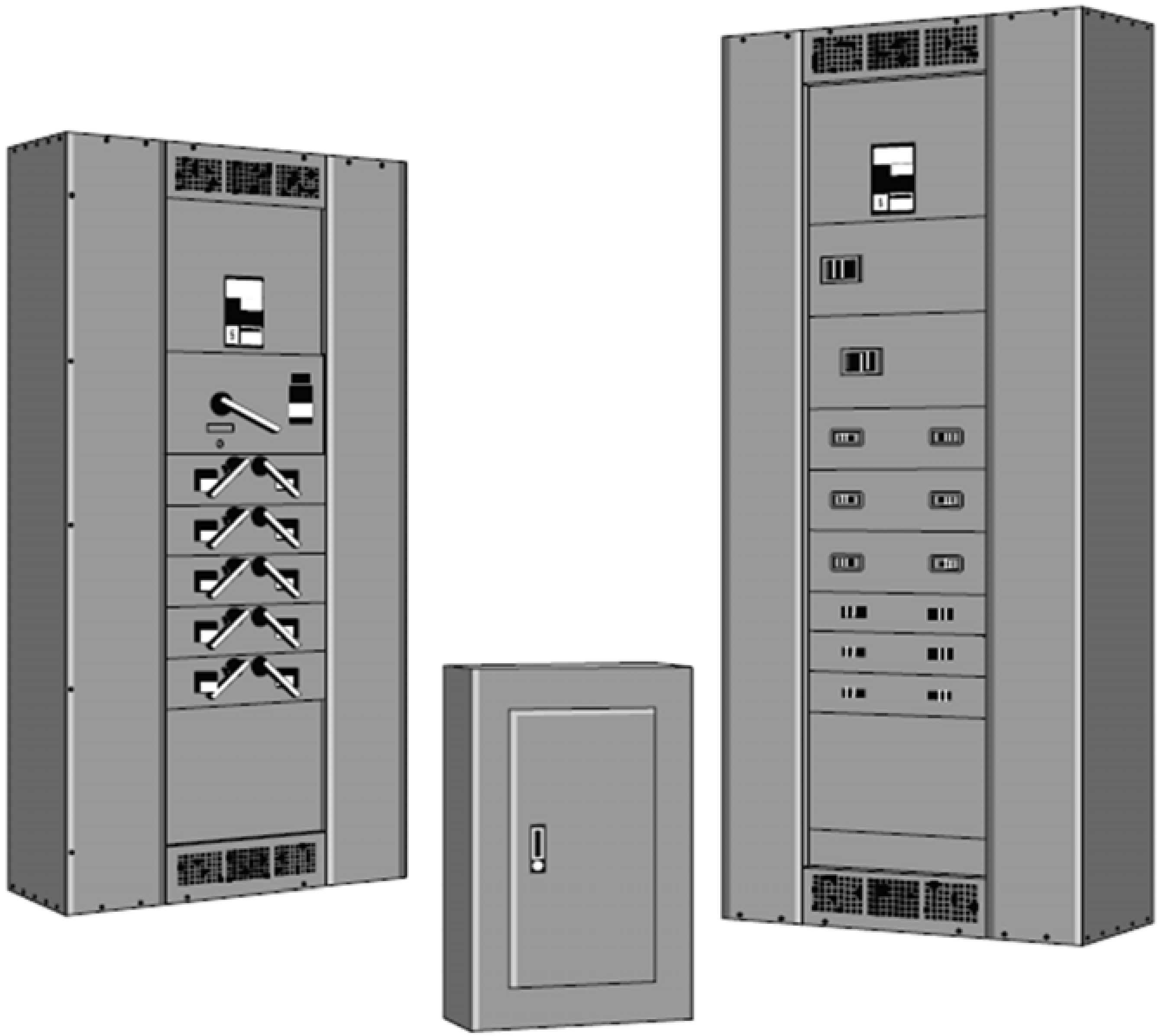
Typical Commercial Power Panel

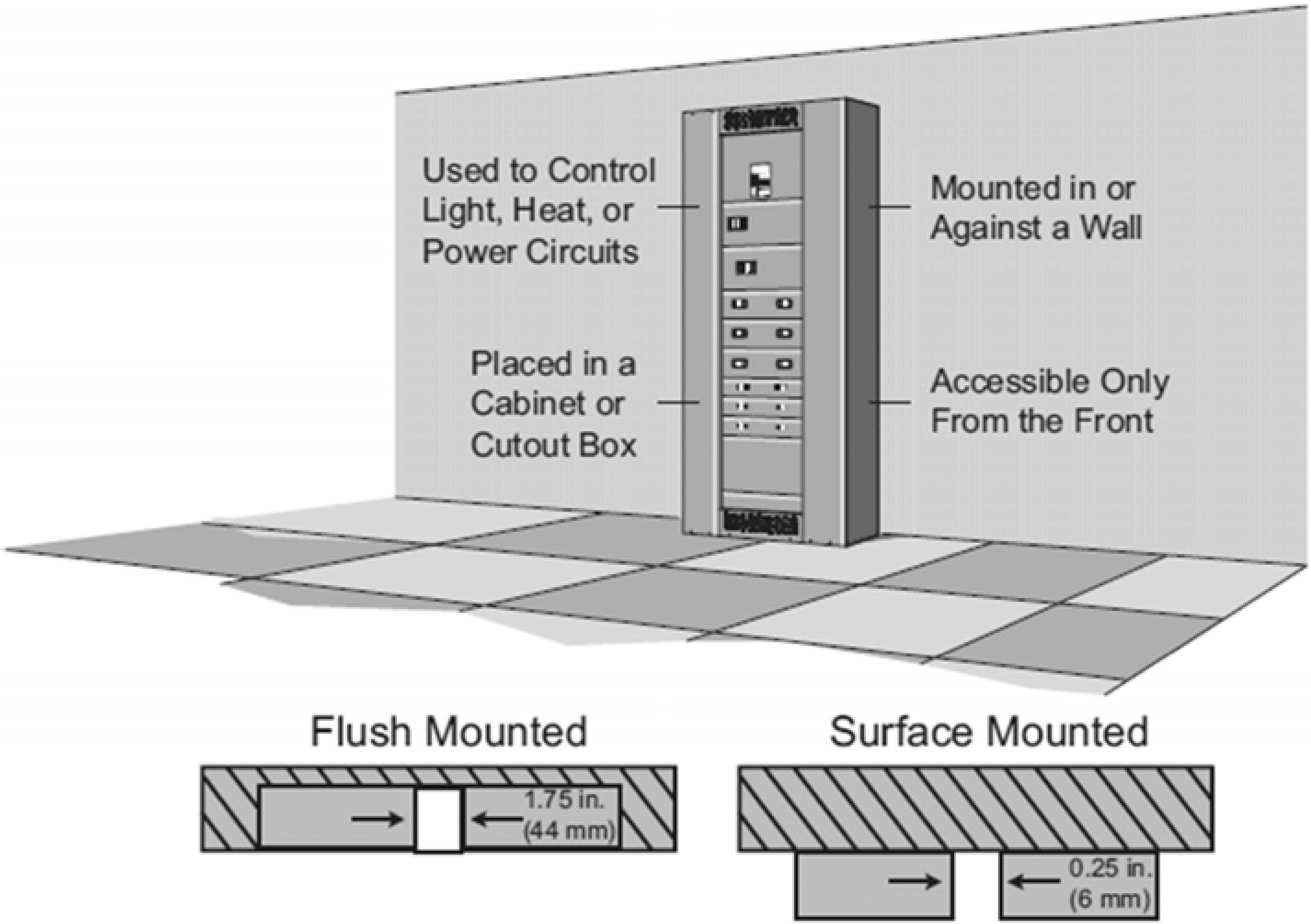




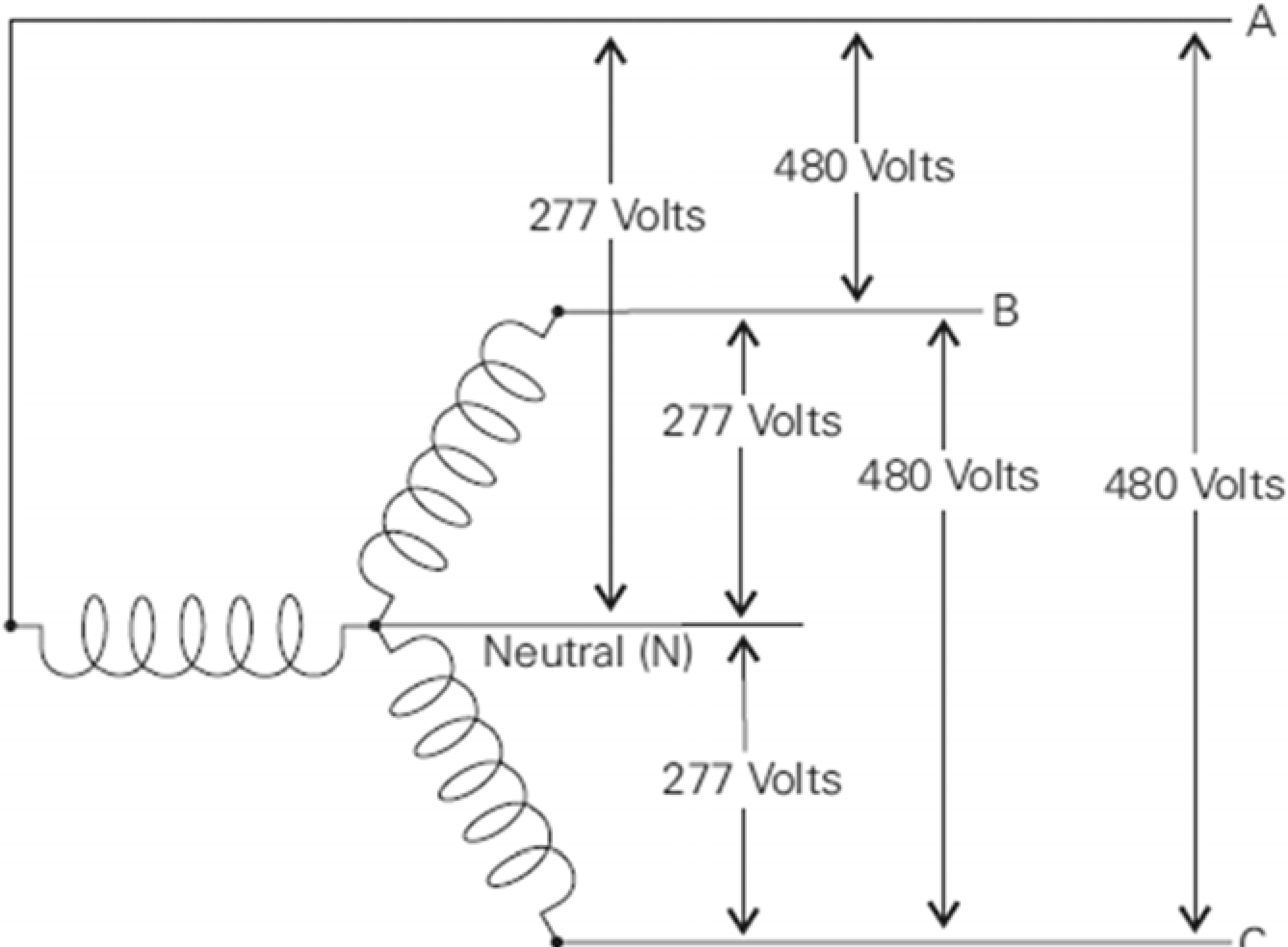
Utility Power
Exterior Wall
Disconnect Switch
Transformer
Switchgear in
Outdoor Enclosure
Switchboard
Motor Control
Power Panelboard
Lighting and Appliance
Panelboard

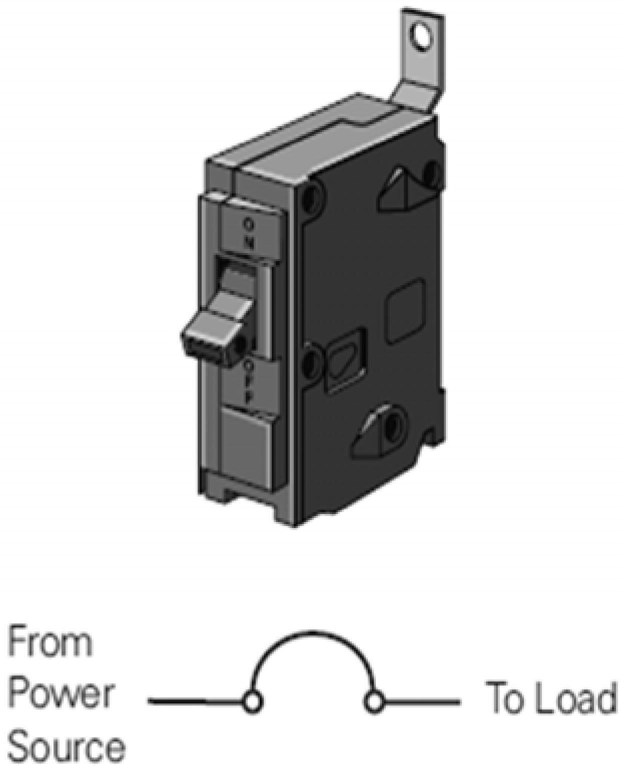
- T*he National Electrical Code®* (*NEC®*) defines a panel board as *a single panel or group of panel units designed for assembly in the form of a single panel, including buses and automatic overcurrent devices, and equipped with or without switches for the control of light, heat, or power circuits; designed to be placed in a cabinet or cutout box placed in or against a wall, partition, or other support; and accessible only from the front* (Article 100-Definitions).



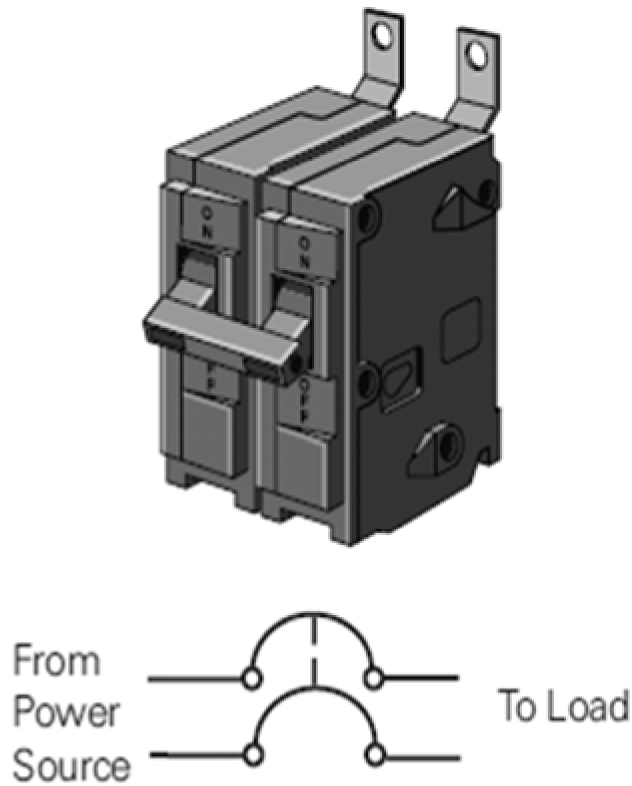


For additional information, refer to *National Electrical Code*® Article 408, Switchboards and Panelboards.

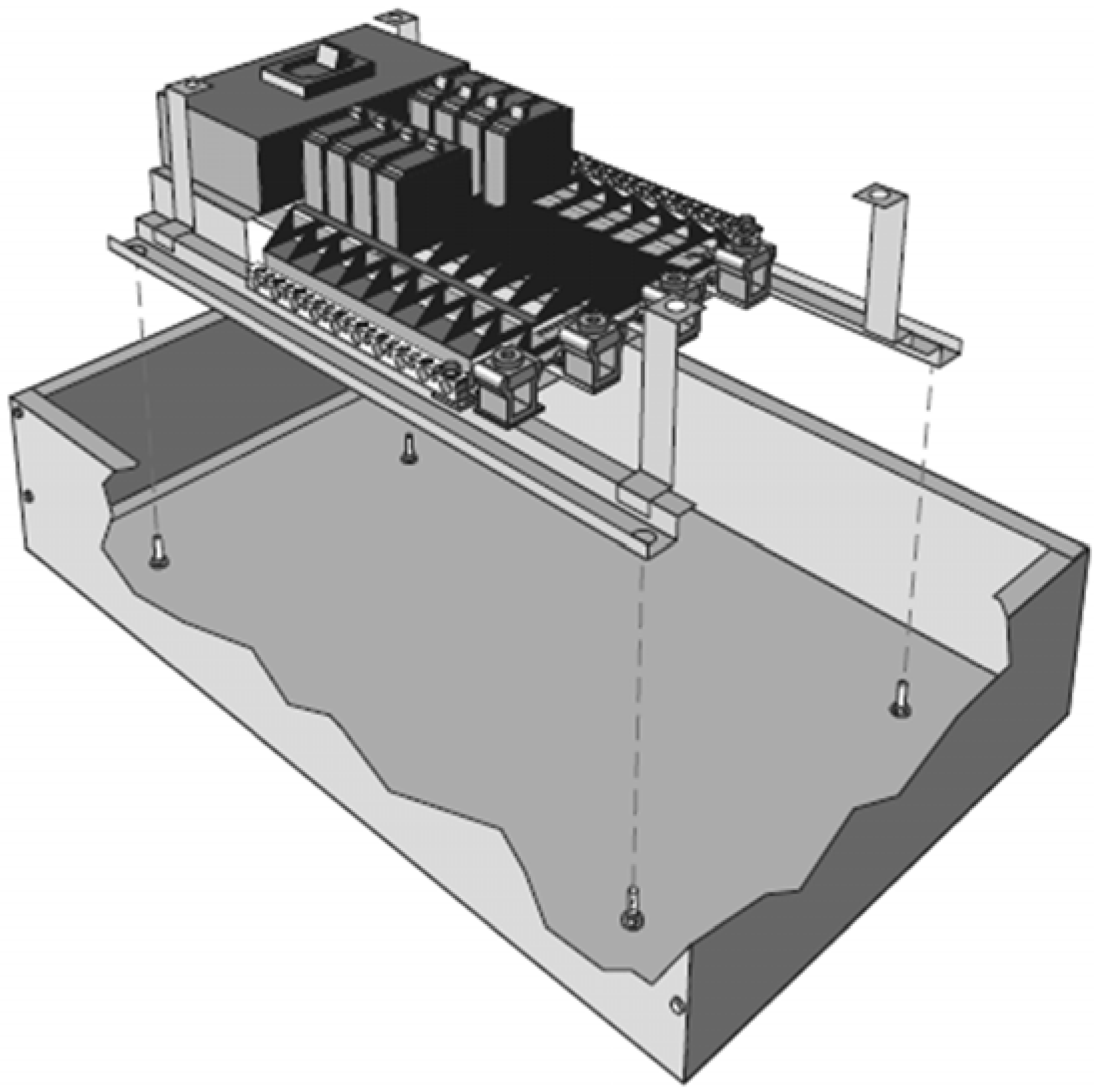

A
277 Volts
480 Volts
B
277 Volts
480 Volts
480 Volts
Neutral (N)
277 Volts
C

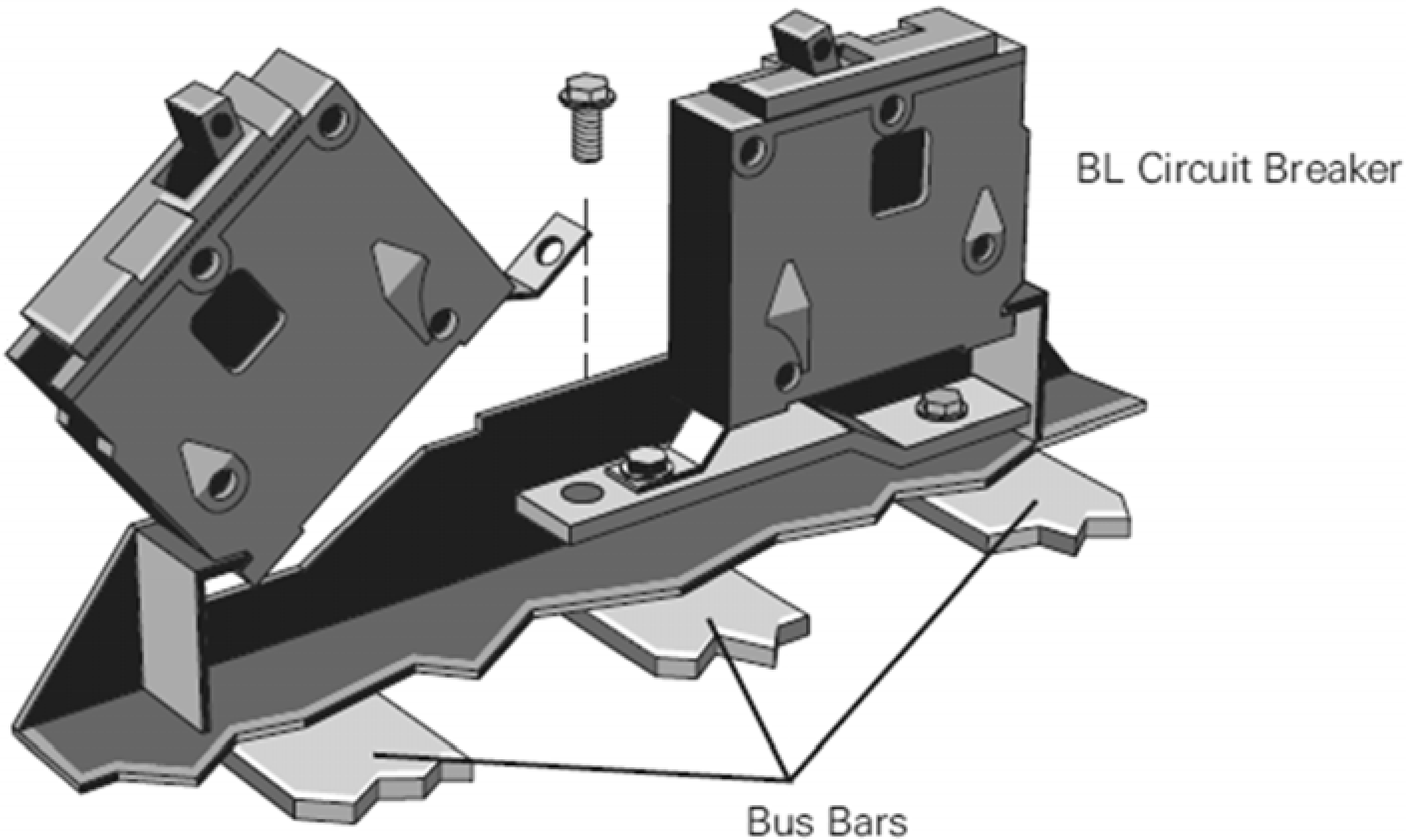


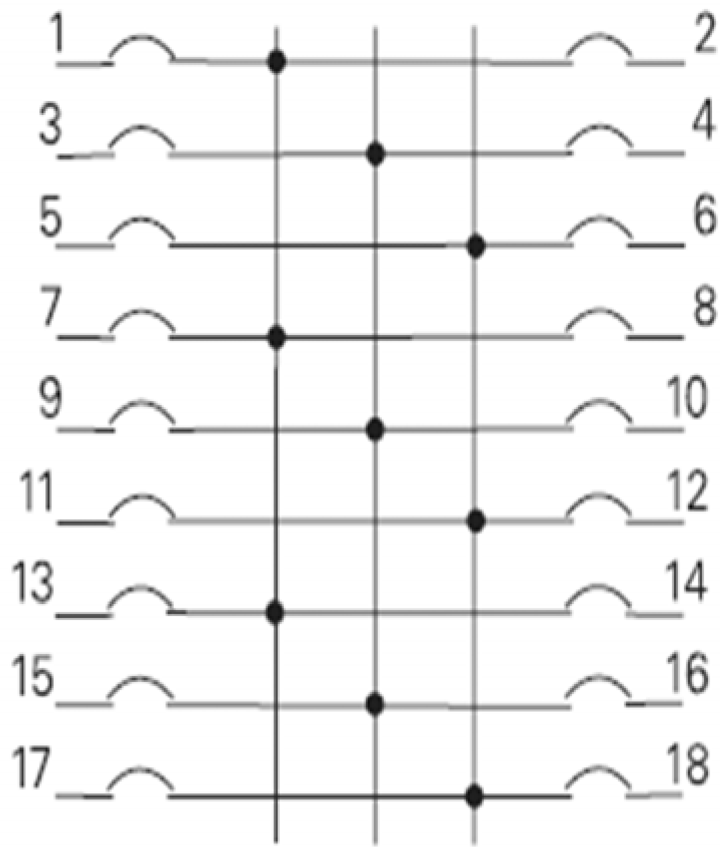
1-Pole Circuit Breaker
One Overcurrent Device



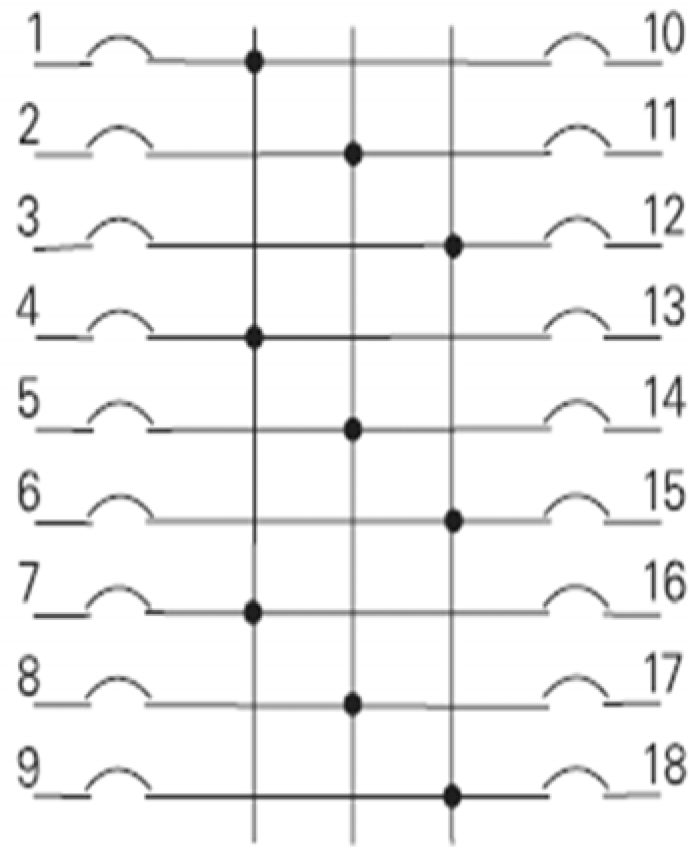
2-Pole Circuit Breaker
Two Overcurrent Devices




BL Circuit Breaker
Bus Bars



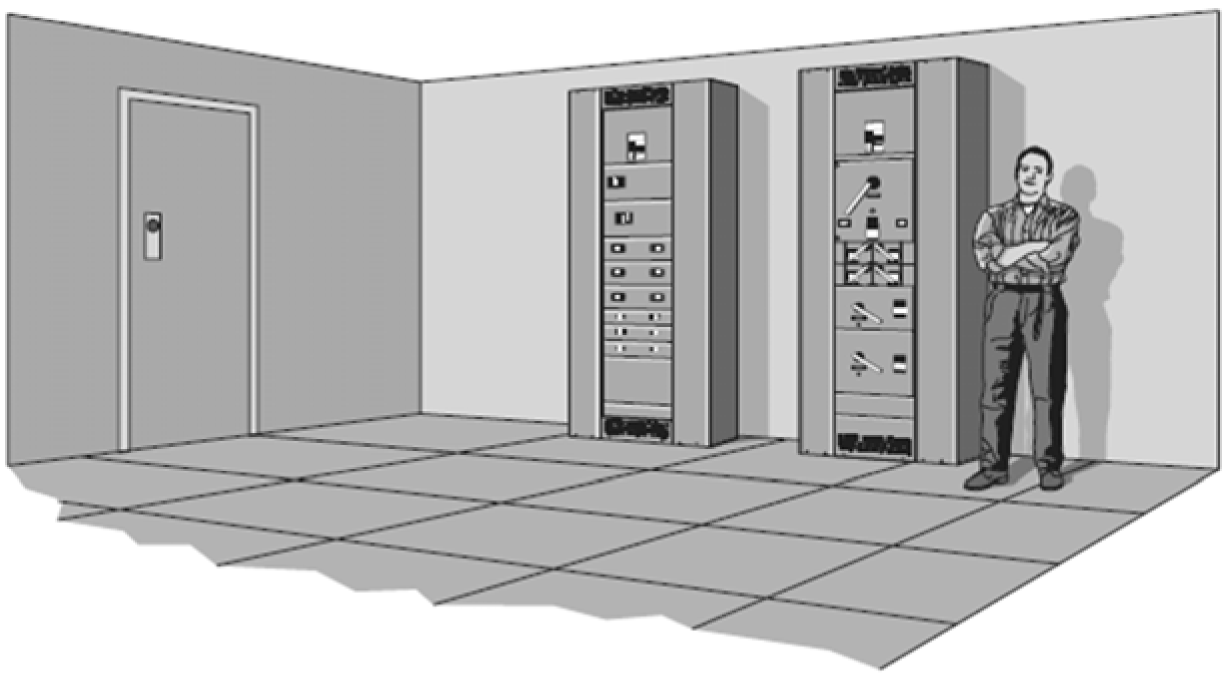
NEMA Numbering

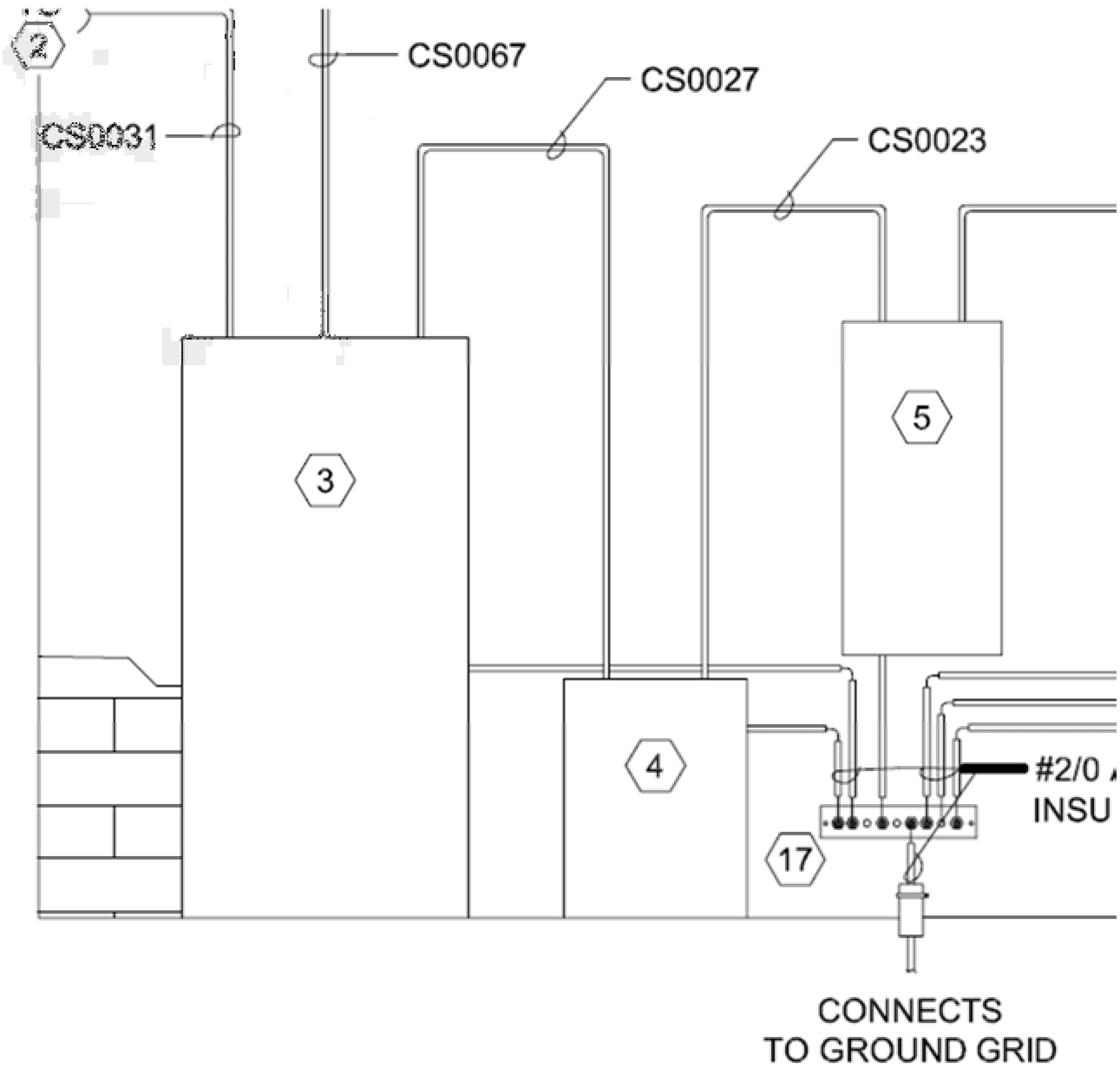


Vertical Numbering

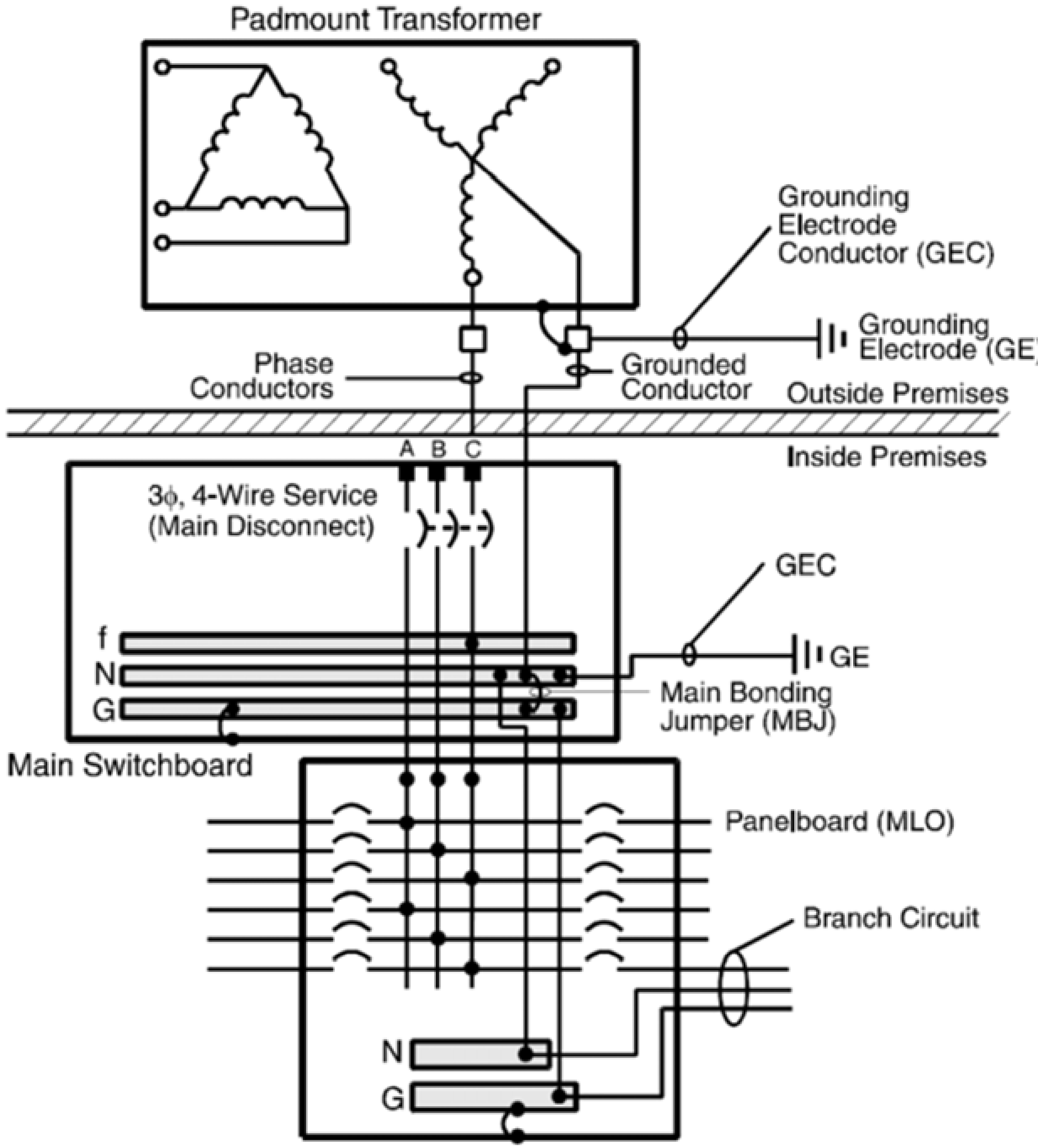
The intent of Article 110.26 is to provide enough **working space** for personnel to examine, adjust, service, and maintain energized equipment. Article 110.26 sets requirements for depth, width, and height of a working space.

In addition, Article 110.26 discusses entrance requirements to the working space as well as requirements for dedicated equipment space for indoor and outdoor applications. Refer to this article if you have questions about working space requirements.





- 3: Power Panel free standing
- 4: Control Power Transformer
- 5: Lighting Panel


Padmount Transformer
Grounding
Electrode
Conductor (GEC)
Grounding
Electrode (GE)
Phase
Conductors
Grounded
Conductor
Outside Premises
Inside Premises
A B C
3ϕ, 4-Wire Service
(Main Disconnect)
GEC
GE
f
N
G
Main Bonding
Jumper (MBJ)
Main Switchboard
Panelboard (MLO)
Branch Circuit
N
G

Type PRL1a Panelboard

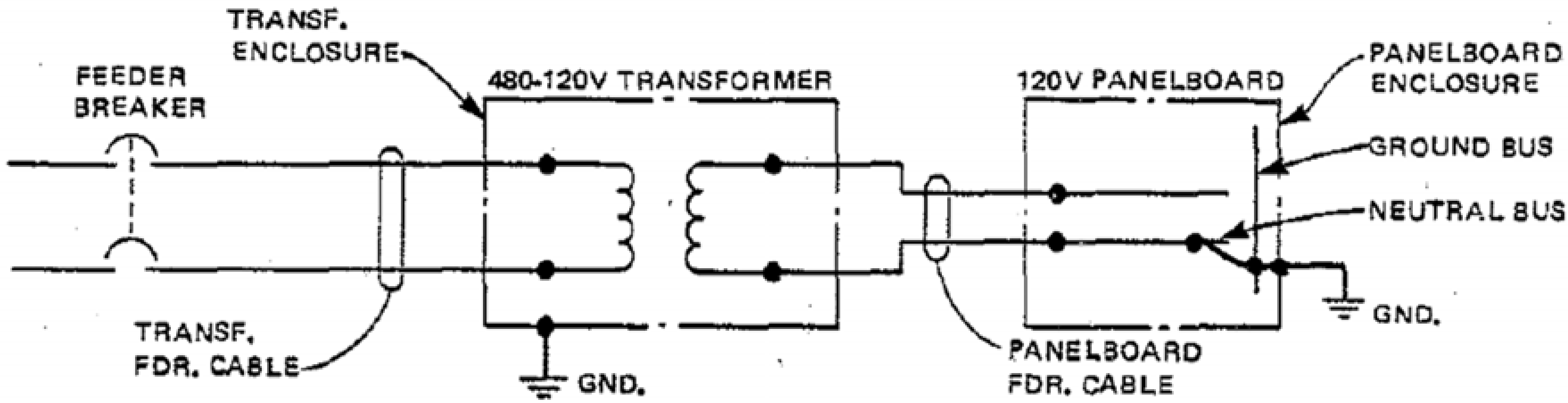
Panel Name:	LP-1					Location:	Sub 1
Mounting:	Surface					Voltage:	208Y/120
Enclosure:	NEMA 1					Phase:	3P/4W
Mains:	150A.T.					Short Circuit Rating:	10KA
Bus Ampacity:	225A					Ground Bus:	Yes
Bus Type:	Tinned Copper					Isolated Ground Bus:	No
Branch Breaker Type:	Plug-In					Neutral Bus:	100%
Transformer Supply (kVA):	45kVA					Power Source:	480V SWGR

No.	Load Description	CB		VA--A	VA--B	VA--C		Load Description	CB	No.
		1P20A	>	720					1P20A	
1	R1			949			<	L5		2
		1P20A	>		720				1P20A	
3	R2				1139		<	L6		4
		1P20A	>			540			1P20A	
5	R3					1139	<	L6		6
		1P20A	>	180					1P20A	
7	R4			1329			<	L8		8
		1P20A	>		1139				1P20A	
9	L1				949		<	L9		10
		1P20A	>			190			1P20A	
11	L2					314	<	10		12
		1P20A	>	12					1P20A	
13	Ext. L3			12			<	Spare		14
		1P20A	>		708				1P20A	
15	Emerg. L4				12		<	Spare		16
		1P20A	>						1P20A	
17	Spare					540	<	Ext. R1		18
		1P20A	>						1P20A	
19	Spare						<	Spare		20
		1P20A	>						1P20A	
21	Spare				12		<	Exit Signs		22
		1P20A	>						1P20A	
23	Spare						<	Spare		24
		1P20A	>						1P20A	
25	Spare						<	Spare		26
		1P20A	>						1P20A	
27	Spare						<	Spare		28
		1P20A	>						1P20A	
29	Spare						<	Spare		30

	Ph A	Ph B	Ph C
Total Load -----VA	3202	4679	2723
Total Load -----Amperes	27	39	23
Future Allowance (25%)	7	10	6
Panel Design Amperes	33	49	28

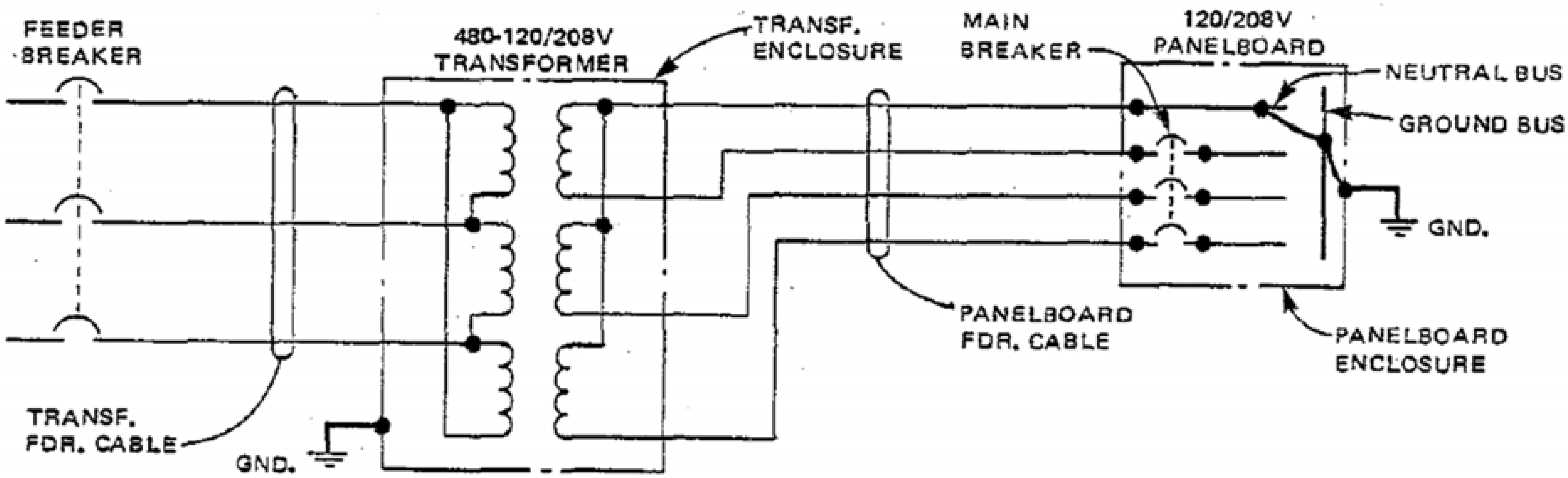
V(l-l)	V (l-n)
208	**120**

PANELBOARD- TRANSFORMER COORDINATION GUIDE



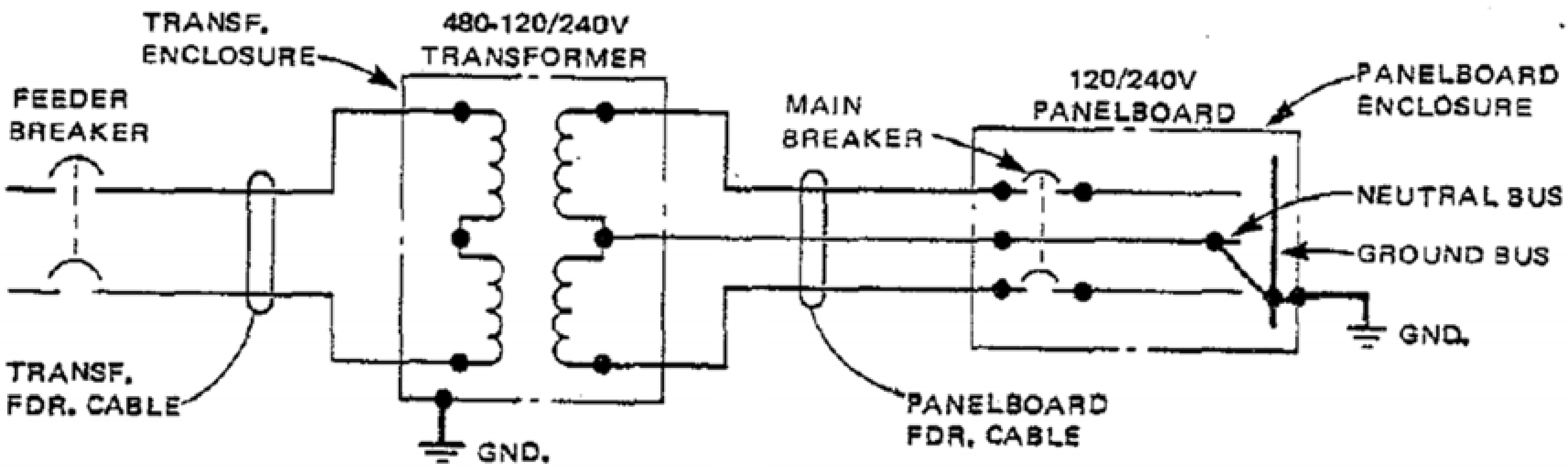
System	Transf Hi Side (Amps)	Transf (kVA)	Transf Low Side (Amps)	Panelboard Main Bus (Amps)
480-120 (1ϕ-2W)	32	15	125	100
	63	30	250	225
	104	50	417	400
	156	75	625	600

PANELBOARD- TRANSFORMER COORDINATION GUIDE



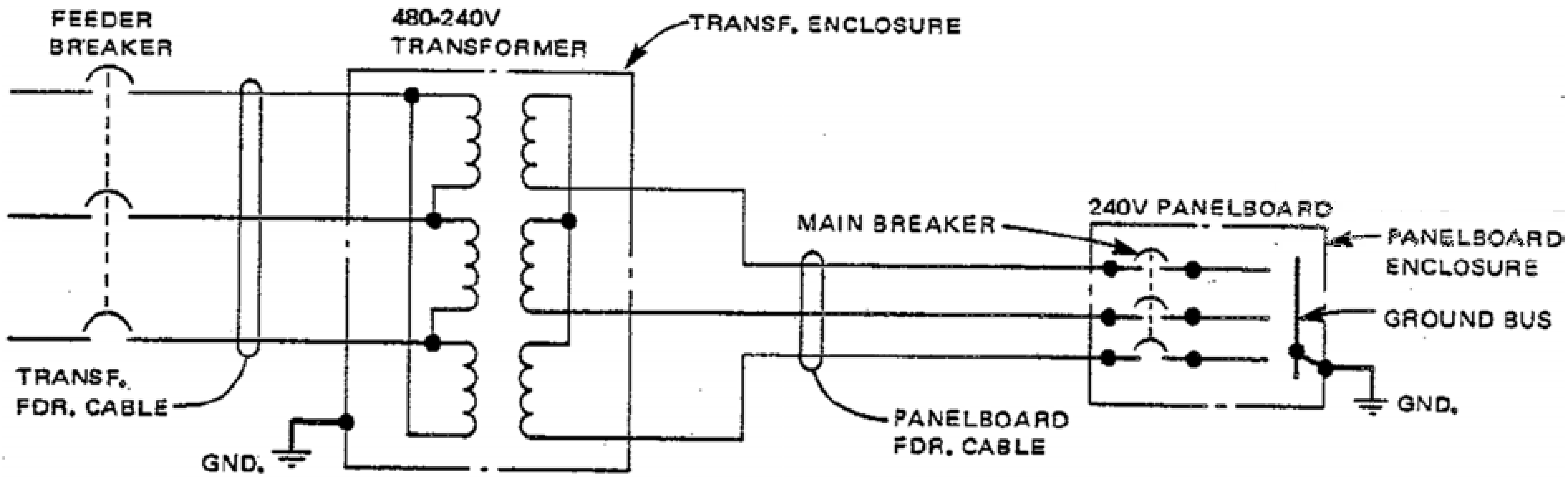
System	Transf Hi Side (Amps)	Transf (kVA)	Transf Low Side (Amps)	Panelboard Main Bus & Main Bkr (Amps)
480-120/208 (3ø-4W)	45	37.5	104	100
	120	100	278	225
	181	150	417	400
	271	225	625	600

PANELBOARD- TRANSFORMER COORDINATION GUIDE



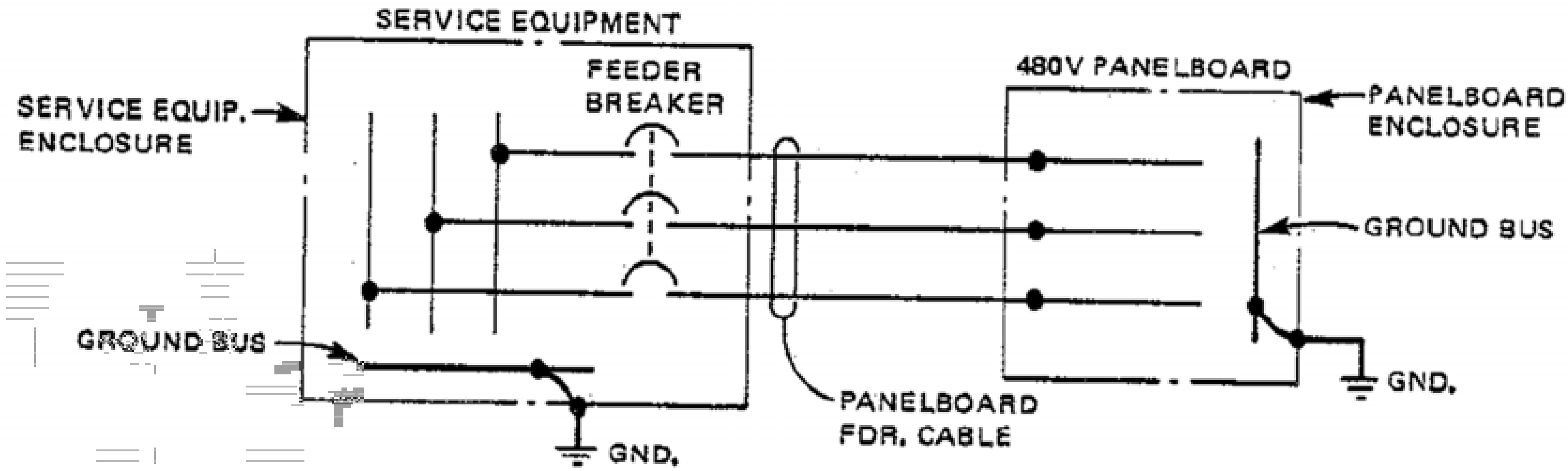
System	Transf Hi Side (Amps)	Transf (kVA)	Transf Low Side (Amps)	Panelboard Main Bus & Main Bkr (Amps)
480-120/240 (1ϕ-3W)	52	25	104	100
	156	75	313	225
	208	100	417	400
	313	150	625	600

PANELBOARD- TRANSFORMER COORDINATION GUIDE



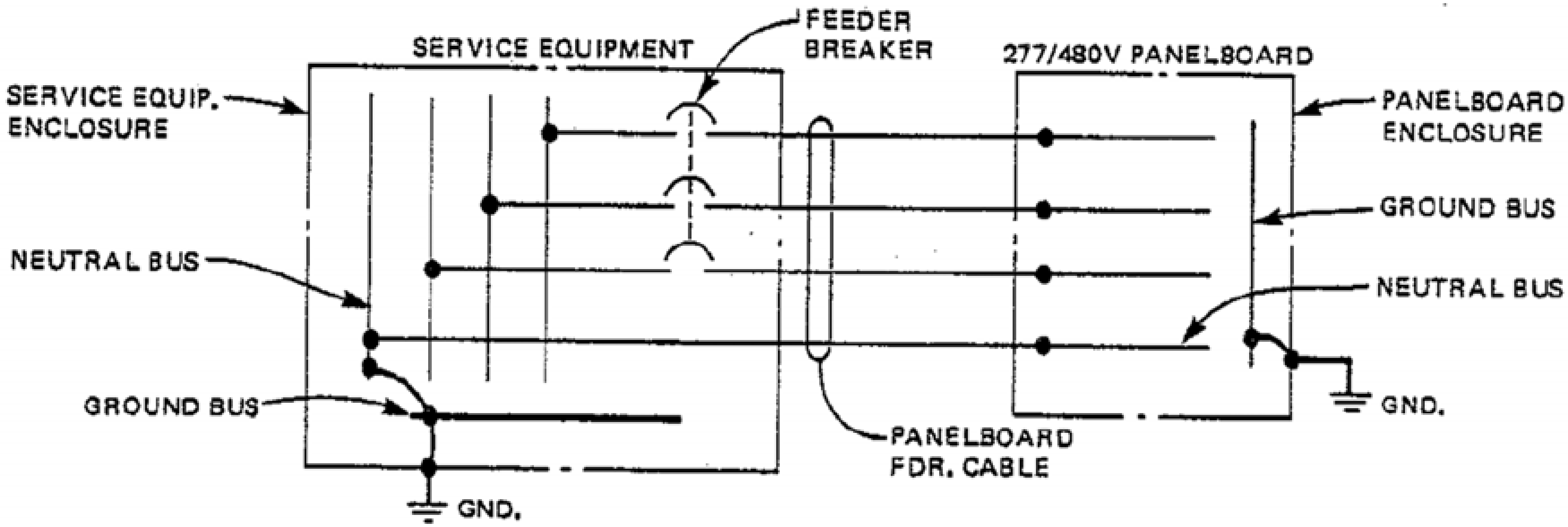
System	Transf Hi Side (Amps)	Transf (kVA)	Transf Low Side (Amps)	Panelboard Main Bus & Main Bkr (Amps)
480-240 (3ϕ-4W)	54	45	108	100
	120	100	241	225
	241	200	482	400
	361	300	723	600

PANELBOARD- TRANSFORMER COORDINATION GUIDE



System	Fdr Bkr Size (Amps)	Panelboard Main Bus (Amps)
480 (3ø-3W)	100	100
	225	225
	400	400
	600	600

PANELBOARD- TRANSFORMER COORDINATION GUIDE

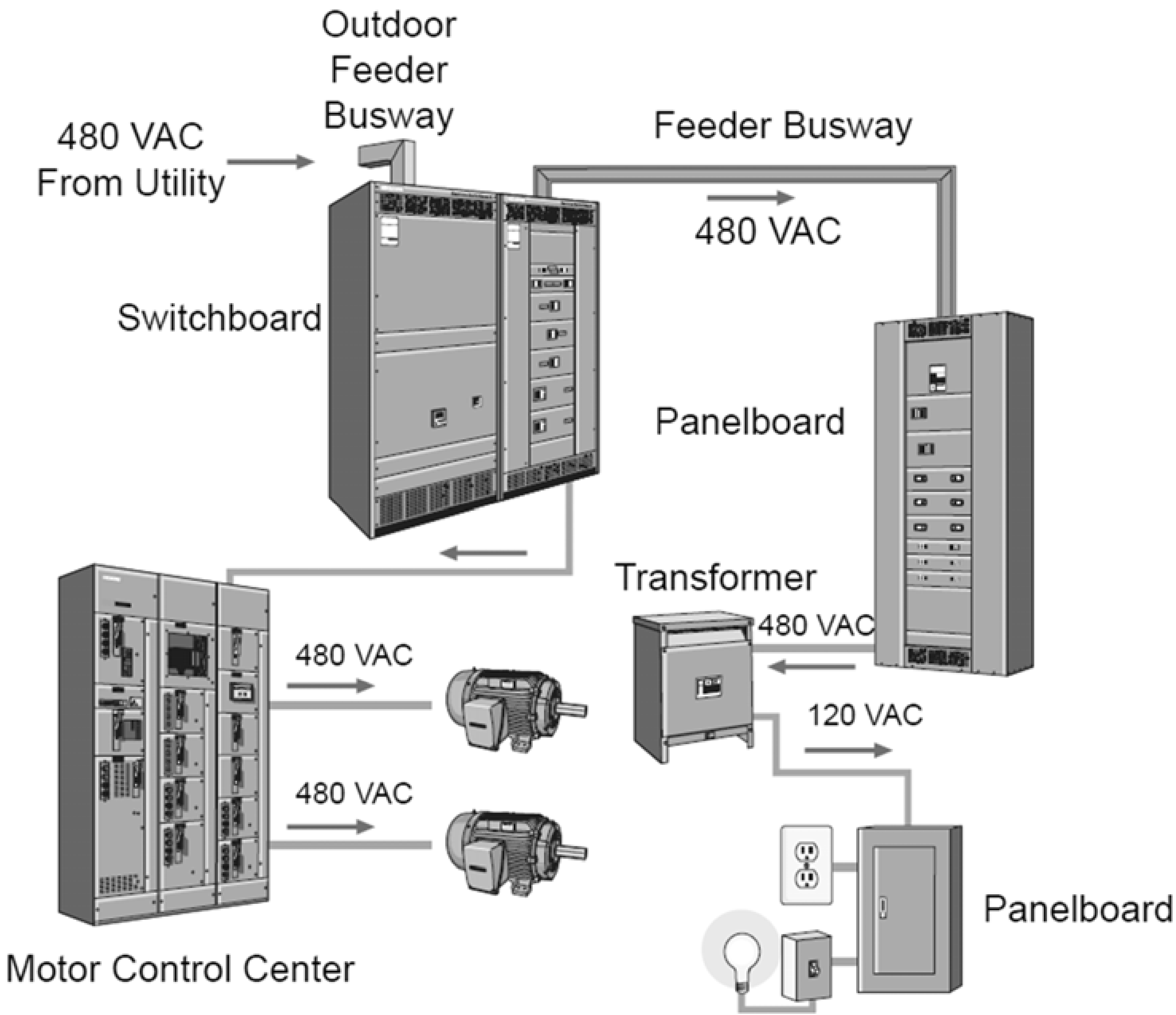


System	Fdr Bkr Size (Amps)	Panelboard Main Bus (Amps)
480 (3ϕ–4W)	100	100
	225	225
	400	400
	600	600

Understanding Power Concepts

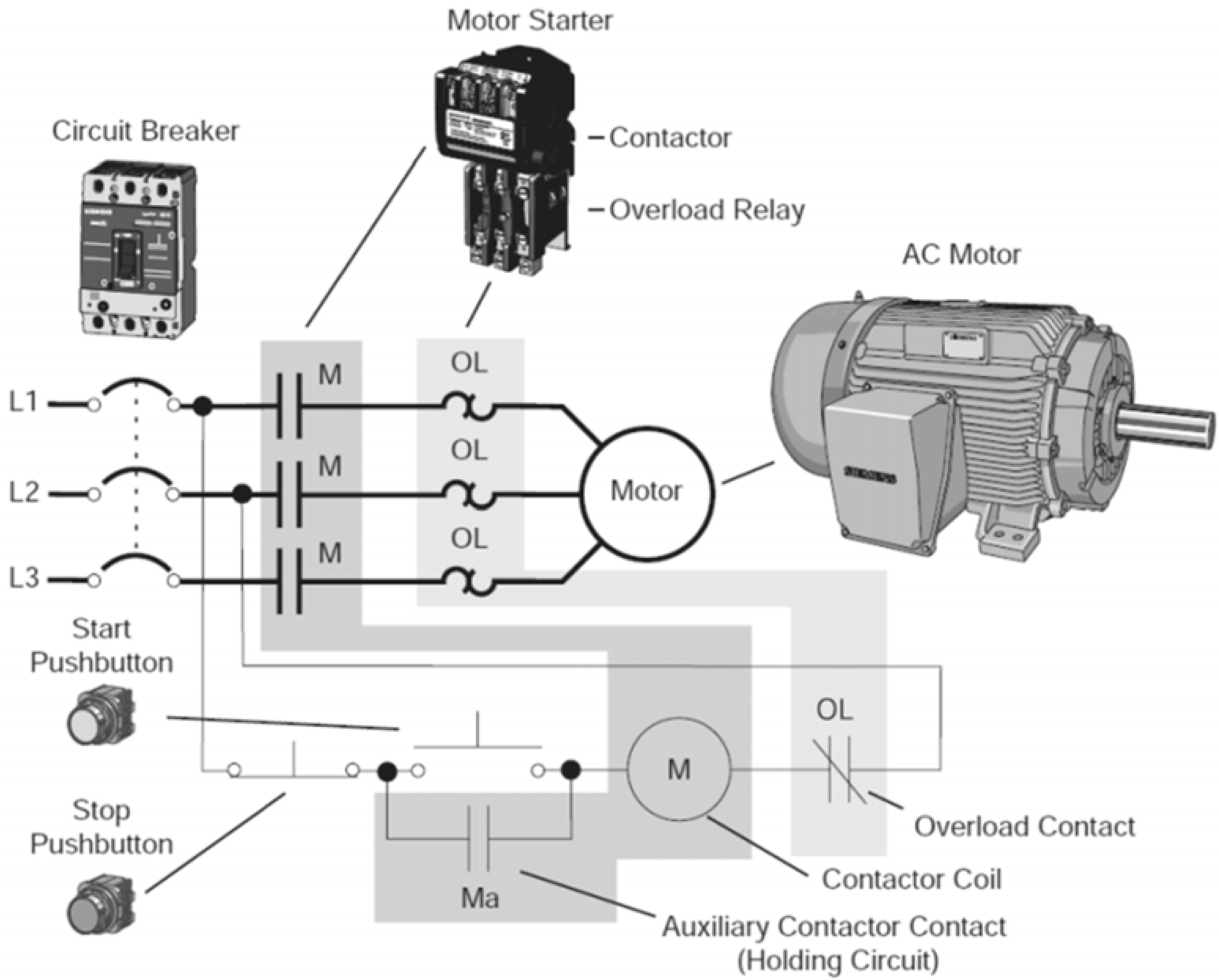
Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- ***<u>MCC</u>***
- DC/UPS Systems

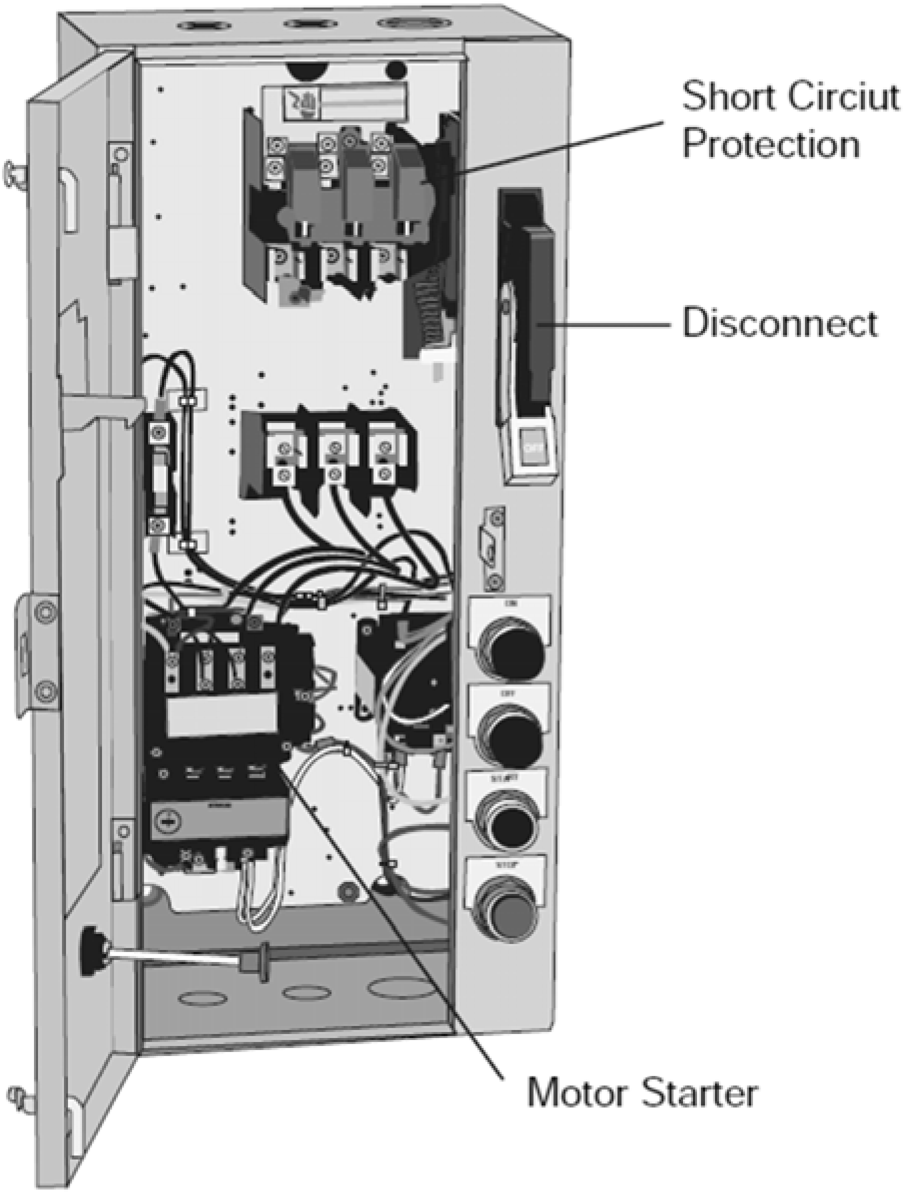

Outdoor
Feeder
Busway
480 VAC
From Utility
Feeder Busway
480 VAC
Switchboard
Panelboard
Transformer
480 VAC
480 VAC
480 VAC
120 VAC
Panelboard
Motor Control Center

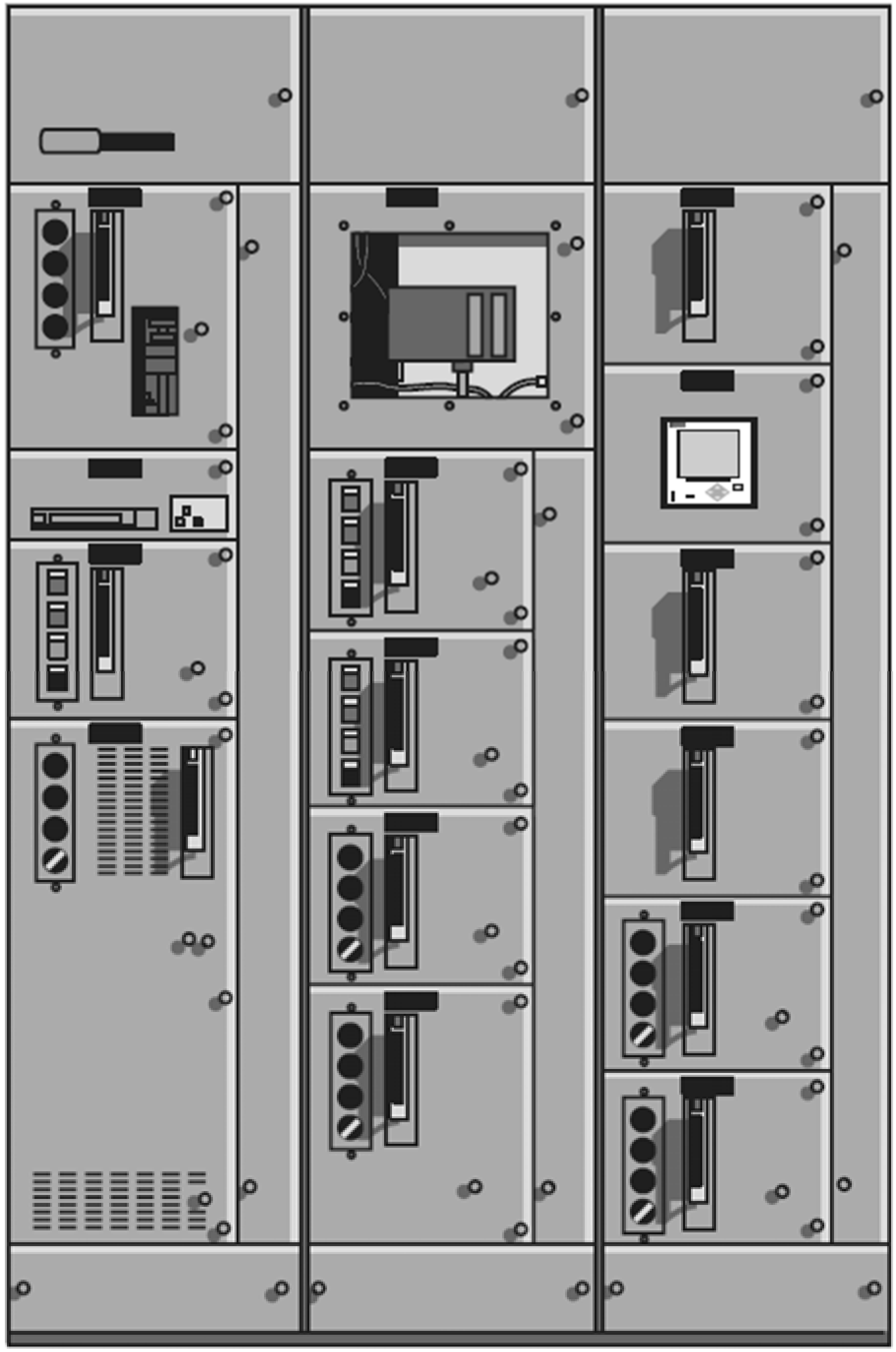
Technical Data

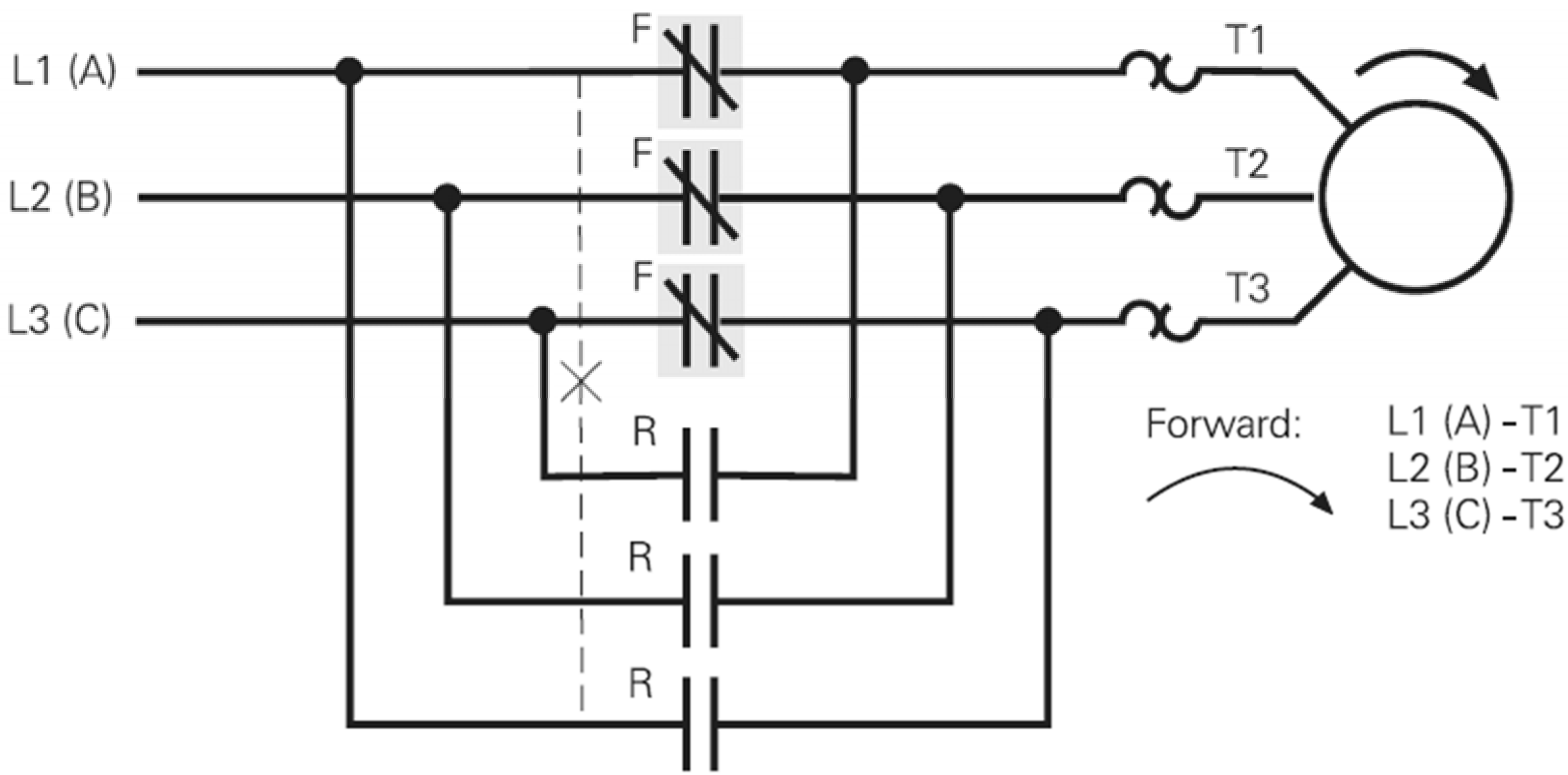
Electrical Ratings	
Available nominal operating voltages	208Vac, 240Vac, 480Vac, 600Vac
Available power system types	3 phase, 3 wire; 3 phase, 4 wire
Frequency	60 Hz
Voltage tolerance	+/-10%
Frequency tolerance	+/-1%
Short circuit current withstand, 480Vac	42KA, 65KA, 100KA[1]
Short circuit current withstand, 600Vac	25KA, 42KA, 65KA[1]
Continuous Current Ratings	
Horizontal main bus	800A, 1200A, 1600A, 2000A [2], 2500A, 3200A [3], 4000A [3]
Vertical distribution bus	800A, 1600A
Neutral bus (horizontal)	800A, 1200A, 1600A
Neutral bus (vertical)	800A
Ground bus	400A
Seismic Ratings/Testing	
	IBC2006, CBC 2007, AC156
	ASCE/SEI 7-05



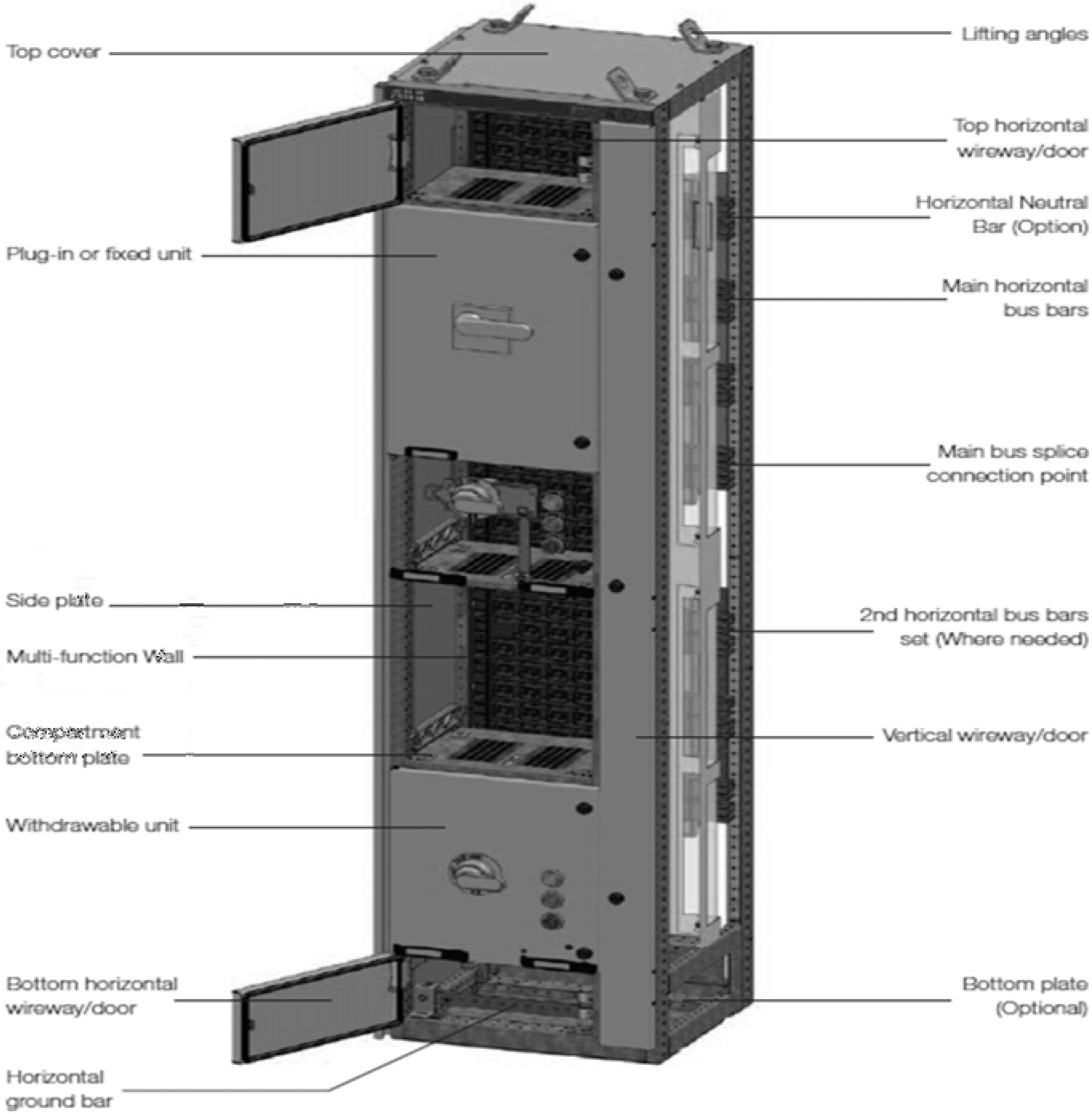
Motor Starter
Contactor
Overload Relay
Circuit Breaker
AC Motor
L1
L2
L3
M
M
M
OL
OL
OL
Motor
Start
Pushbutton
Stop
Pushbutton
M
OL
Ma
Overload Contact
Contactor Coil
Auxiliary Contactor Contact
(Holding Circuit)


Short Circiut
Protection
Disconnect
Motor Starter

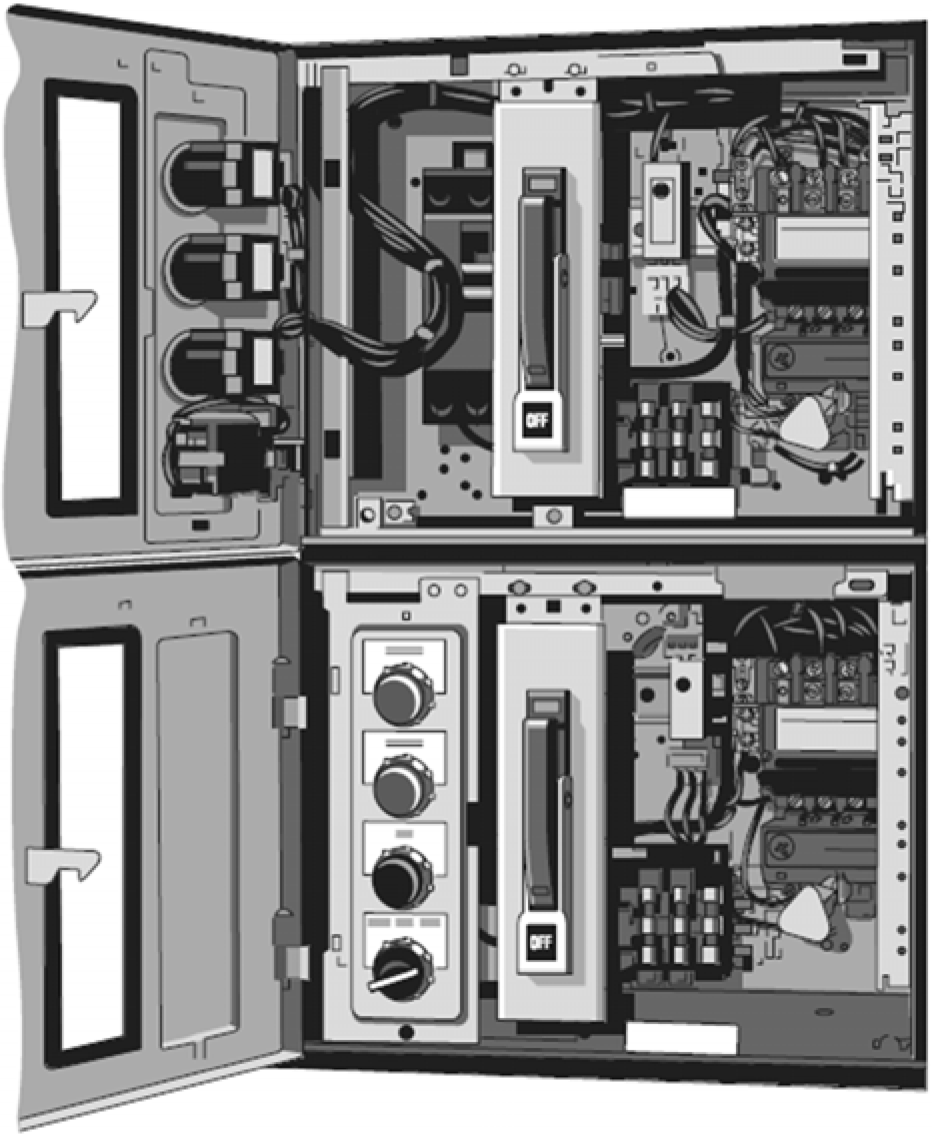



L1 (A)
L2 (B)
L3 (C)
F
F
F
R
R
R
T1
T2
T3
Forward:
L1 (A) - T1
L2 (B) - T2
L3 (C) - T3

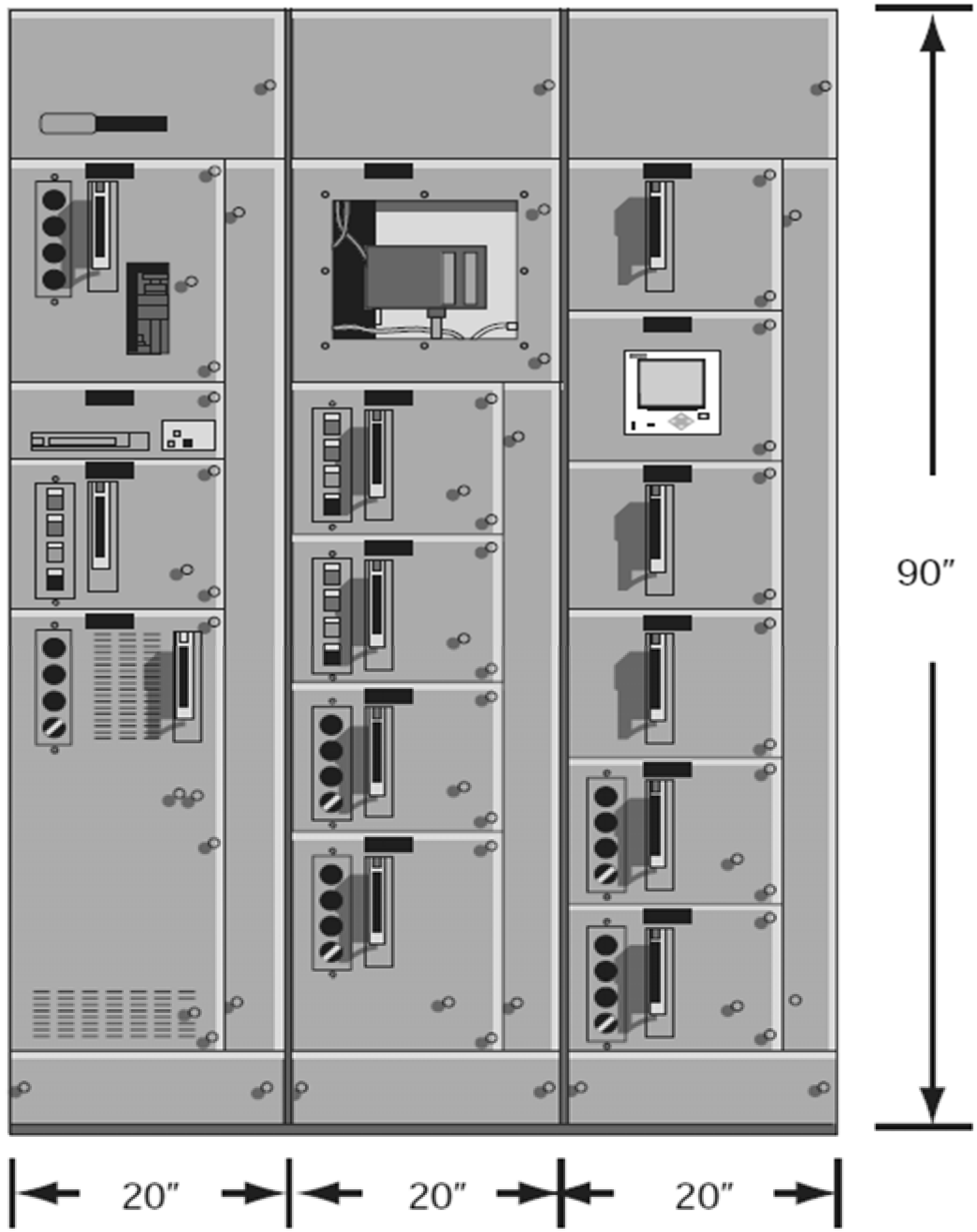
- FVNR - Full-Voltage, Non-Reversing
- FVR - Full-Voltage, Reversing
- 2S1W - Two-Speed, One Winding, Reconnectable Consequent Pole Unit
- 2S2W - Two-Speed, Two Winding
- PW - Full-Voltage, Part Winding
- RVAT - Reduced-Voltage Auto-Transformer (Closed Transition)
- YD - Wye Delta (Open or Closed Transition)
- RVSS - Reduced-Voltage Solid State (Soft Starter)
- VFD - Variable Frequency Drive



Top cover
Lifting angles
Top horizontal wireway/door
Horizontal Neutral Bar (Option)
Plug-in or fixed unit
Main horizontal bus bars
Main bus splice connection point
Side plate
2nd horizontal bus bars set (Where needed)
Multi-function Wall
Compartment bottom plate
Vertical wireway/door
Withdrawable unit
Bottom horizontal wireway/door
Bottom plate (Optional)
Horizontal ground bar



Combination Motor Control Units

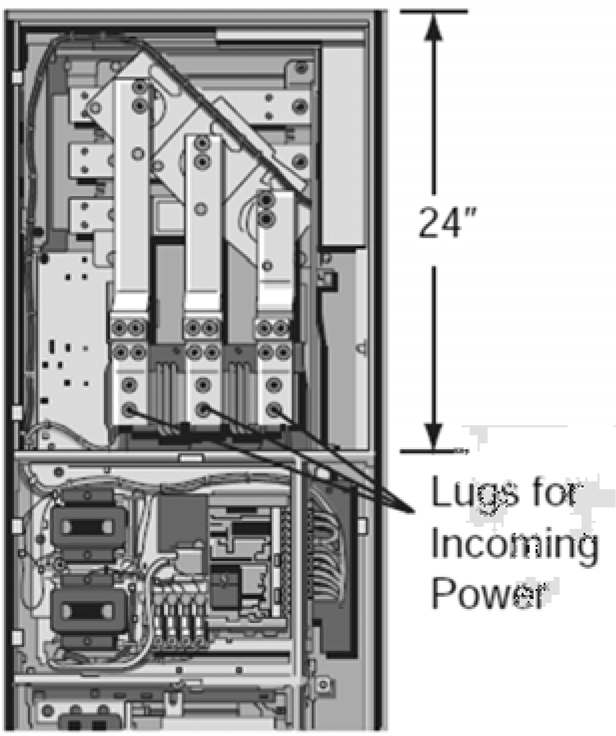


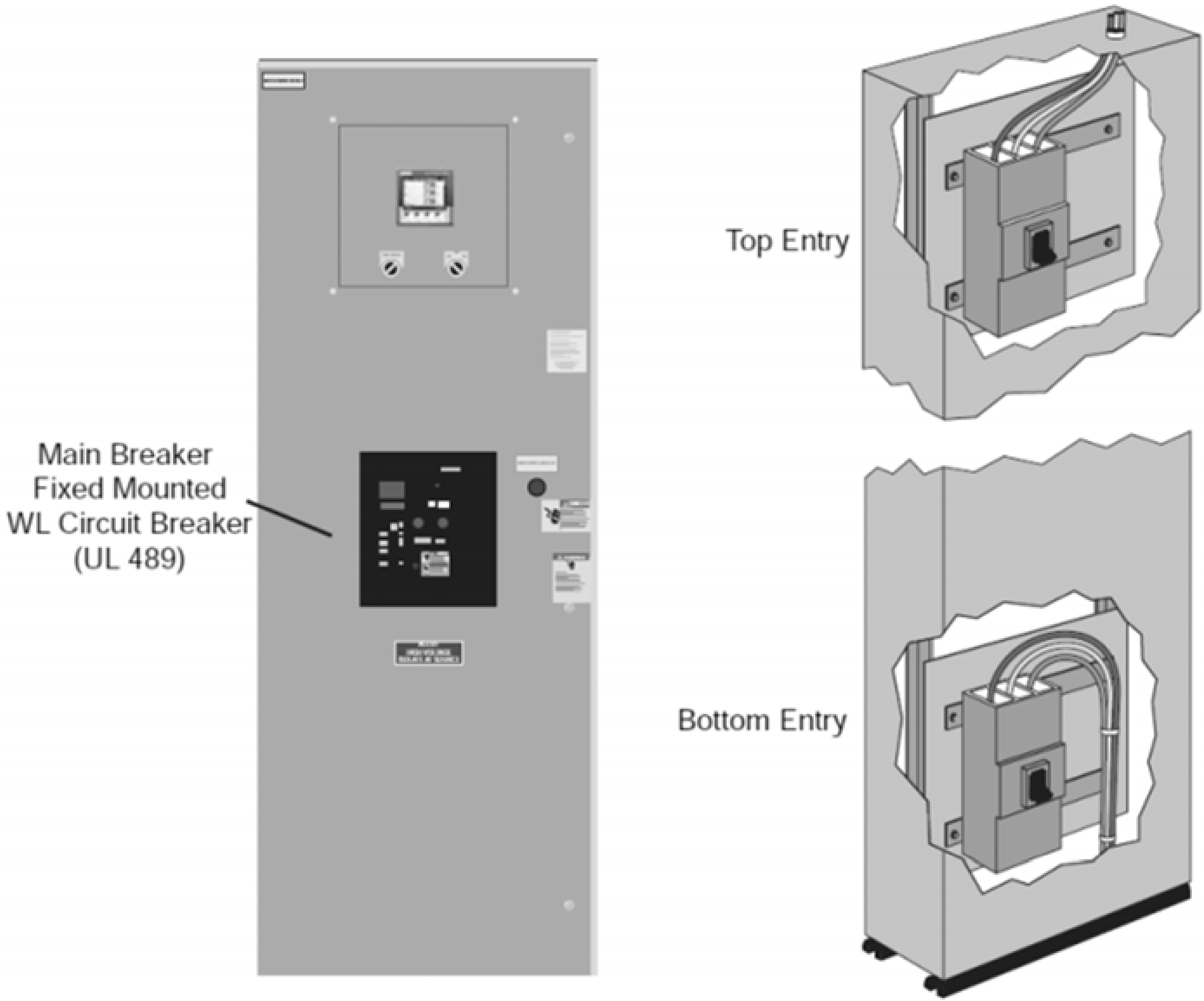
Three Vertical Sections

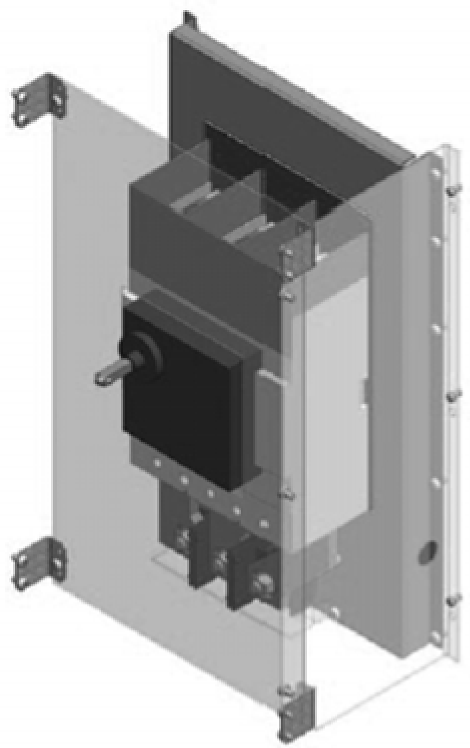
NEMA standard 250 and UL publications 50 and 508 provide similar enclosure type definitions. The following enclosures types are available for tiastar motor control centers.

- Type 1 - Standard - Indoor
- Type 1A - Gasket Front - Indoor
- Type 2 - Drip-Proof - Indoor
- Type 12 - Dust Tight - Indoor
- Type 3R - Rainproof - Outdoor

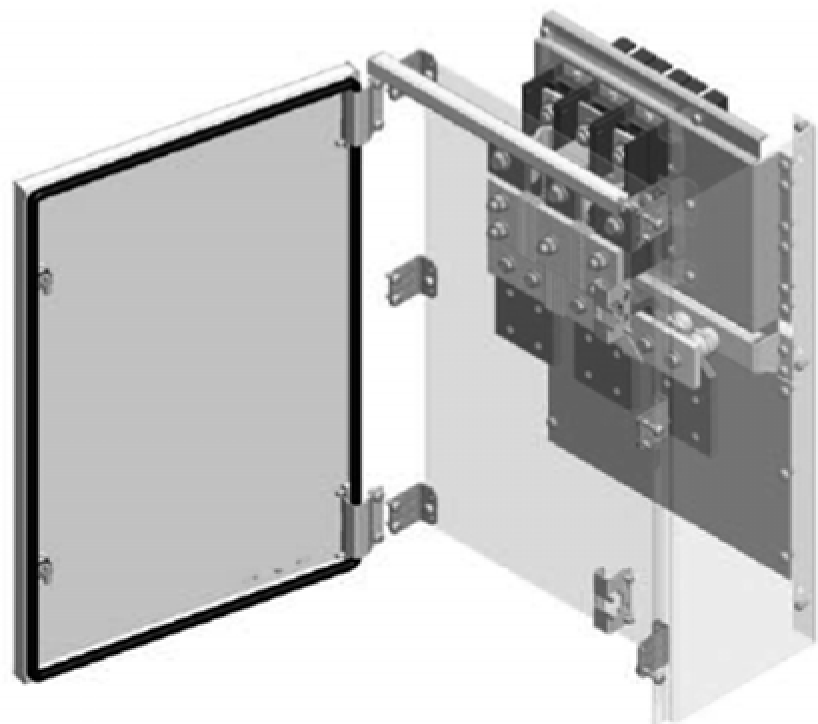
When using **main lugs,** the amount of vertical space required varies with the amperage rating and the bus bracing. When the main lugs are located on the top, as in the following illustration, additional vertical space is needed at the top. In this example, main lugs rated for 600 amps are located on the top of the MCC, and 24" of vertical space is required. A motor control center can also have the lugs located at the bottom.




Main Breaker
Fixed Mounted
WL Circuit Breaker
(UL 489)
Top Entry
Bottom Entry

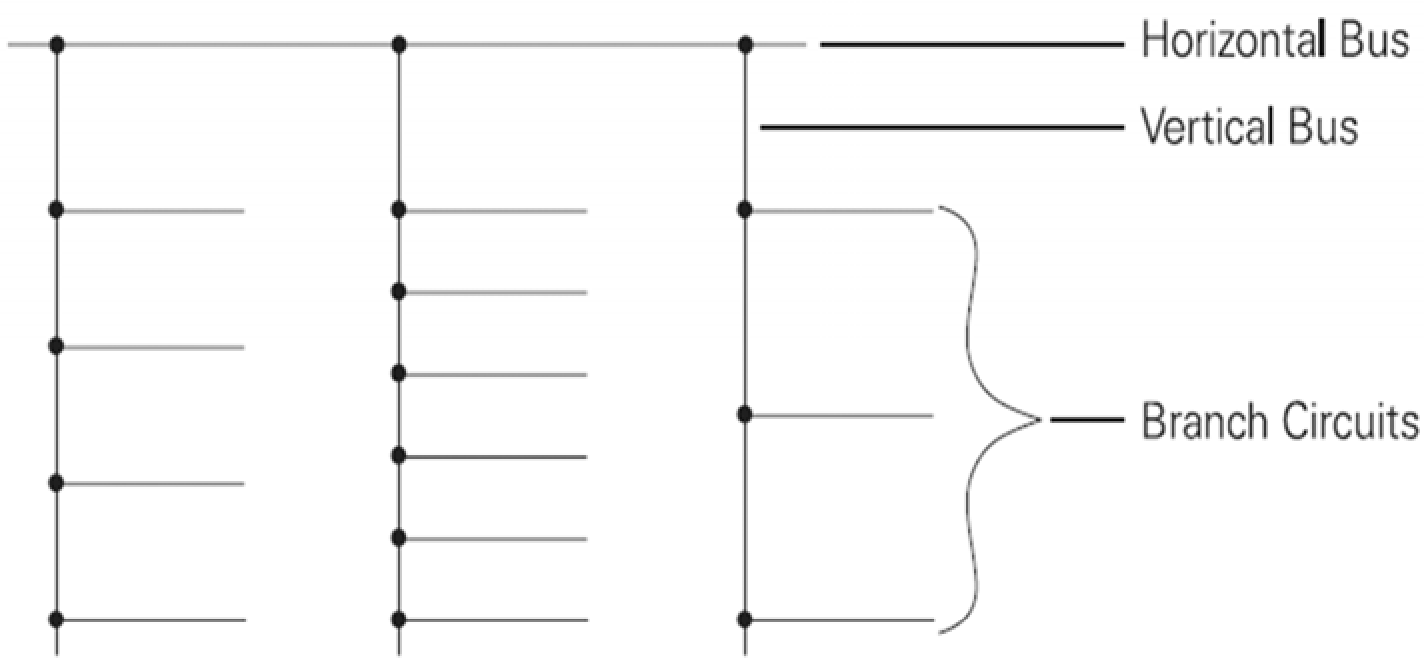


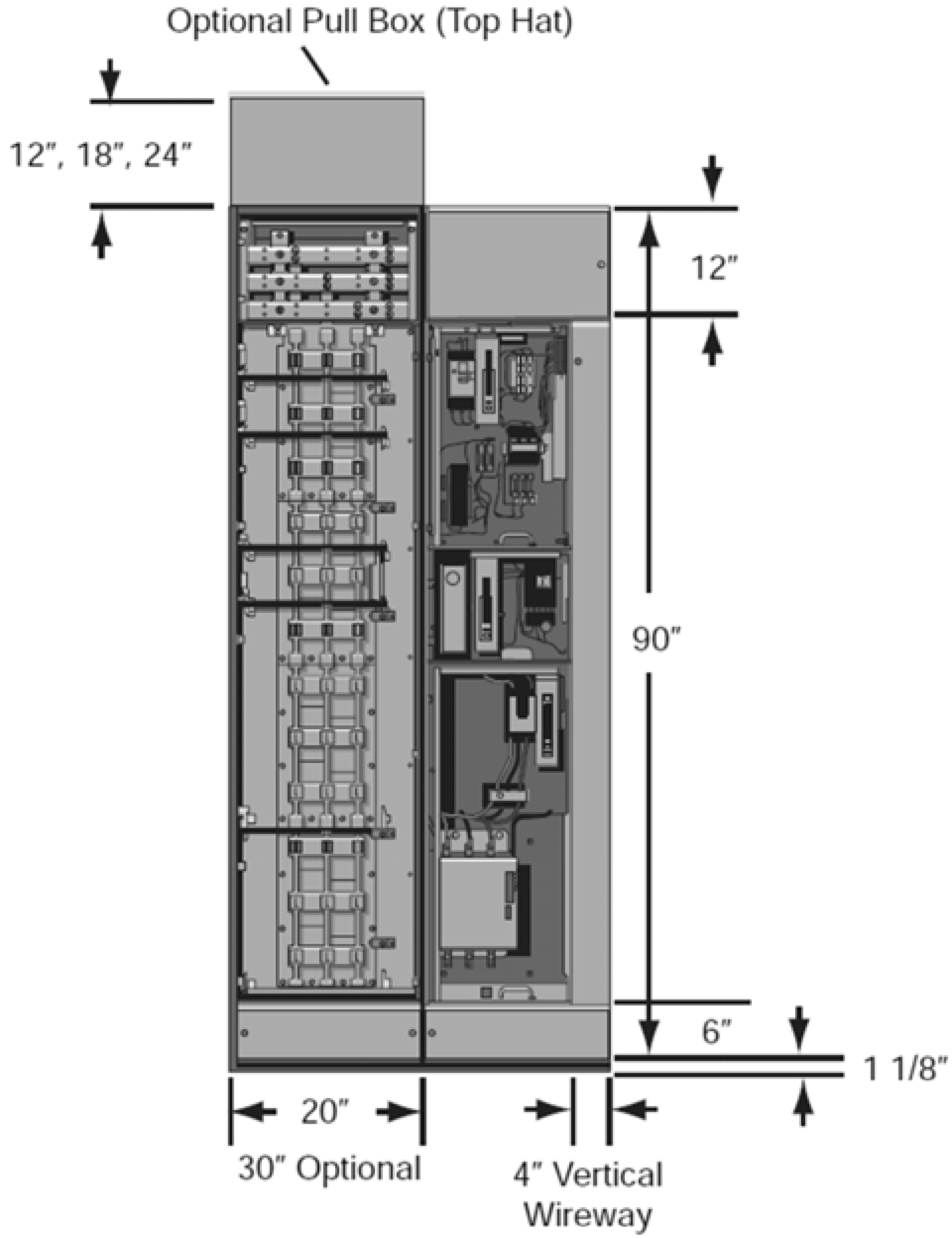
Plug-in Circuit Breaker



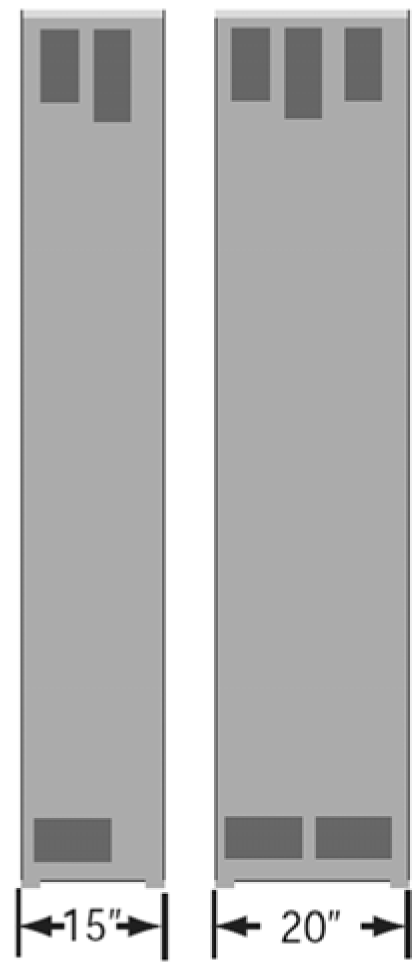
Plug-in Main Lug Unit

A **bus** is a conductor that serves as a common connection for two or more circuits. It is represented schematically by a straight line with a number of connections made to it.





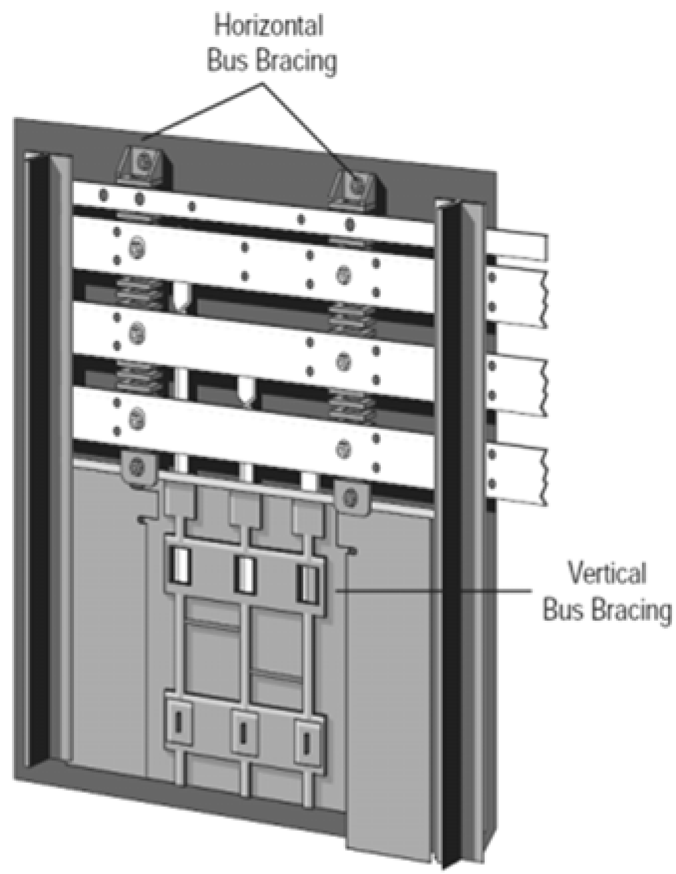
Front View

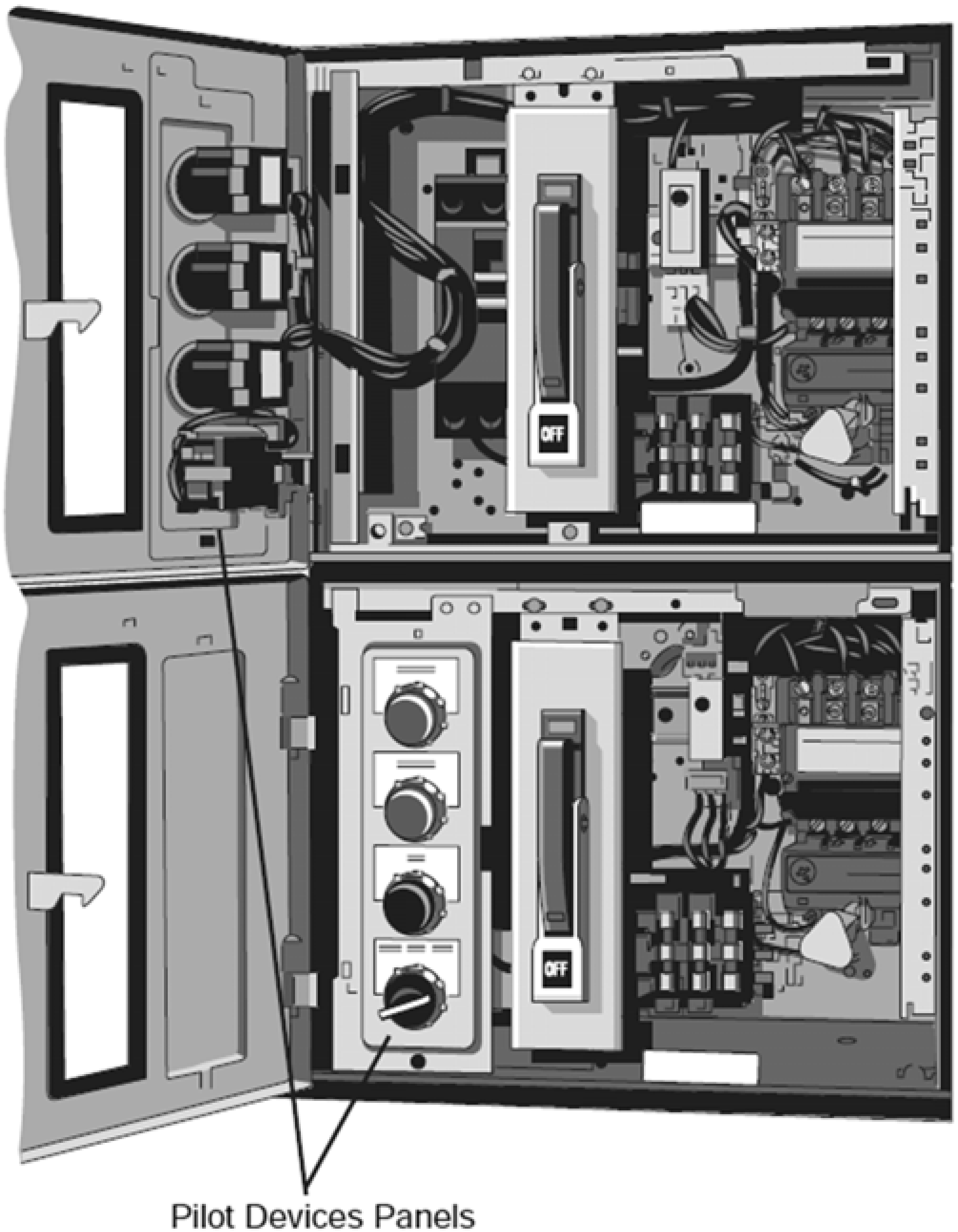


Side View

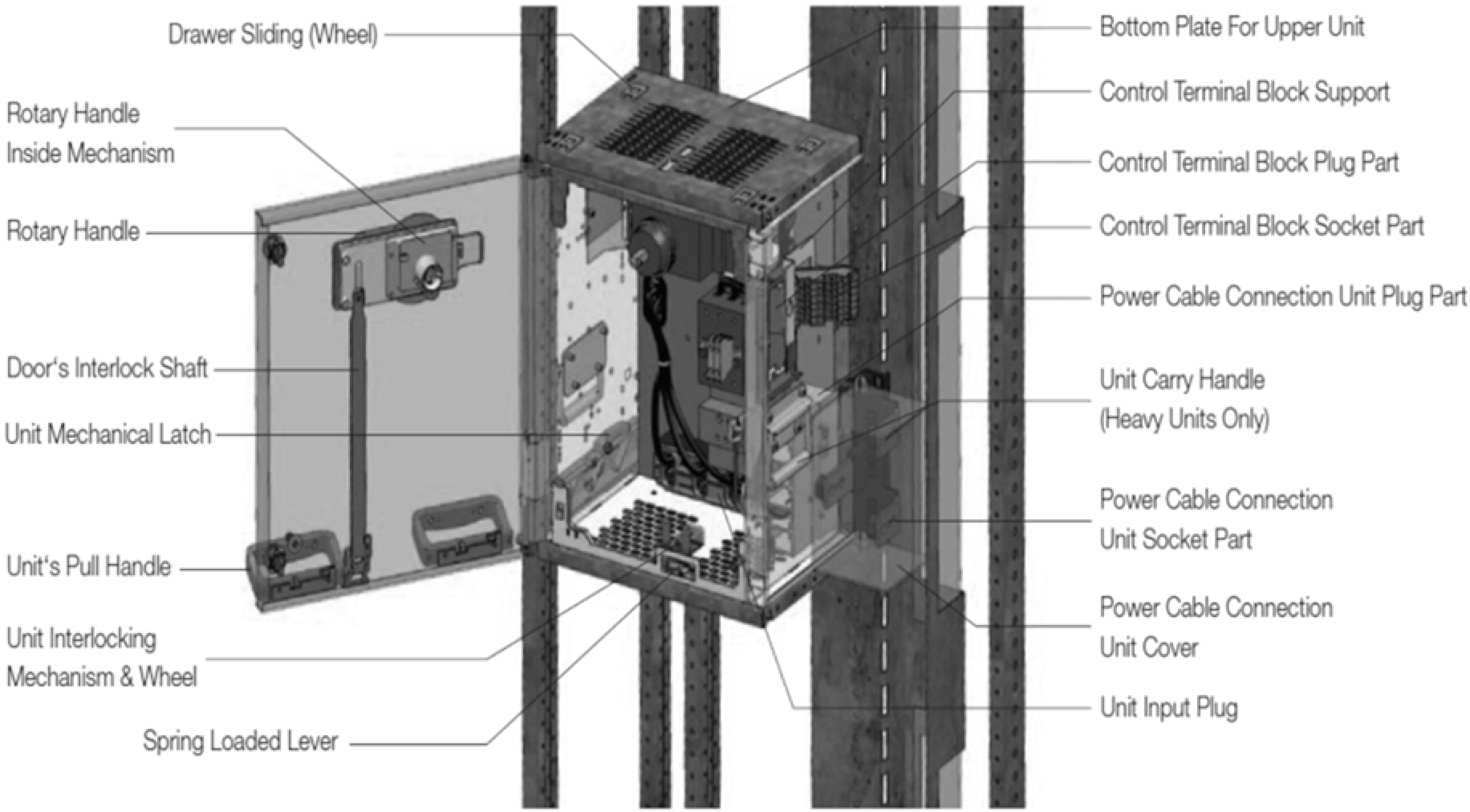
- Bus bars must be braced to withstand this potential current. The bus bars used in motor control centers are braced for 42 kA interrupting rating with optional bracing available to 100 kA.

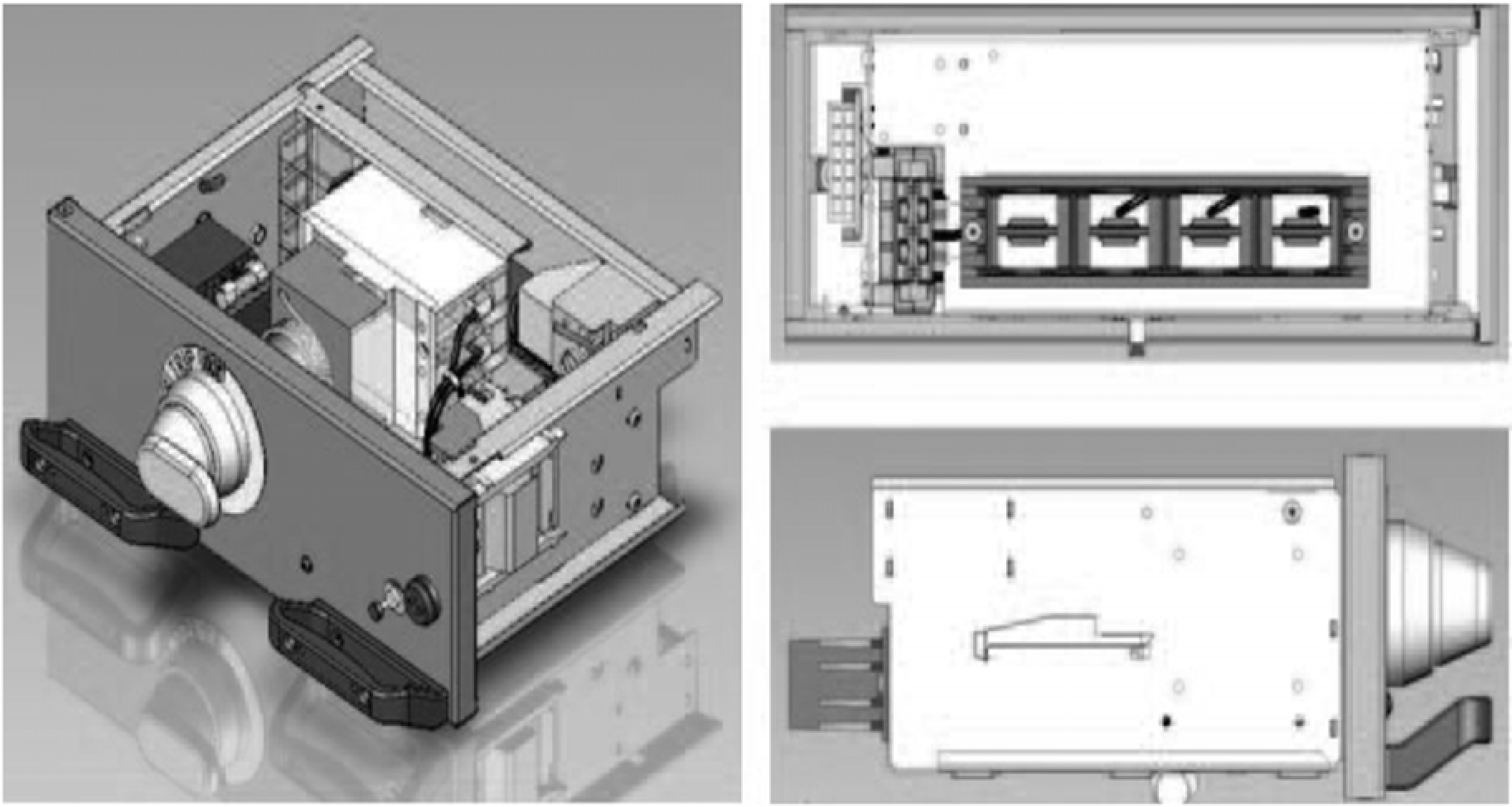
- Verify with the manufacturer on available kA rating.




OFF
OFF
Pilot Devices Panels

Withdrawal-able Buckets

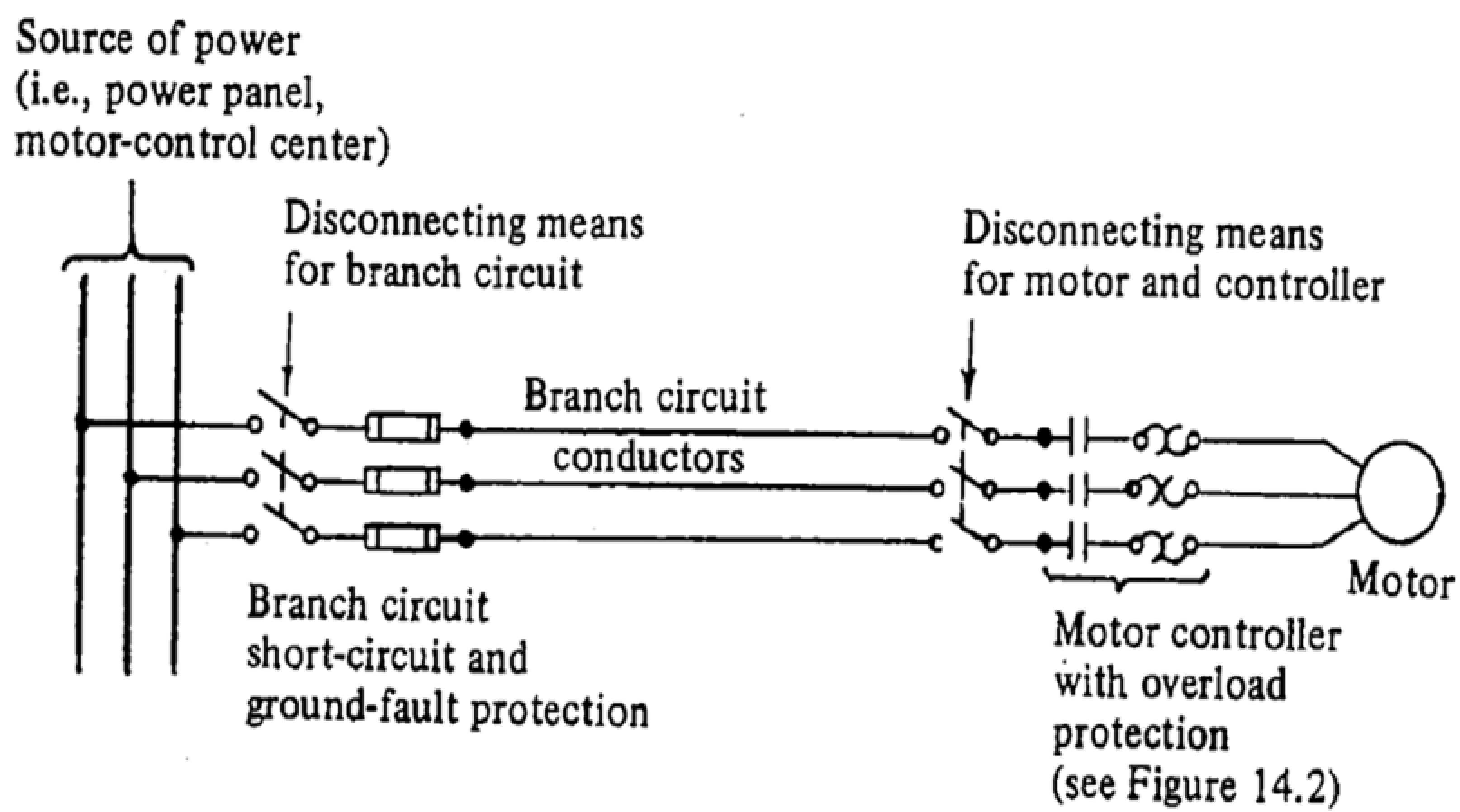




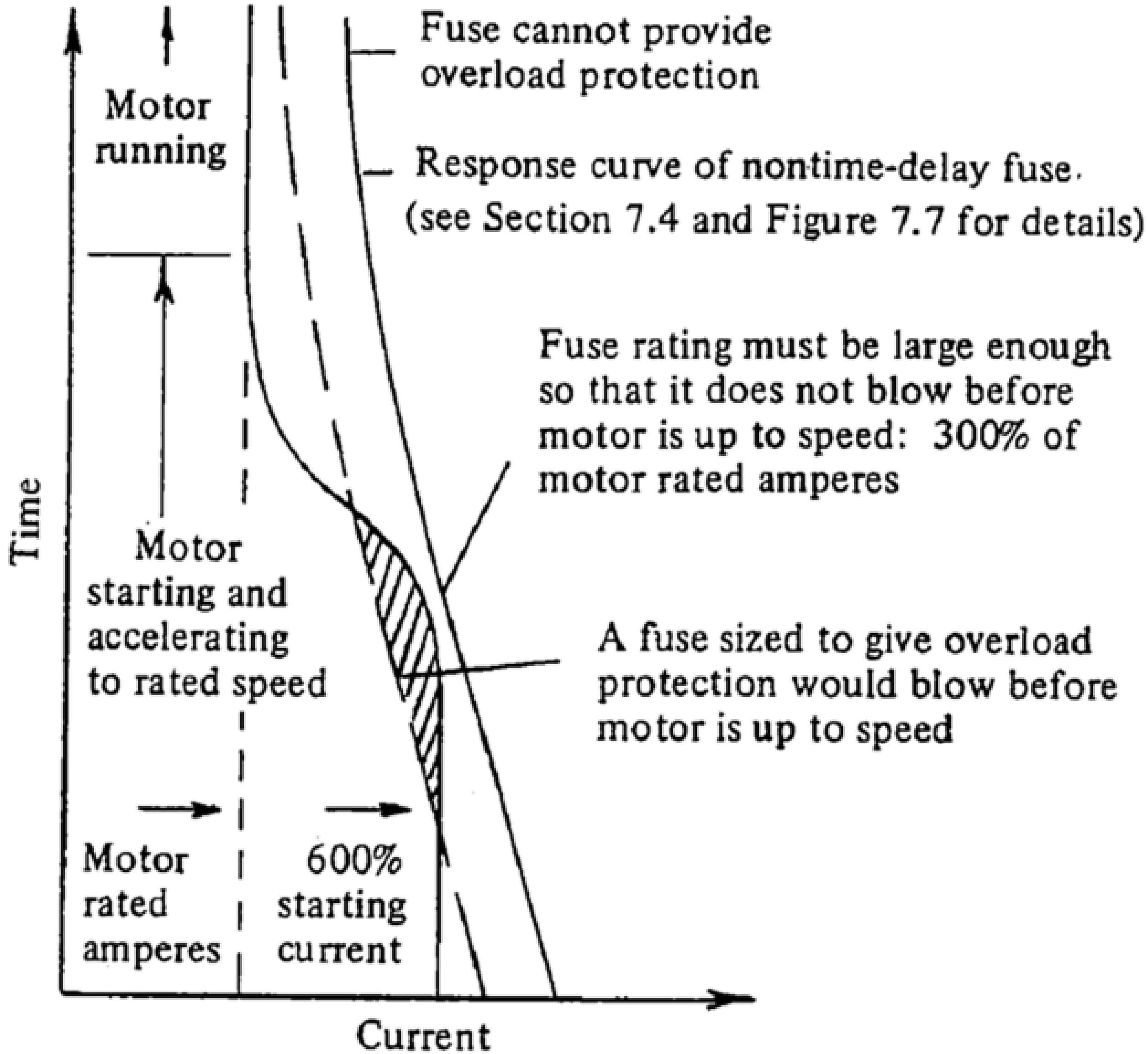
6E Withdrawable Motor Starter

Variable Speed Drive

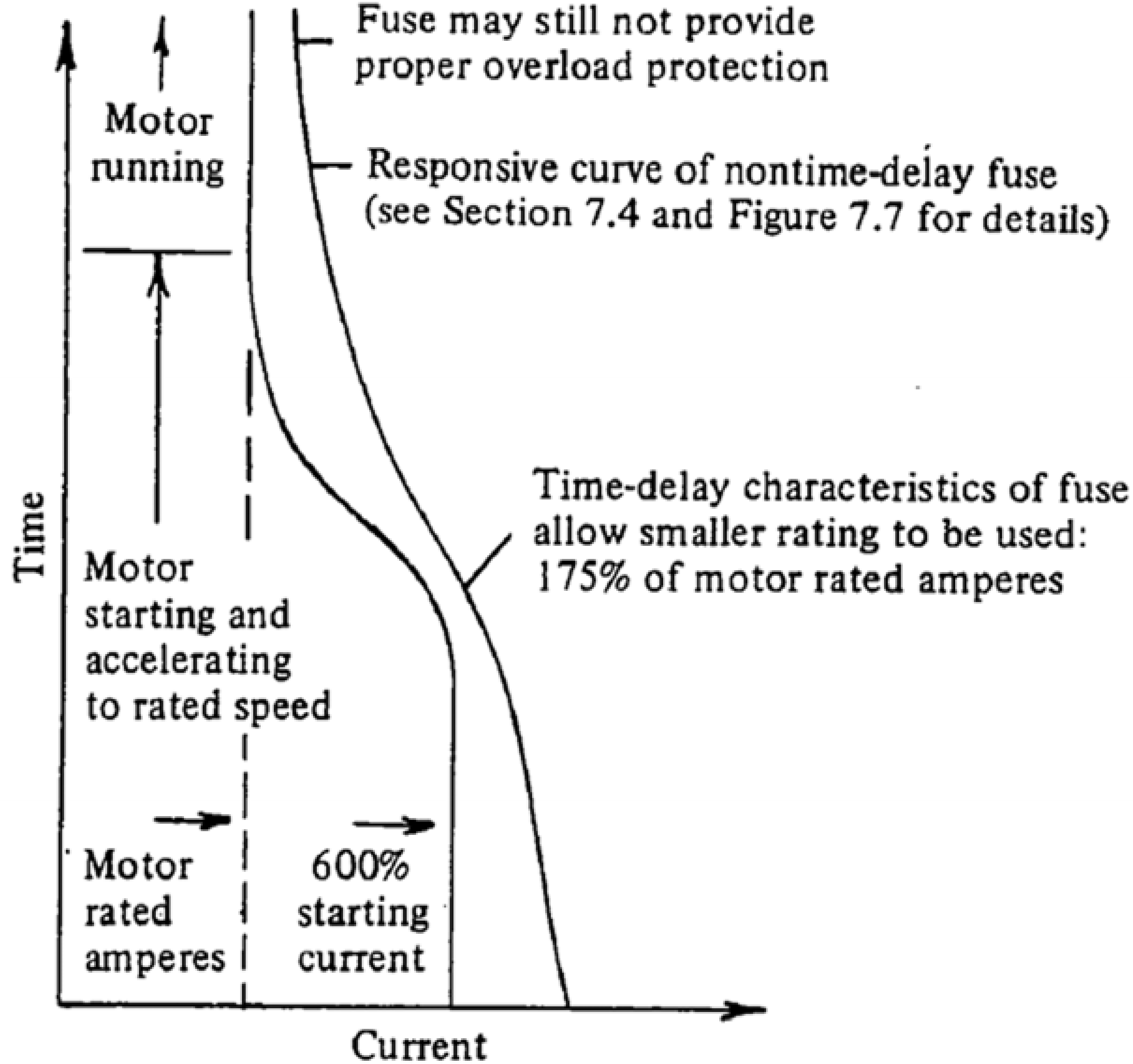
Solid State Reduced Voltage Starter (SSRV)



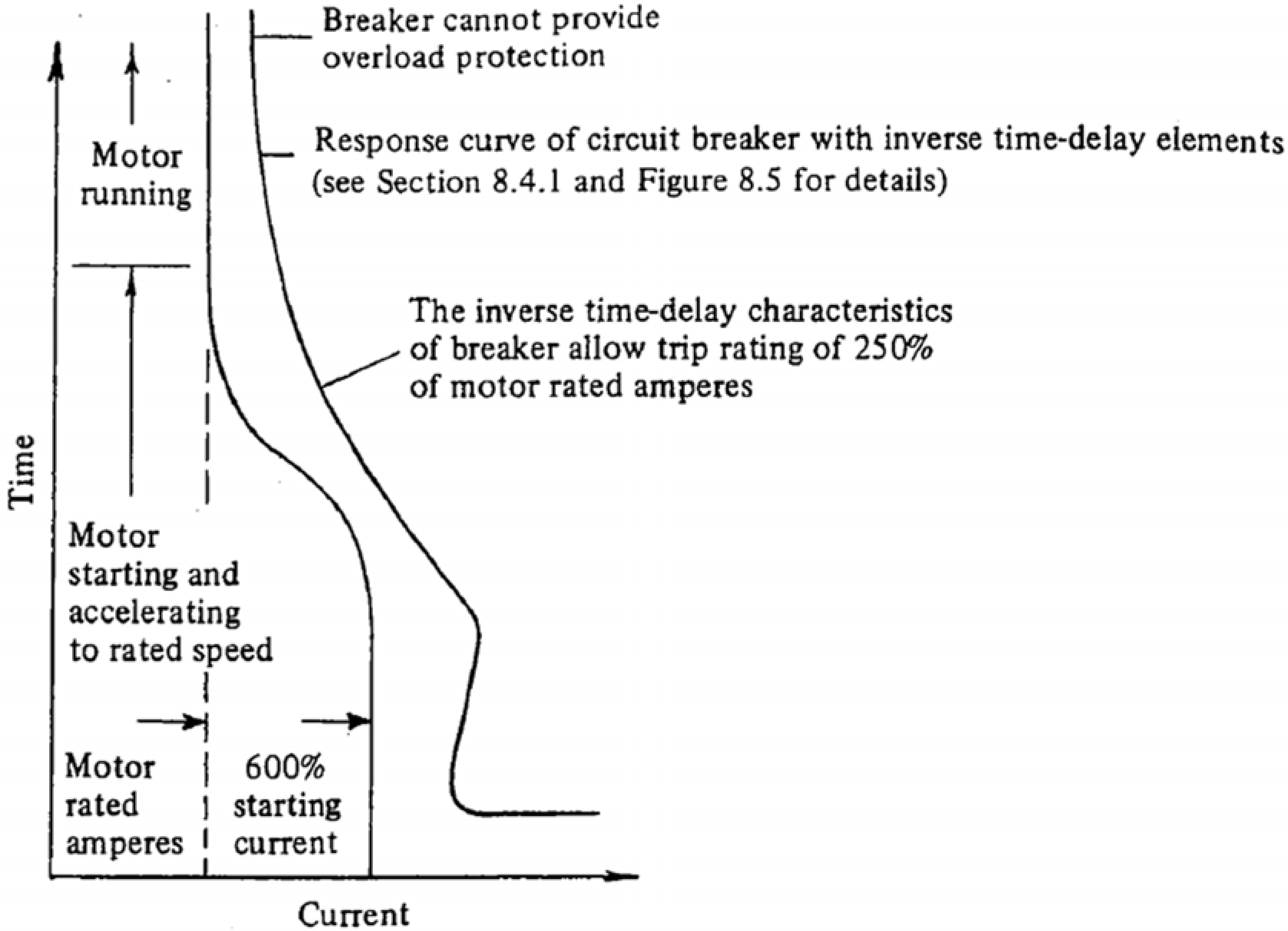
(a) Three-line diagram



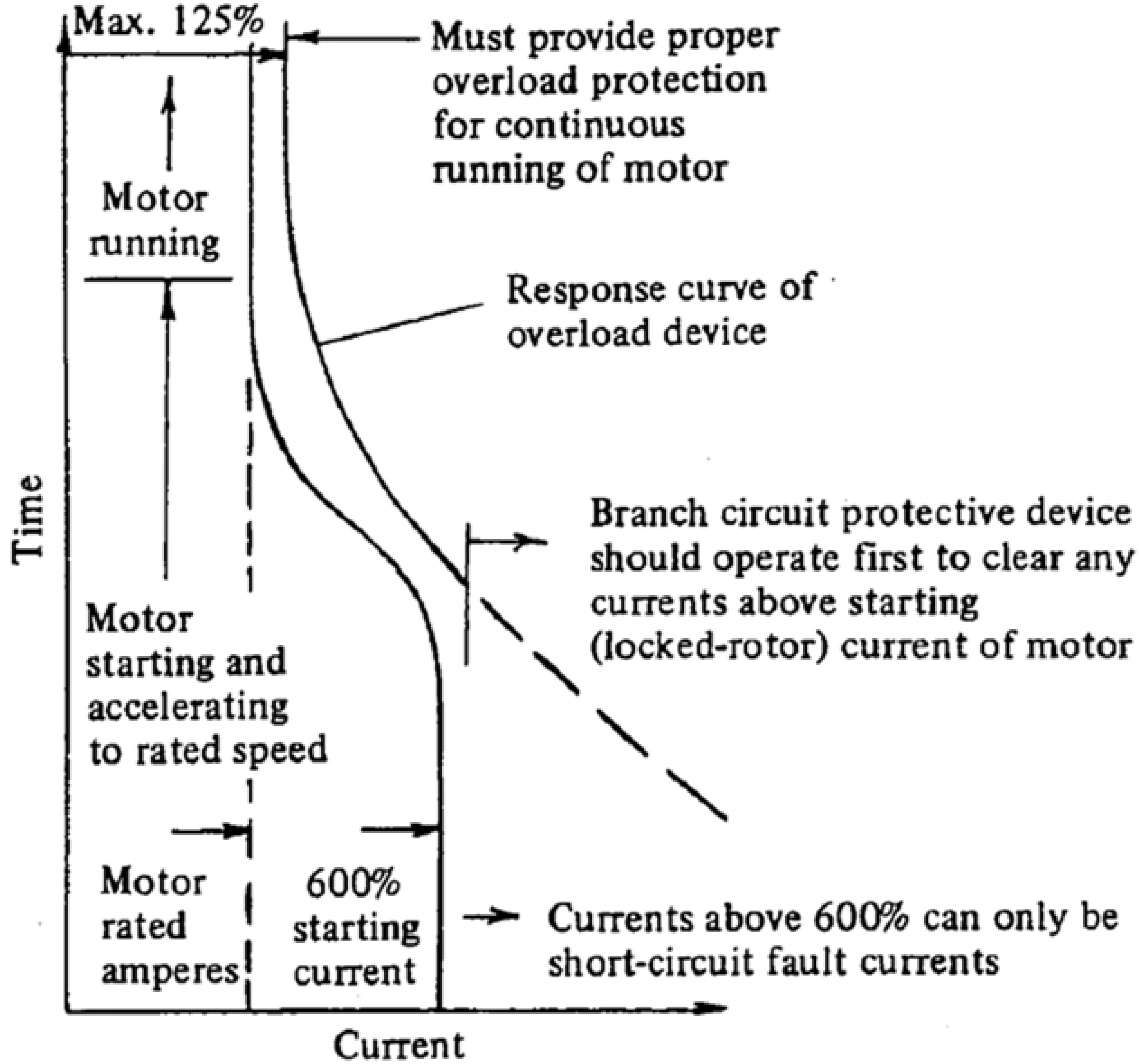
(a) Motor starting using nontime-delay fuses



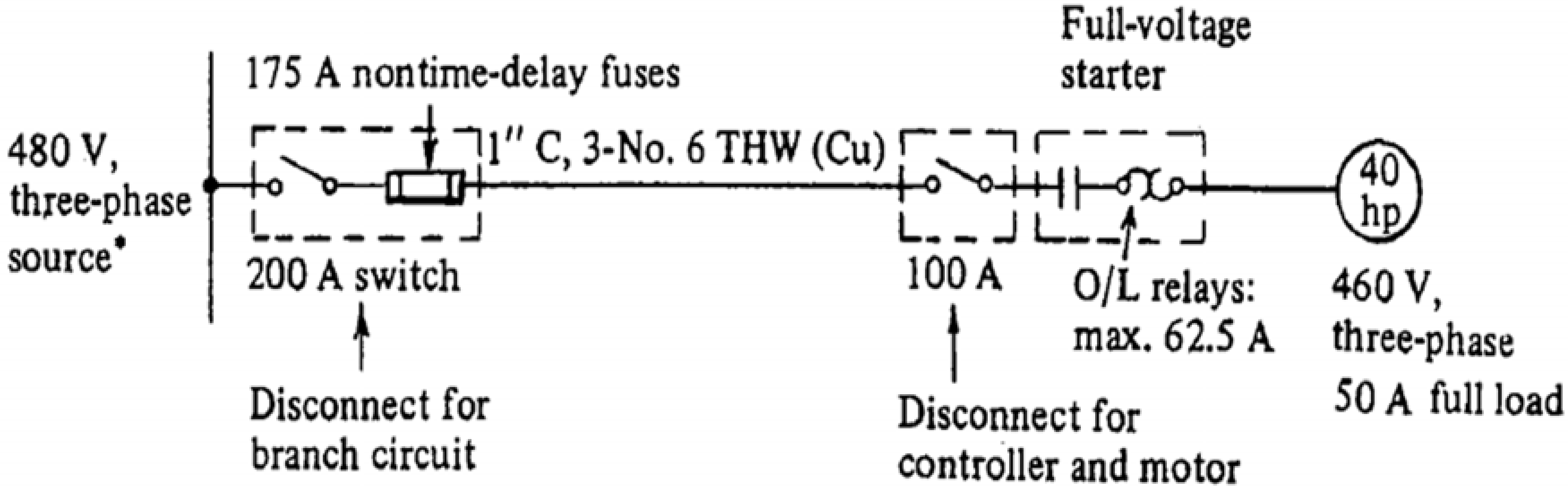
(b) Motor starting using time-delay fuses



Breaker cannot provide overload protection
Response curve of circuit breaker with inverse time-delay elements (see Section 8.4.1 and Figure 8.5 for details)
The inverse time-delay characteristics of breaker allow trip rating of 250% of motor rated amperes
Motor running
Time
Motor starting and accelerating to rated speed
Motor rated amperes
600% starting current
Current


Max. 125%
Must provide proper overload protection for continuous running of motor
Motor running
Response curve of overload device
Time
Branch circuit protective device should operate first to clear any currents above starting (locked-rotor) current of motor
Motor starting and accelerating to rated speed
Motor rated amperes
600% starting current
Currents above 600% can only be short-circuit fault currents
Current

Low Voltage MCC



175 A nontime-delay fuses
Full-voltage
starter
480 V,
three-phase
source*
1" C, 3-No. 6 THW (Cu)
40
hp
200 A switch
100 A
O/L relays:
max. 62.5 A
460 V,
three-phase
50 A full load
Disconnect for
branch circuit
Disconnect for
controller and motor

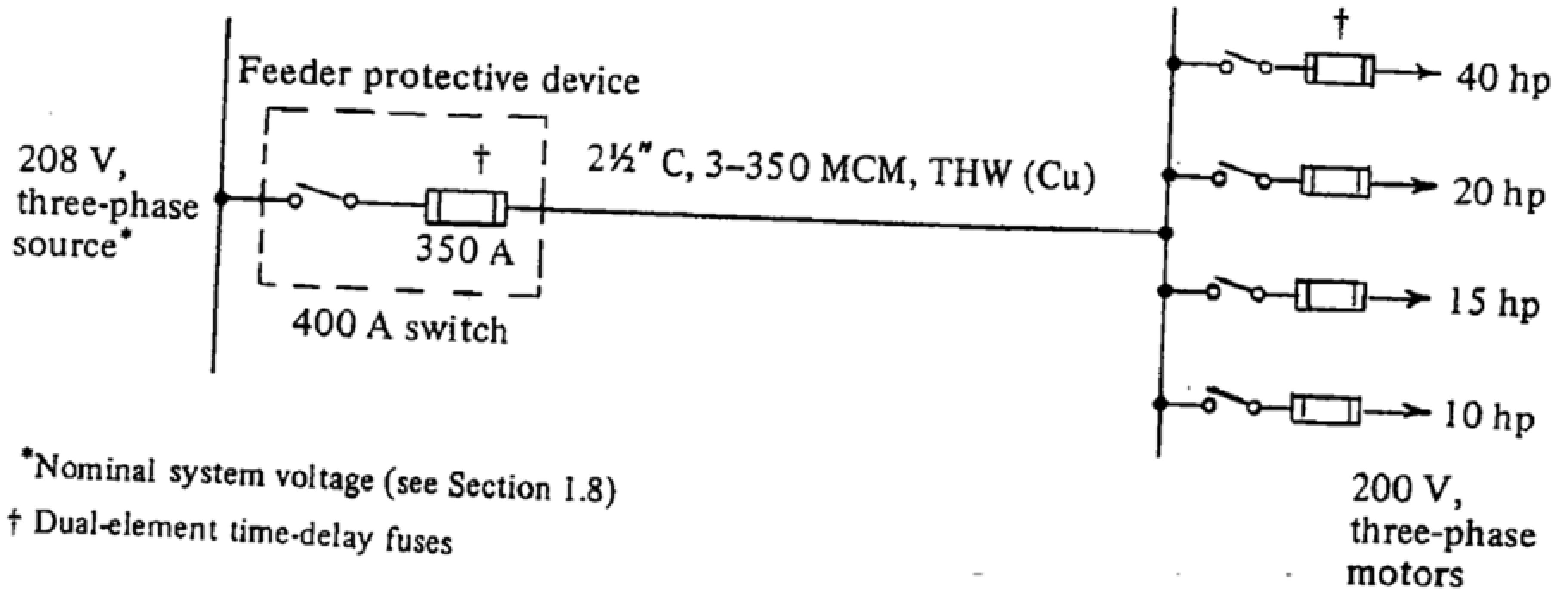
Design the feeder for the following group of 200 V, three-phase squirrel-cage induction motors: 1-10 hp, 1-15 hp, 1-20 hp, and 1-40 hp. The individual motors will be protected by dual-element (time-delay) fuses, and they will be started full voltage. The feeder will also be protected using dual-element fuses mounted in a motor circuit switch. Feeder conductors will be type THW copper.

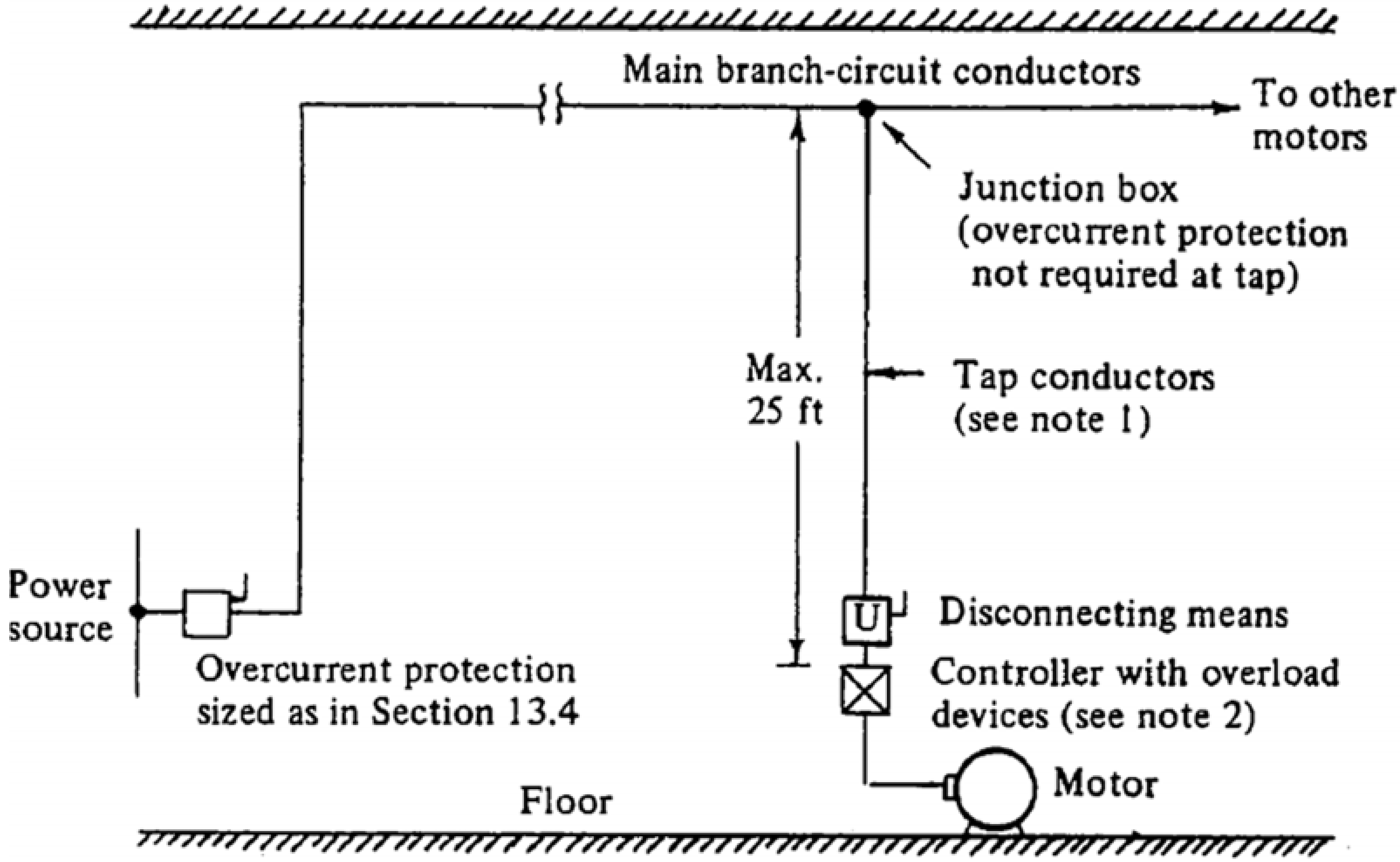
Motor Horsepower	Motor Full-Load Amperes	Feeder Calculations: Ampacity		Feeder Calculations: Protection	
40	104 × 1.15[a] = 120 A	125% of 120	= 150	175%[b] of 120	= 210
20	54 × 1.15 = 62 A	Plus 100% of remaining	= 142		= 142
15	42 × 1.15 = 48 A				
10	28 × 1.15 = 32 A				
		Min. ampacity	= 292 A	Max. rating	= 352 A

[a] Values from Table 13.2 for 230 V are increased by 15% for 200 V motors from the footnote to the table. *Note:* The 1.15 factor used here is not related to the service factor.

[b] As in Table 13.3, using time-delay fuses.

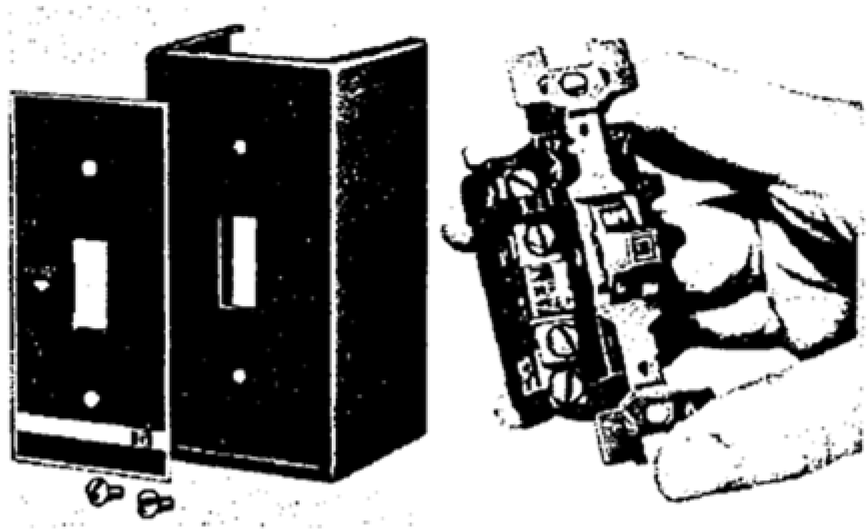
1. Feeder conductors and conduit:
   From Table 11.1, conductor size = 350 MCM THW (rated 310 A)
   From Table 11.6, conduit size = $2\frac{1}{2}$ in. (three conductors)
2. Feeder protective device:
   From Table 7.1, the nearest standard fuse size is 350 A (<352 A)
   From Table 13.4, the switch size is 400 A


Feeder protective device
208 V,
three-phase
source*
†
350 A
400 A switch
2½" C, 3–350 MCM, THW (Cu)
†
40 hp
20 hp
15 hp
10 hp
200 V,
three-phase
motors
*Nominal system voltage (see Section 1.8)
† Dual-element time-delay fuses

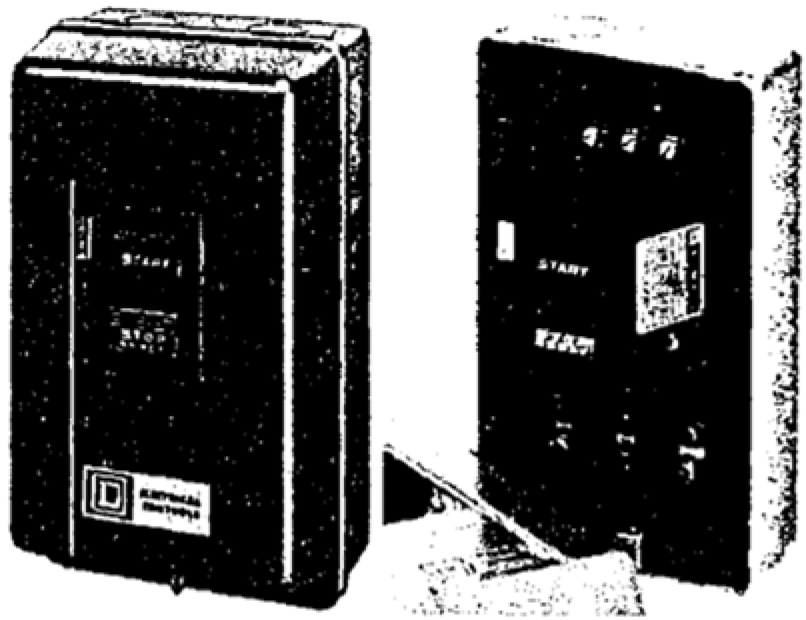


Notes: 1. Minimum one-third ampacity of main branch-circuit conductors or 125% of full-load current of motor, whichever is greater

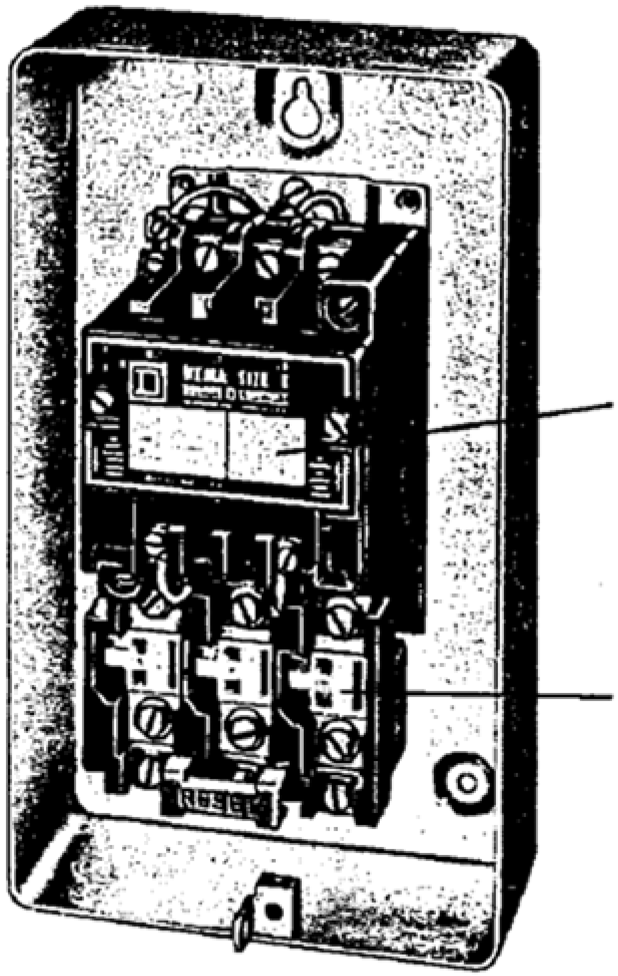
2. Listed for group installation for size of overcurrent protection provided for main branch circuit



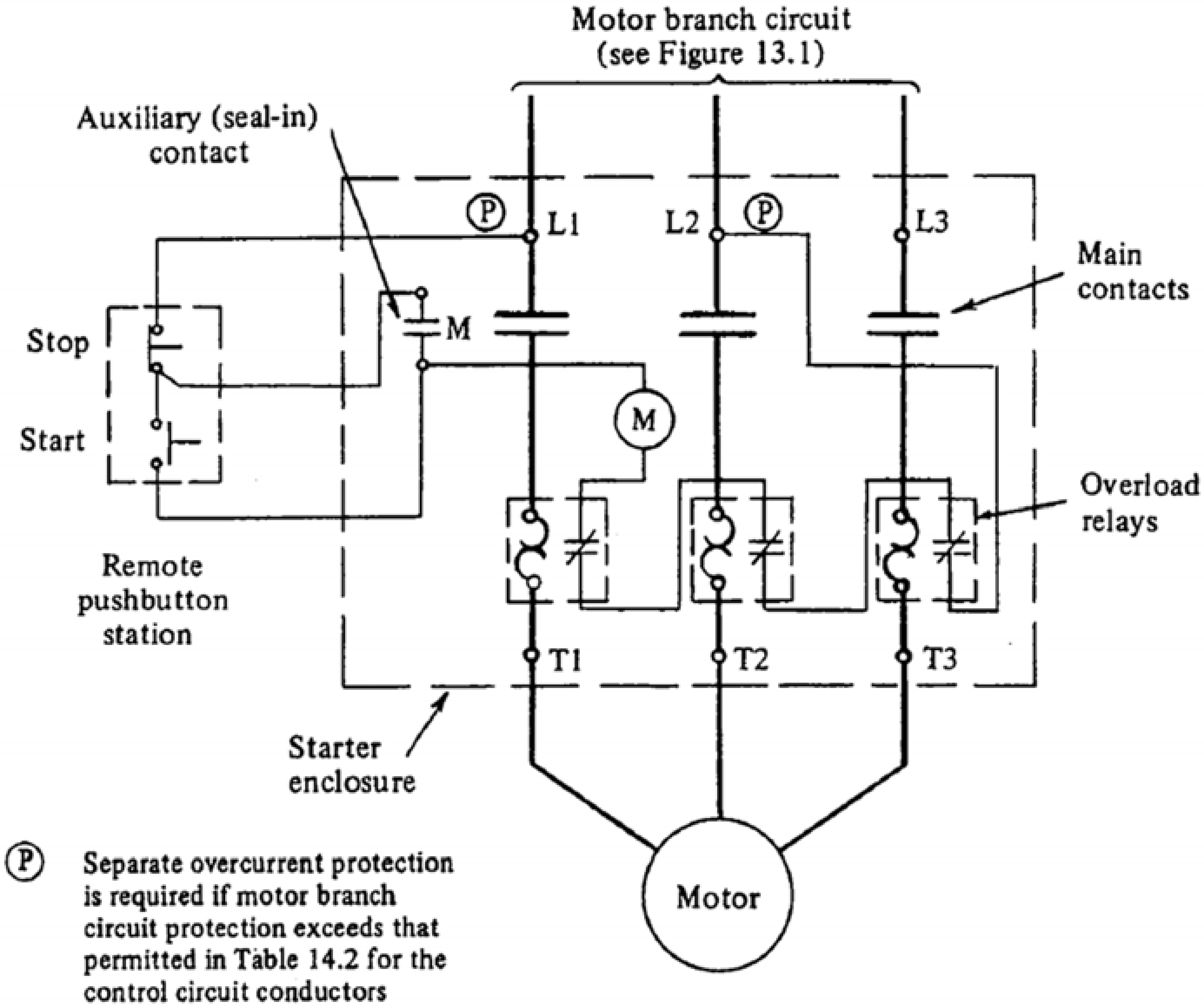
(a) Single-phase manual starter

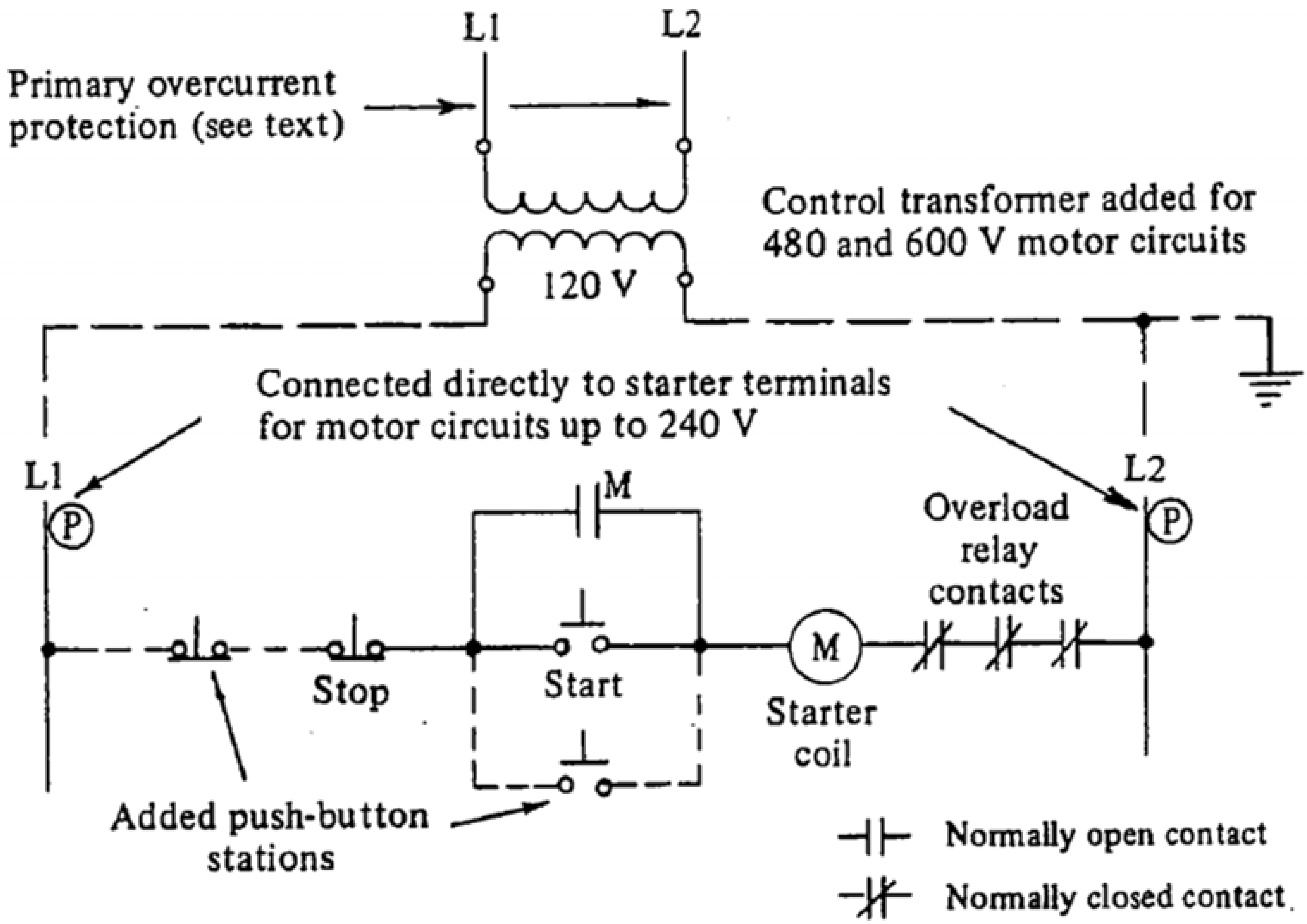


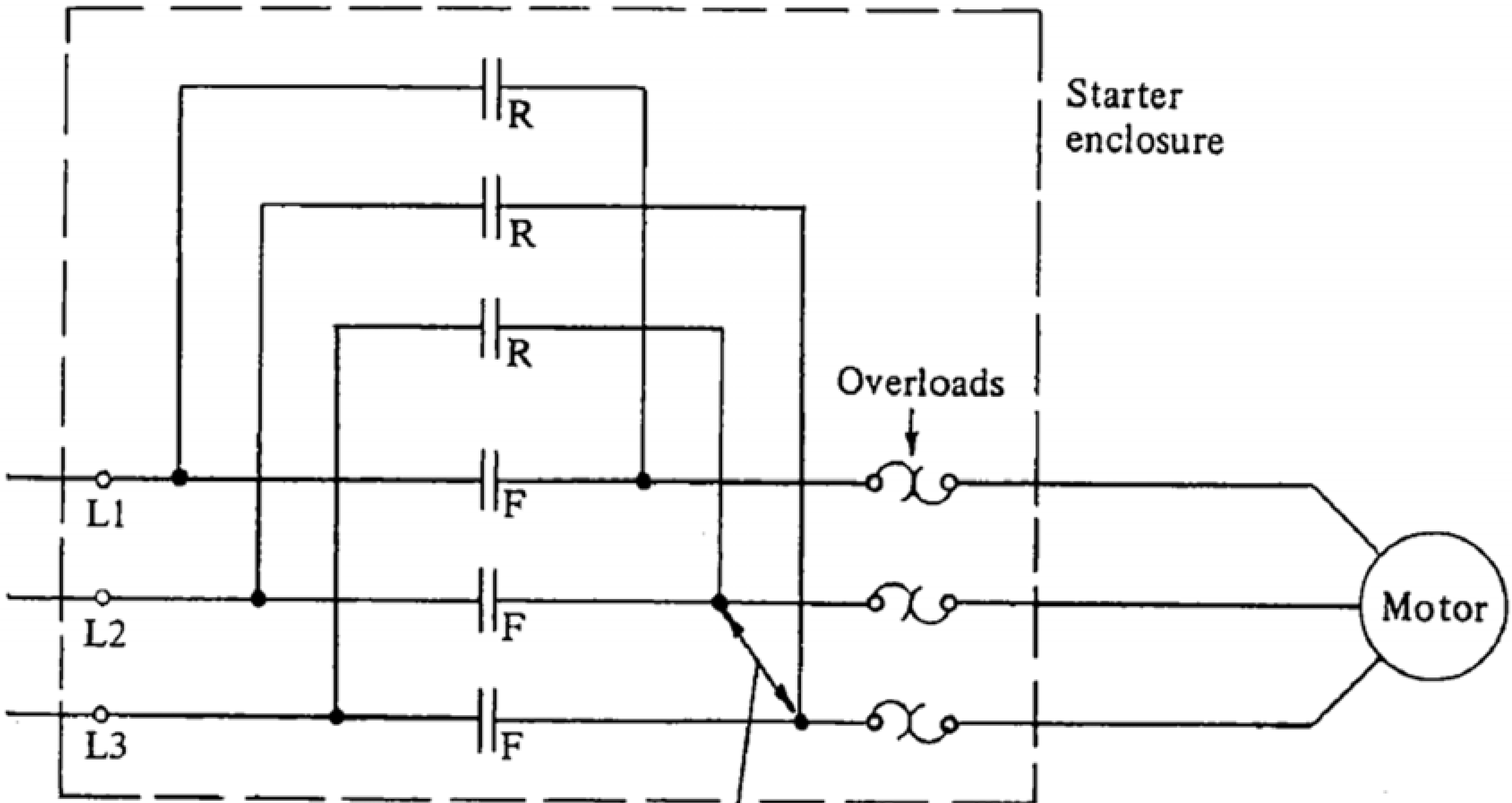
(b) Three-phase manual starter



(c) Three-phase magnetic starter (cover removed)

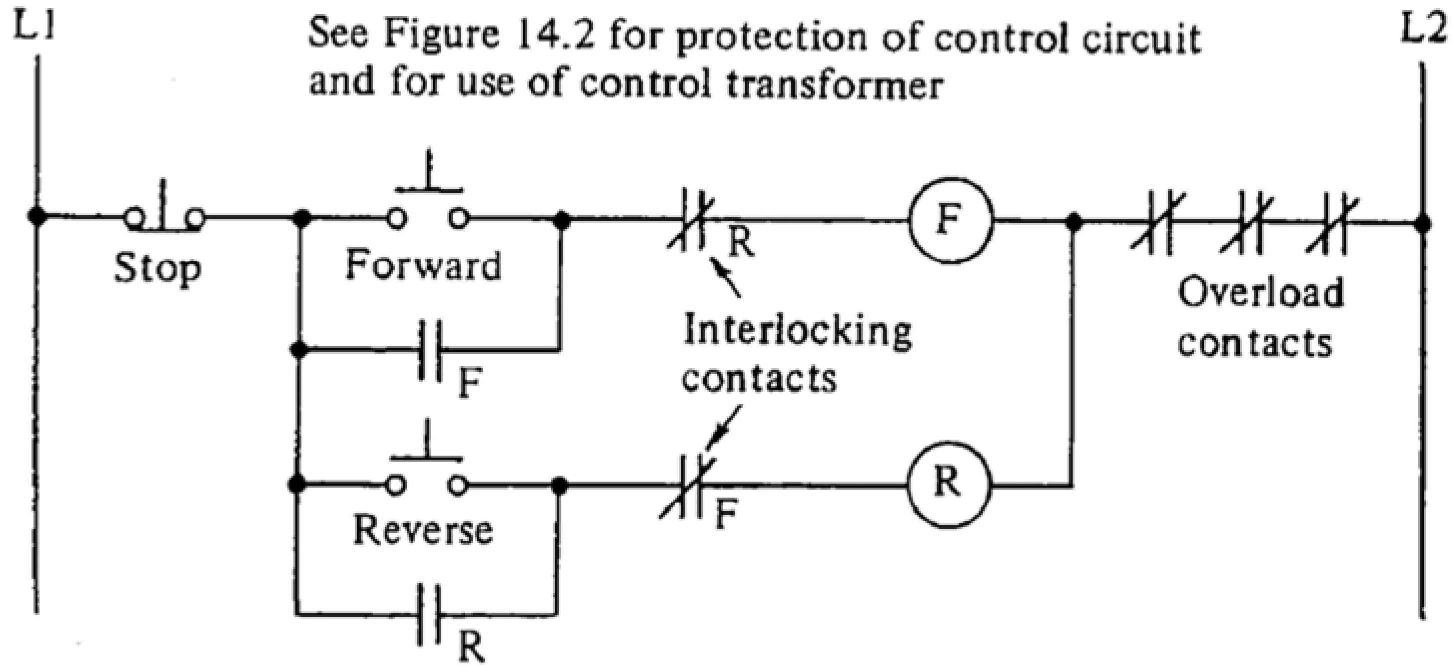

Motor branch circuit
(see Figure 13.1)
Auxiliary (seal-in)
contact
P
L1
L2
P
L3
Main
contacts
Stop
M
Start
M
Overload
relays
Remote
pushbutton
station
T1
T2
T3
Starter
enclosure
Motor
P Separate overcurrent protection
is required if motor branch
circuit protection exceeds that
permitted in Table 14.2 for the
control circuit conductors

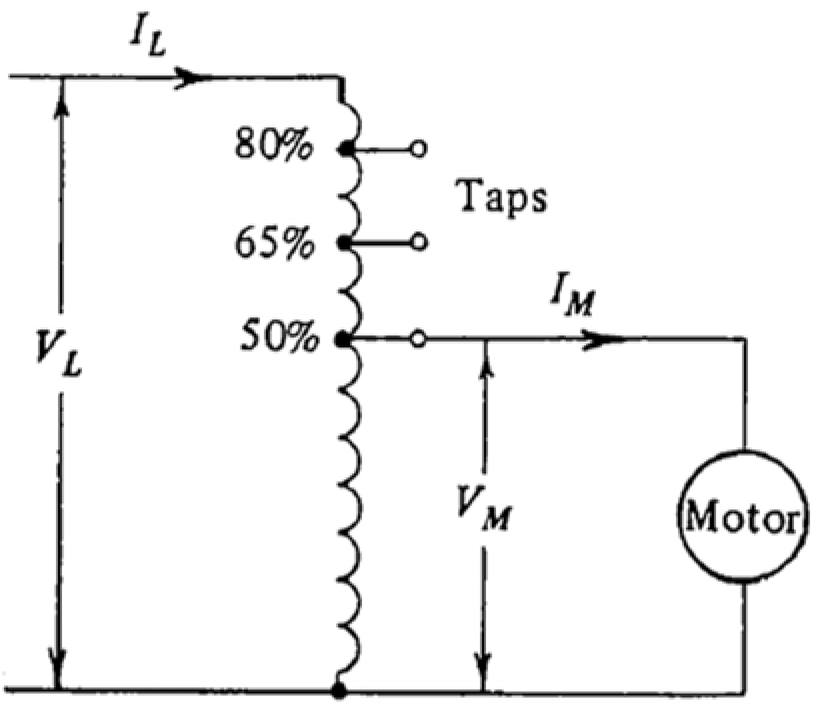

L1
L2
Primary overcurrent
protection (see text)
Control transformer added for
480 and 600 V motor circuits
120 V
Connected directly to starter terminals
for motor circuits up to 240 V
L1
P
L2
P
M
Overload
relay
contacts
Stop
Start
M
Starter
coil
Added push-button
stations
Normally open contact
Normally closed contact



Lines 2 and 3 are interchanged when reversing contactor (R) closes

Note: Power connections only are shown


L1
See Figure 14.2 for protection of control circuit
and for use of control transformer
L2
Stop
Forward
F
R
F
Interlocking
contacts
Overload
contacts
Reverse
R
F
R
R

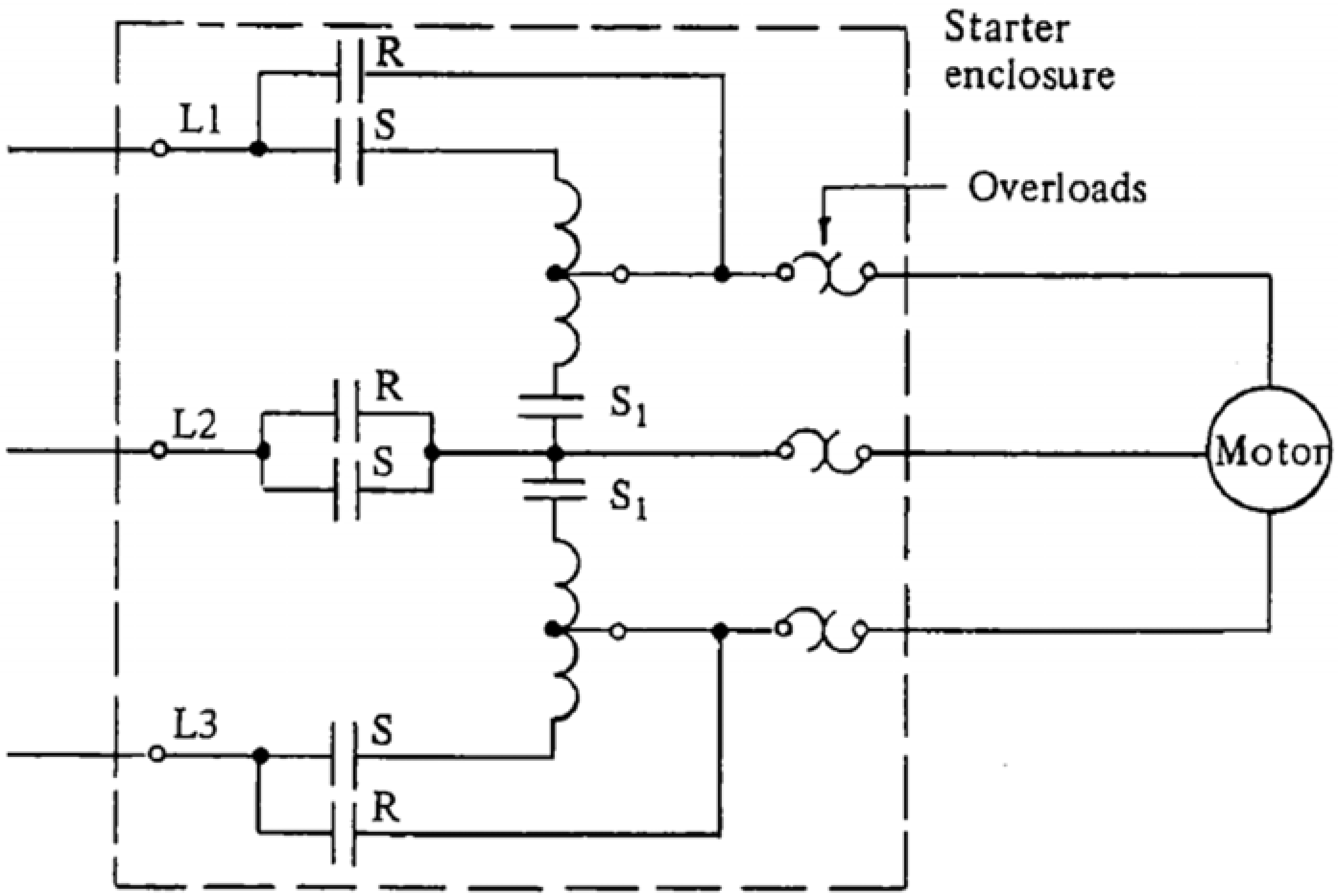


$$I_M = \left(\frac{V_M}{V_L}\right)(I_{ST}\ \text{FV})$$

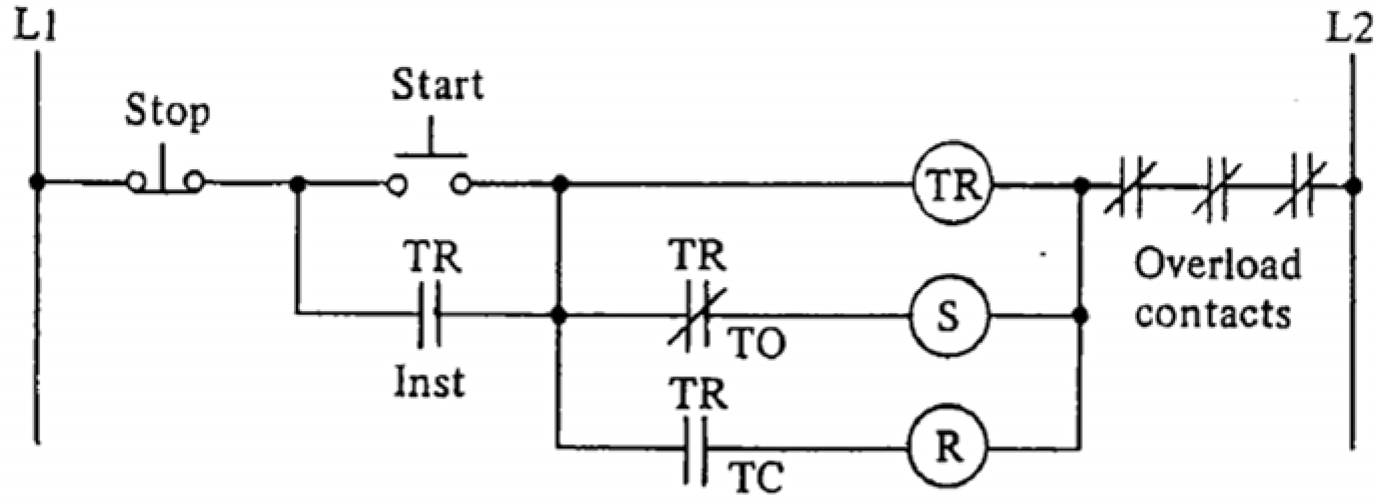
$$I_L = \left(\frac{V_M}{V_L}\right) I_M$$

$$I_L = \left(\frac{V_M}{V_L}\right)^2 (I_{ST}\ \text{FV})$$

$\dfrac{V_M}{V_L}$ α percentage tap on transformer



Note: This diagram shows the power connections only



See Figure 14.2 for protection of control circuit and use of control transformer

S, start contactor

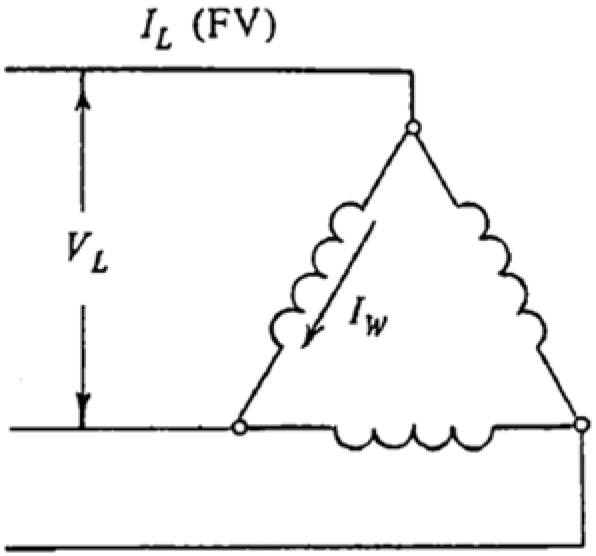
R, run contactor

TR, timing relay

Inst, instantaneously closing contact

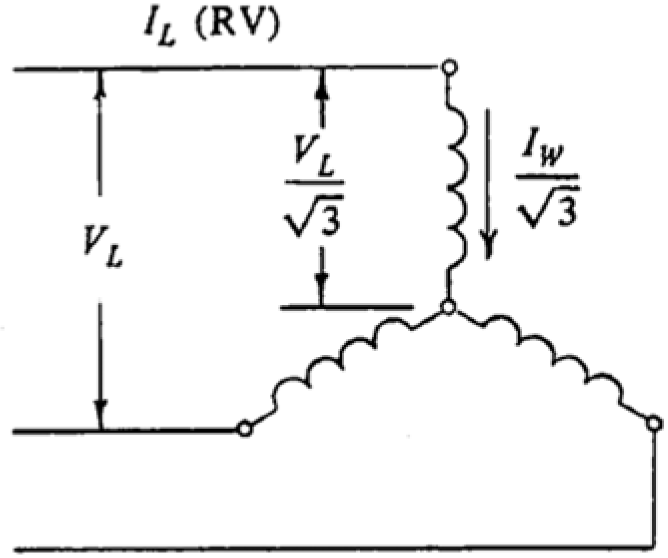
TO, time opening contact

TC, time closing contact



$I_L\ (\mathrm{FV}) = \sqrt{3}\, I_W$

Motor started in the delta configuration
(i.e., full voltage)

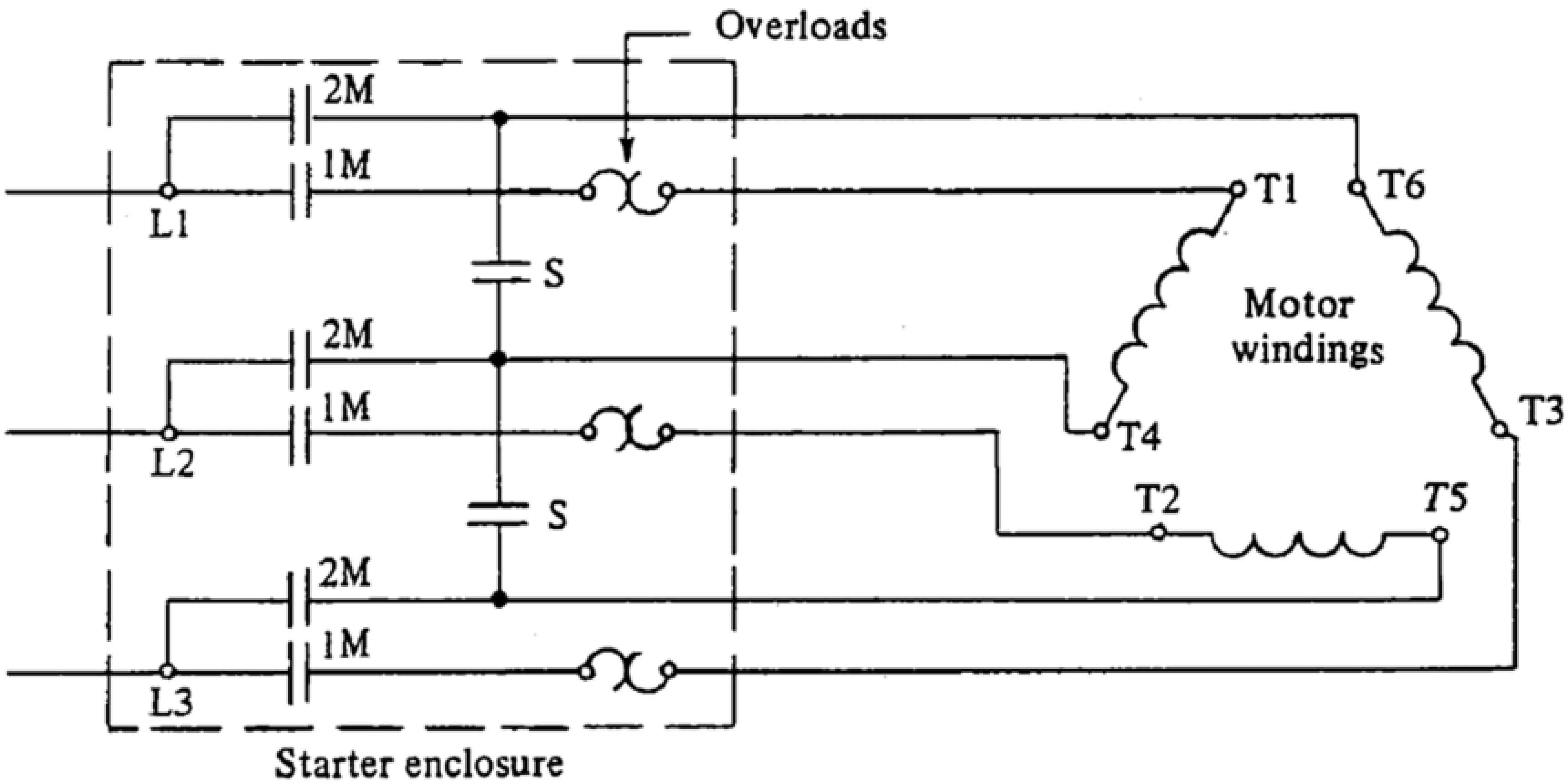


$$I_L\ (\mathrm{RV}) = \frac{I_W}{\sqrt{3}}$$

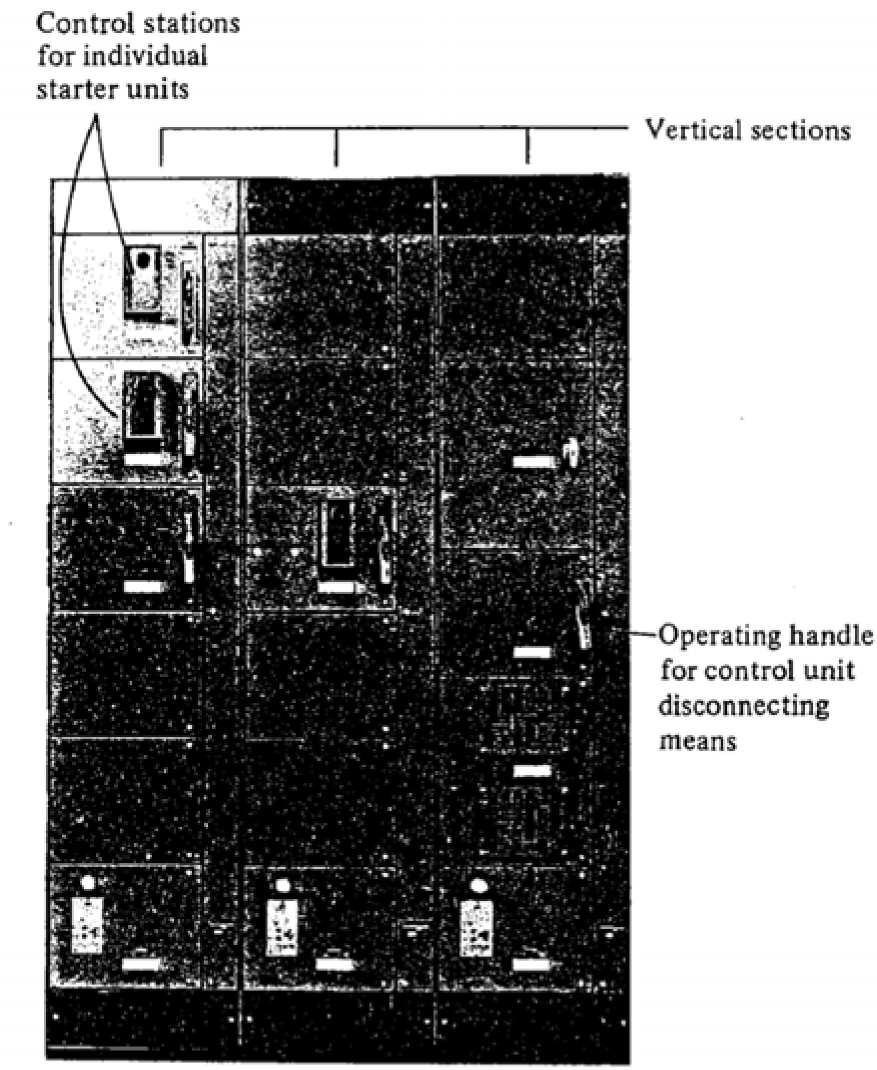
$$\frac{I_L\ (\mathrm{RV})}{I_L\ (\mathrm{FV})} = \frac{I_W/\sqrt{3}}{\sqrt{3}\, I_W} = \frac{1}{\sqrt{3}} \times \frac{1}{\sqrt{3}} = \frac{1}{3}$$

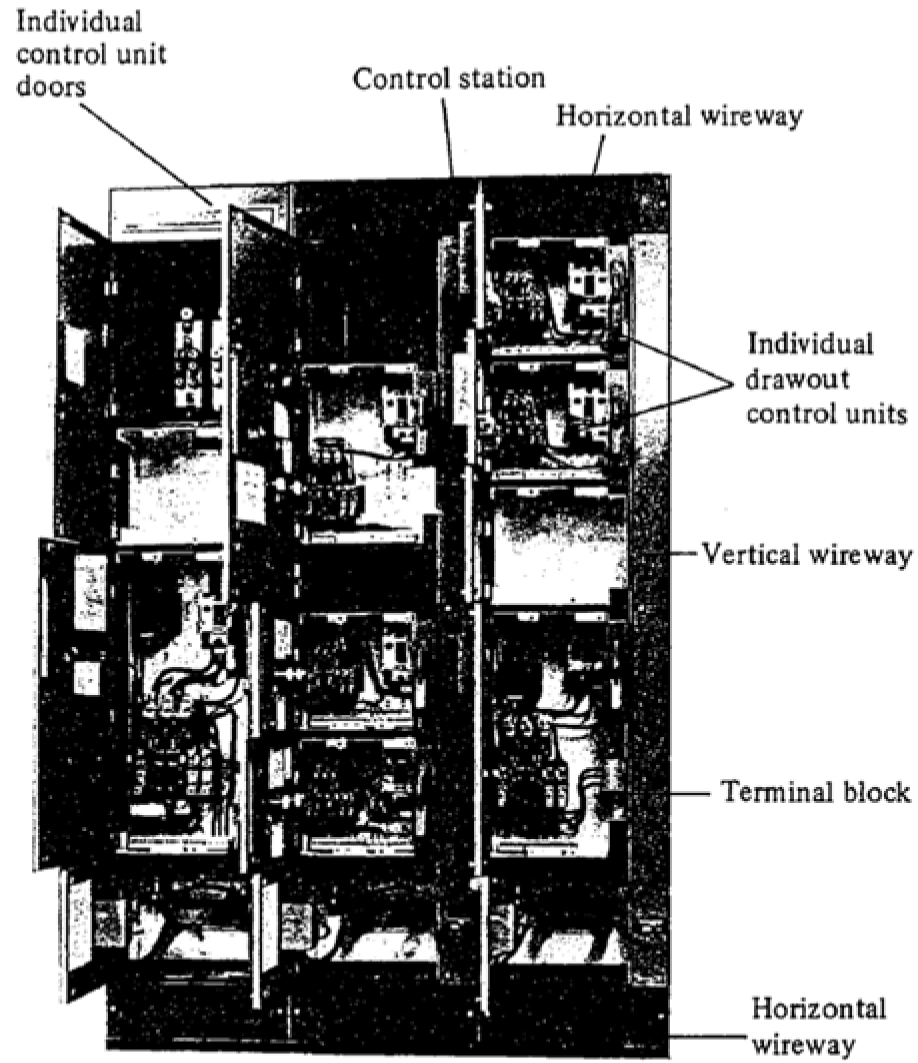
$$\text{Torque} \propto \left(\frac{V_L/\sqrt{3}}{V_L}\right)^2 = \left(\frac{1}{\sqrt{3}}\right)^2 = \frac{1}{3}$$

Motor started in the wye configuration
(i.e., reduced voltage)



Note: This diagram shows the power connections only


Control stations
for individual
starter units
Vertical sections
Operating handle
for control unit
disconnecting
means


Individual
control unit
doors
Control station
Horizontal wireway
Individual
drawout
control units
Vertical wireway
Terminal block
Horizontal
wireway

Starter Size[b]	Combination Starter Units — Number of Space Factors Required: Full Voltage Nonreversing	Full Voltage Reversing	Reduced Voltage Autotransformer	Reduced Voltage Wye–Delta[c]
Circuit Breaker Type				
1	2	3	—	—
2	2	3	6	5
3	4	4	9	6
4	4	4	9	7
5	6	10	12	12[d]
6	12	12[d]	12[e]	—
Fusible Switch Type[f]				
1	2	3	—	—
2	2	3	6	5
3	4	5	10	8
4	6	6	10	12
5	7	12[d]	12	12[e]
6	12	12[d]	12[e]	—

Feeder Tap Units

Circuit Breakers		Fusible Switches	
Amperes	Space Factors	Amperes	Space Factors
100	2[g]	30	2[g]
150	2[g]	60	2[g]
225	3	100	2
400	4	200	4
		400	6

[a] Based on one space factor = 6 inches. Space factors based on $4\frac{3}{8}$, $6\frac{1}{2}$, and 7 inches are also common. All space requirements should be confirmed by manufacturer.

[b] See Table 14.1 for horsepower ratings.

[c] Horsepower ratings are higher than for other types of starters.

[d] Requires structure 24 inches wide.

[e] Requires structure 28 inches wide.

[f] Using UL class J fuses.

[g] Can be dual mounted (two breakers or switches in one drawout unit).

A motor-control center is to control the following motors using the type of starters given in Table 14.4. In addition, two 30kW, three-phase heating loads are to be supplied. The source of supply is 480 V, three-phase, and the motors are rated at 460 V, three-phase. The control units are the fusible switch type. Determine **(a)** the overall size of the motor-control center, and **(b)** the ampacity rating of the main bus.

Number	HP	Type of Starter
4	$7\frac{1}{2}$	Full voltage, nonreversing (FVNR)
5	10	Full voltage, nonreversing (FVNR)
2	20	Full voltage, nonreversing (FVNR)
2	30	Full voltage, nonreversing (FVNR)
2	40	Full voltage, reversing (FVR)
1	100	Reduced voltage, nonreversing (RVNR; autotransformer type)

(a) Based on Table 14.3, the space requirements for motor starters are given in Table 14.5.

TABLE 14.5

Motor Starters				
Motor HP	Type of Starting	Starter Size (Table 14.1)	No. of Space Factors Each Unit	No. of Space Factors Total
$7\frac{1}{2}$	FVNR	1	2	$4 \times 2 = 8$
10	FVNR	1	2	$5 \times 2 = 10$
20	FVNR	2	2	$2 \times 2 = 4$
30	FVNR	3	4	$2 \times 4 = 8$
40	FVR	3	5	$2 \times 5 = 10$
100	RVNR	4	10	$1 \times 10 = 10$
				Total for starters = 50

Additional space factors are determined.

—Two 30 kW heating loads:

$$\text{load current} = \frac{30 \times 1000}{1.732 \times 480} = 38 \text{ A}$$

which requires two 60 A switches, dual mounted: 2 space factors
— Allowance for main incoming feeder cables: 1 space factor

Total required space factors is found.

$$50 + 2 + 1 = 53$$

— Maximum possible space factors per vertical section = 12
— Minimum number of vertical sections = $53/12 \approx 5$
— Total number of space factors = $5 \times 12 = 60$

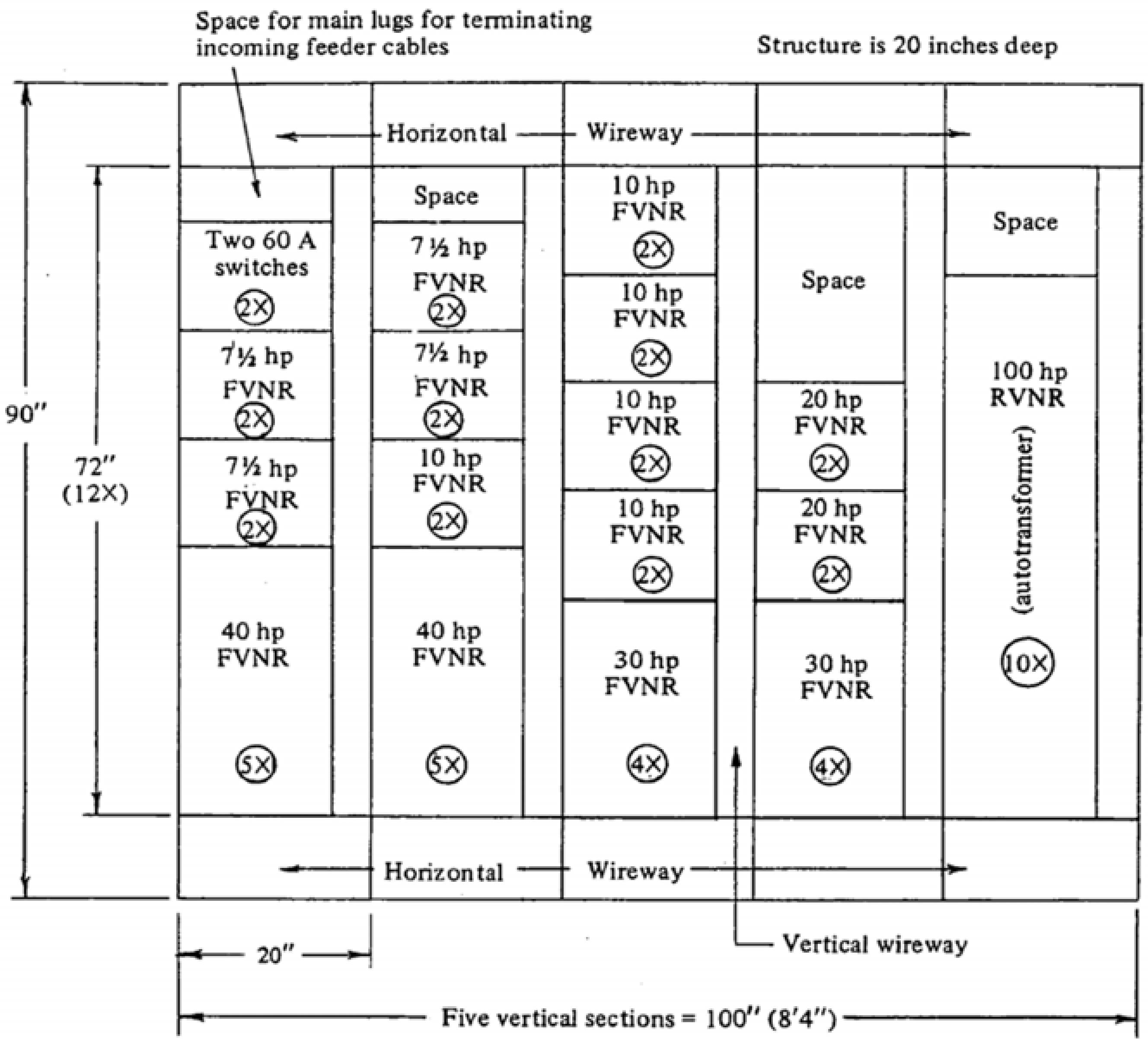
Number used = 53

Number of spare space factors = 7

Figure 14.8 shows a suggested layout for the motor-control center. This example is meant to show the procedure only for laying out an MCC. The manufacturers should be consulted for their exact space requirements.

Motor HP	FLMA (A) (Table 13.2)		
100	123	125% of largest = 1.25 × 124 =	155
$7\frac{1}{2}$	11		4 × 11 = 44
10	14		5 × 14 = 70
20	27	Plus 100% of remaining	2 × 27 = 54
30	40		2 × 40 = 80
40	52		2 × 52 = 104
Two 30 kW heaters			2 × 38 = 76
			Minimum ampacity = 583 A

Select the standard main bus rating of 600 A.



(5X) Number of space factors based on 6″ per space factor (see Table 14.3 for space requirements)

FVNR, full-voltage, nonreversing starter
FVR, full-voltage, reversing starter
RVNR, reduced-voltage, nonreversing starter;
Starters are 460 volt, three-phase

MCC Load Summary

Equip. No.	Description	BHP	Rated hp	Connected Load[1] (kVA)	Intermittent Load (kVA)	Running Load (kVA)	Peak Load (kVA)	Stand-by Load (kVA)
MCC #300								
WO-1	Welding Outlet			20	20		20	
HTR-1	Heater			40		40	40	
LP-7	Lighting Panel			100		100	100	
MP-304	Pump	43	50	50		50	50	
MP-304A	Pump (Spare)	43	50	50				
MP-305	Pump (Future)	20	25	25		25	25	
MP-305A	Pump (Future Spare)	20	25	25				
LP-8	Lighting panel (Stand-by)			50		50	50	50
MP-308	Firepump (Stand-by)		30	30		30	30	30
	Total			390	20	295	315	80
Load Center #100								
MP-101	Pump		200	200		200	200	
MP-102	Compressor		250	250		250	250	
MP-103	Pump		200	200		200	200	
MP-104	Compressor		250	250		250	250	
MCC#300	MCC #300			390	20	295	315	80
	Total			1290	20	1195	1215	80

(1) For motors where power factor and efficiency are not known, assume 1 hp load requires 1kVA.

Connected Load

- The load summary should include a calculation of connected load.
- Connected load is the sum of electric ratings for all equipment served by the system, including planned future loads.

Running Load

- **Running load** is the actual electrical load of the facility during operation.

- Running load is used to size utility service, generators, transformers, feeders, motor control centers, circuit breakers, and uninterruptible power supplies. To determine running load, individual loads must be identified as either continuous, intermittent, or spare.

- *Running load* is the sum of all continuous loads, including planned future continuous loads.

- *Intermittent loads* are included on a percentage basis; spare loads are not included in running load calculation.

MCC Load Summary

- A **continuous load** is defined as a load that is expected to operate continuously for 3 hours or more.
-
- **Intermittent loads** are loads that operate continuously for periods of less than 3 hours.
- **Spare loads** are operated only when other loads are not operating.

MCC Load Summary

- Power factor and efficiency must be known to calculate the running load.
-
- **Power factor** is defined as the ratio of real power (kW) to apparent power (kVA). A load with a low power factor (e.g., a motor) draws more current than a load with a higher power factor.
- **Efficiency** is defined as the ratio of output power to input power.

MCC Load Summary

- Initially, only estimated horsepower ratings may be available, and power factor and efficiency must be estimated.
- When power factor and efficiency are not known, consider 1 hp of load to require 1 kVA of power.
- As actual power factors and efficiencies become available, particularly for large motors, the load summary should be updated.

MCC Load Summary

- Two factors used to calculate the running load of motors for the sizing of transformers are demand factor and run factor.
- ***Demand factor*** is the ratio of actual operating load to nameplate rating.
- ***Run factor*** is the percentage of hours operating per day, expressed as a decimal equivalent.
- These factors generally are not used in the load summary.
- However, in cases where many large intermittent motors are connected to a bus, run factors and demand factors should be included in the running load calculations for economic reasons.

MCC Load Summary

- **Peak load**, the maximum instantaneous load drawn by a system during a stated period of time, is obtained when the facility is operating at full capacity and the maximum instantaneous intermittent load is energized.

- All intermittent loads on a system normally will not be energized at the same time. Therefore, to estimate peak load the process must be evaluated to determine when the maximum intermittent load will be energized.

- Peak load is the sum of the running load and the maximum instantaneous intermittent load.

MCC Load Summary

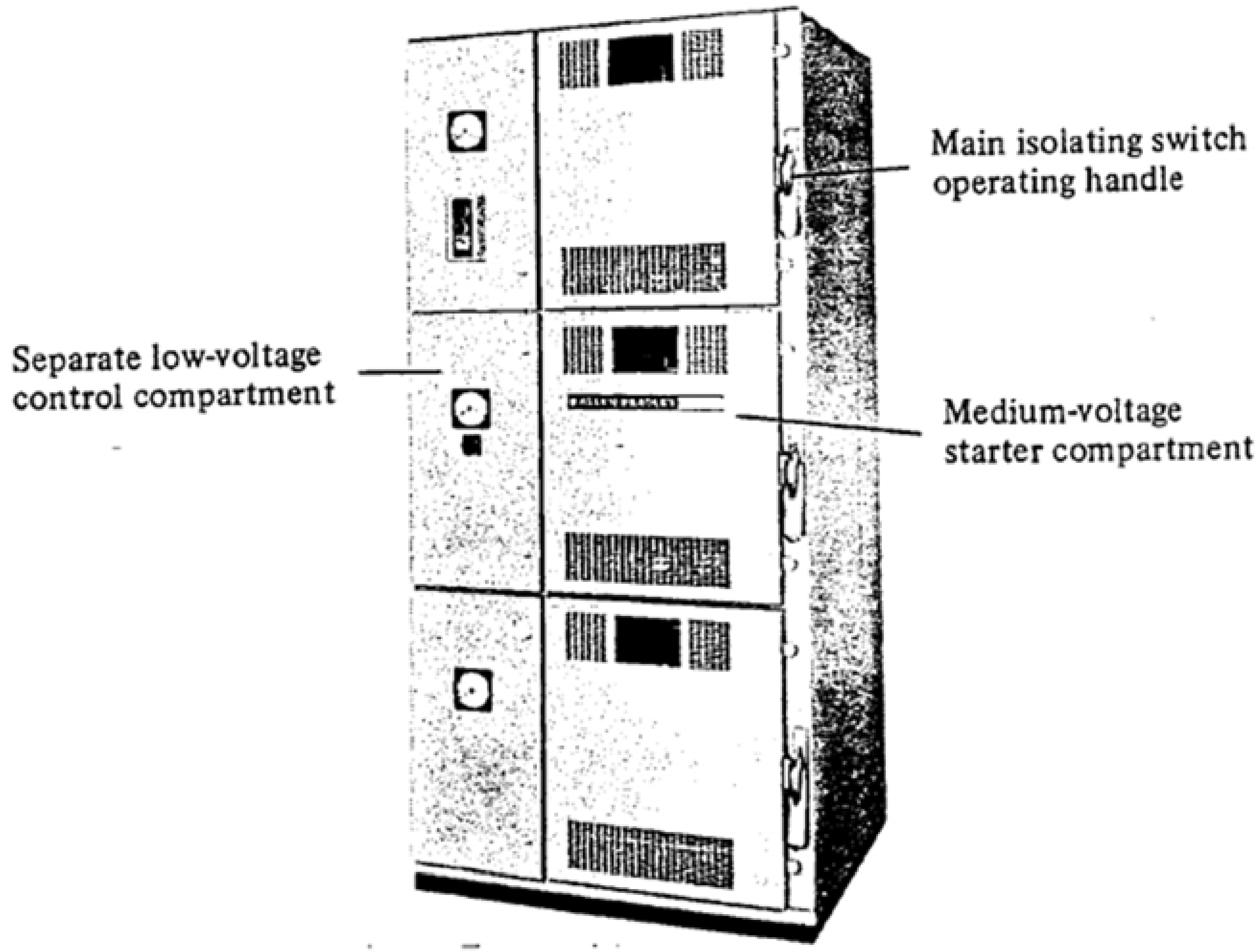
- Stand-by loads should be identified on the load summary to enable the electrical system designer to design the stand-by power system.

- Typically, stand-by loads include critical loads that cause damage to the process or product if power is interrupted, loads required for black start-up of a generator (e.g., jacket water heaters and pumps), selected plant lighting and HVAC loads, and sewage pumps.

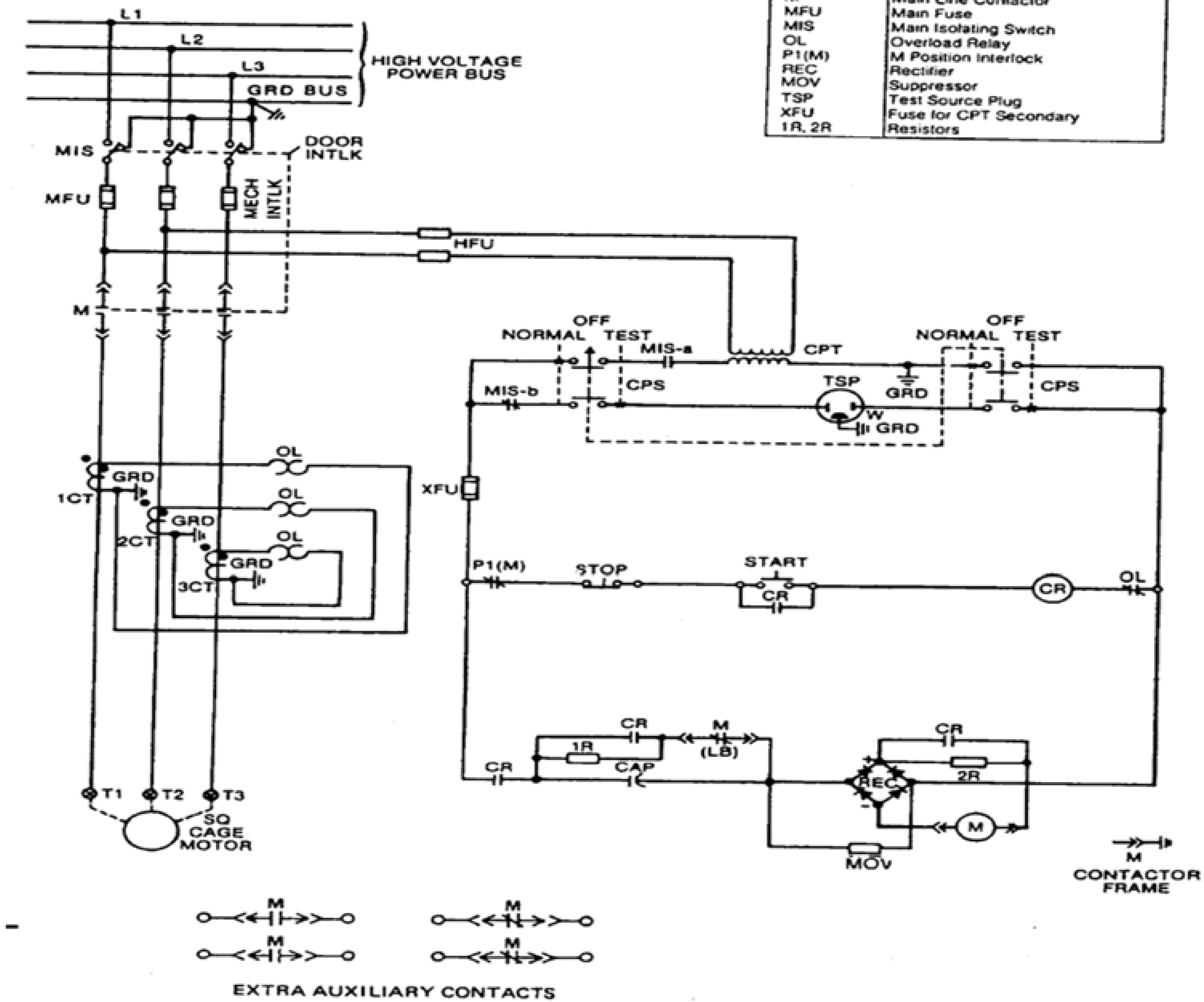
Equip. No.	Description	BHP	Rated hp	Connected Load[1] (kVA)	Intermittent Load (kVA)	Running Load (kVA)	Peak Load (kVA)	Stand-by Load (kVA)
MCC #300								
WO-1	Welding Outlet			20	20		20	
HTR-1	Heater			40		40	40	
LP-7	Lighting Panel			100		100	100	
MP-304	Pump	43	50	50		50	50	
MP-304A	Pump (Spare)	43	50	50				
MP-305	Pump (Future)	20	25	25		25	25	
MP-305A	Pump (Future Spare)	20	25	25				
LP-8	Lighting panel (Stand-by)			50		50	50	50
MP-308	Firepump (Stand-by)		30	30		30	30	30
	Total			390	20	295	315	80
Load Center #100								
MP-101	Pump		200	200		200	200	
MP-102	Compressor		250	250		250	250	
MP-103	Pump		200	200		200	200	
MP-104	Compressor		250	250		250	250	
MCC#300	MCC #300			390	20	295	315	80
	Total			1290	20	1195	1215	80

(1) For motors where power factor and efficiency are not known, assume 1 hp load requires 1kVA.

Medium Voltage MCC


Main isolating switch operating handle
Separate low-voltage control compartment
Medium-voltage starter compartment

Designation	Device Description
CAP	Capacitor
CPS	Control Power Switch
CPT	Control Power Transformer
CR	Control Relay
CT	Current Transformer
HFU	Fuse for CPT Primary
LB	Late Break
M	Main Line Contactor
MFU	Main Fuse
MIS	Main Isolating Switch
OL	Overload Relay
P1(M)	M Position Interlock
REC	Rectifier
MOV	Suppressor
TSP	Test Source Plug
XFU	Fuse for CPT Secondary
1R, 2R	Resistors



- Medium-voltage starters are available for controlling large motors where it is more economical to supply them directly from the higher-voltage distribution system.
- Standard medium-voltage starters are rated for a maximum of 5.0 kilovolts and 2500 horsepower.
- Medium-voltage starters using vacuum contactors offer a compact unit allowing many thousands of operations free of mechanical maintenance problems.

Understanding Power Concepts

Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- ***DC/UPS Systems***

DC/UPS SYSTEMS

(Emergency Backup Systems)

Objectives

The participant will know:

- What is an emergency backup system
- Why emergency backup system is needed
- When to use emergency backup system
- Types of emergency backup systems
- Major components of emergency backup systems

What is emergency backup system?

A electric power system that provides alternative power when the normal power supply is not available

Why do we need emergency backup system?

To ensure reliable power source during emergency

When do we need emergency backup system?

- Life threatening loads
  - Operation room (hospitals)
- Safety loads
  - Emergency evacuation lighting
  - Communication systems
  - Fire systems etc.
- Critical processes
  - Production loss
  - Total plant shutdown
  - Data loss

What are the types of emergency systems?

- Interruptible
  - Emergency generators
- Uninterruptible
  - AC (UPS)
  - DC (DC system = battery & battery charger)

Major Components of UPS

- Battery
- Battery Charger/Rectifier
- Inverter
- Static Transfer Switch
- Bypass Line/Transformer/Maint. Bypass
- Distribution Panels

Major Components of DC System

- Battery
- Battery Charger/Rectifier
- Distribution Panels

DC/UPS SYSTEMS
(Emergency Backup Systems)

BATTERY BASICS

Objectives

BASICS of a battery in terms of:

- Type of batteries
- Plate material
- Plate construction

Battery Basic Components

- Positive electrode (plate) ➤ Cathode
  - Receives electrons when battery is discharged
- Negative electrode (plate) ➤ Anode
  - Donates electrons when battery is discharged
- Electrolyte
  - Media for transfer of charges between + and – plates
- Separator
  - Electrically isolates positive electrode from negative
- Battery container (jar)
  - Holds battery parts together

Components of Battery

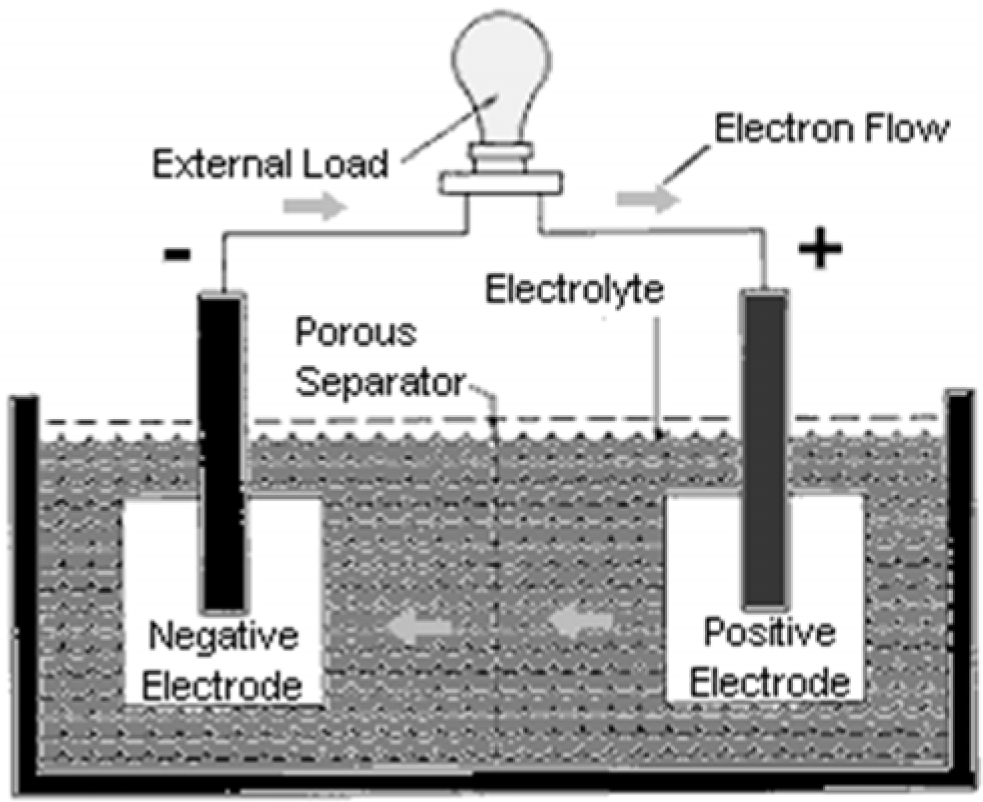
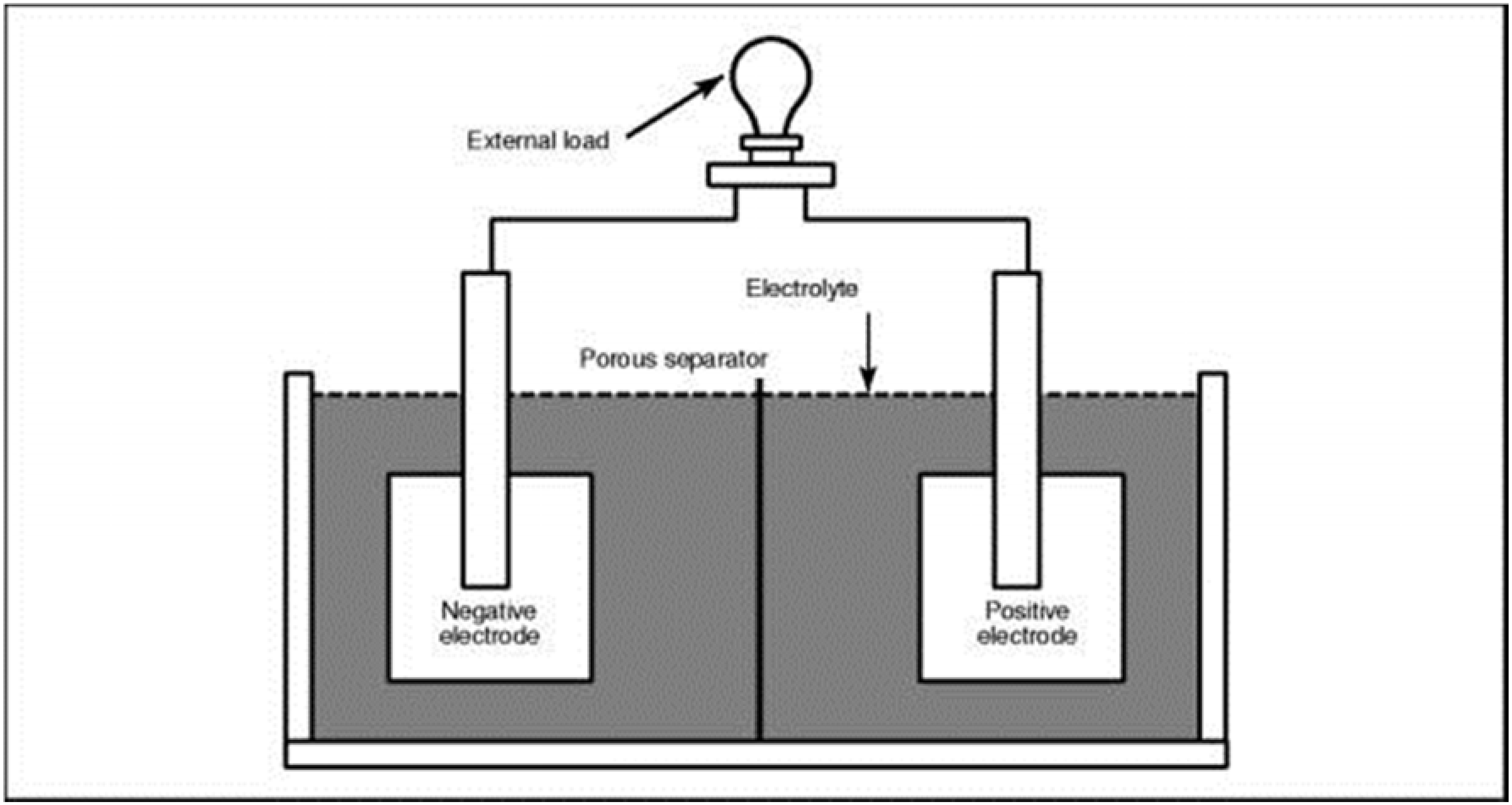
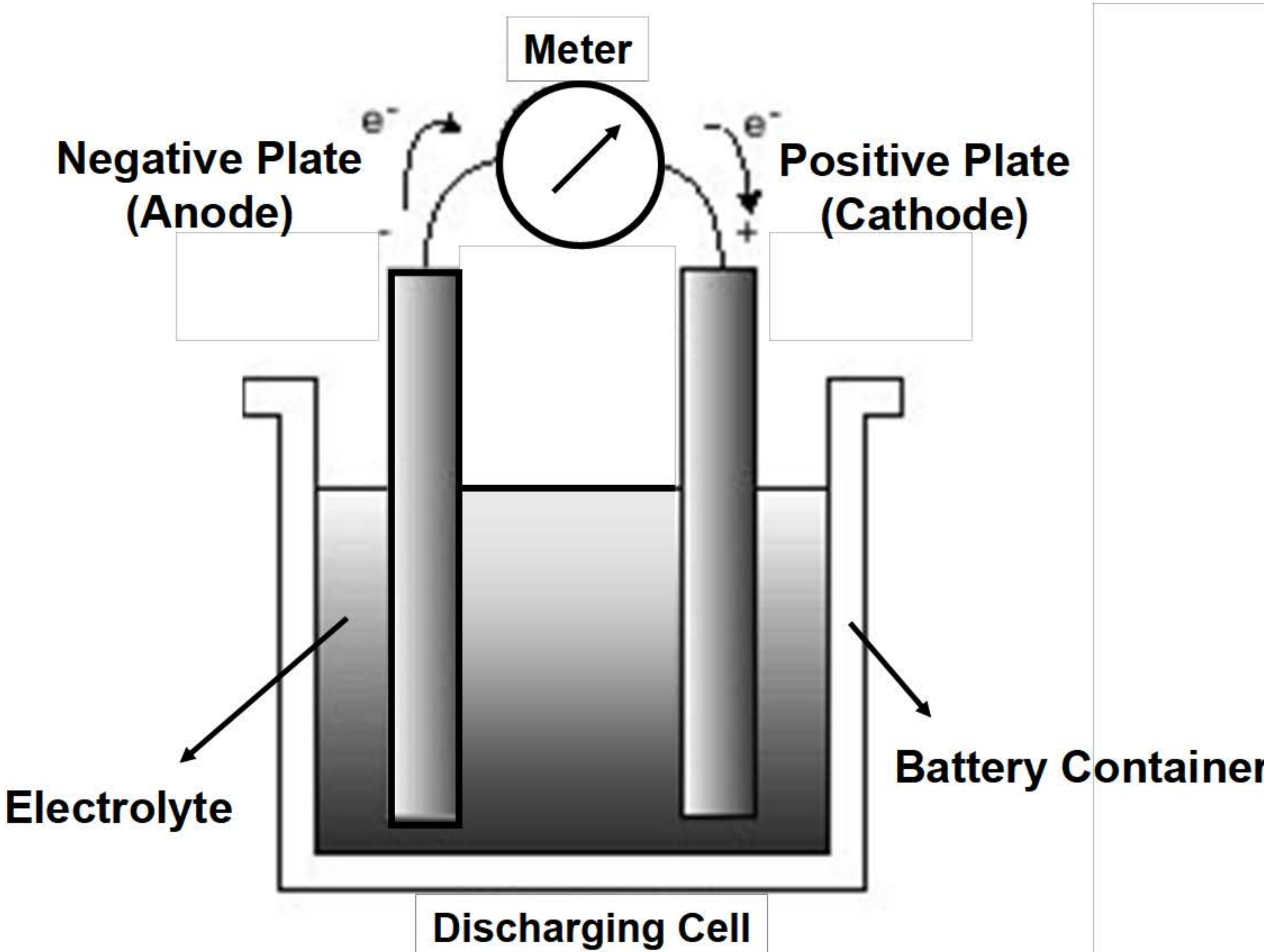


Figure 1 - Components of a Battery Cell (Discharge Circuit)


External load
Electrolyte
Porous separator
Negative electrode
Positive electrode

Battery Components



Types of Batteries

- Nickel Cadmium
- Lead Acid
- Valve Regulated Lead Acid

Flooded (Nickel Cadmium, Lead Acid)

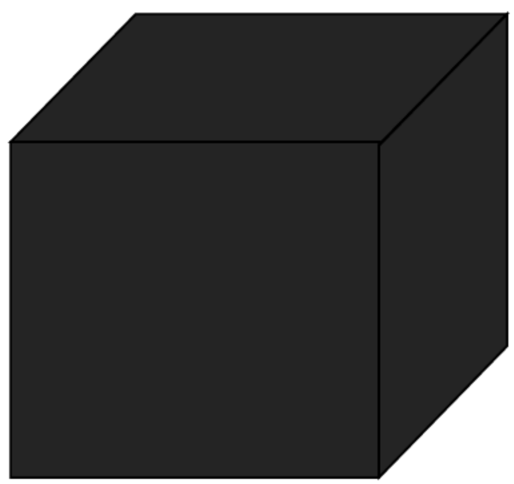
Lead Acid (Lead Acid, Valve Regulated Lead Acid)

Electrochemistry of Batteries

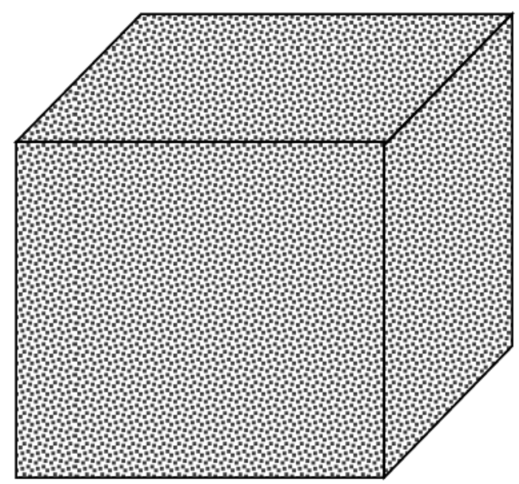
Lead Acid:

- **Positive Plate:** Lead Dioxide (PbO_2)
- **Negative Plate:** Pure Spongy Lead (Pb)
- **Electrolyte:** Dilute Sulfuric Acid (H_2SO_4)

Solid vs. Spongy Active Material



Solid



Spongy

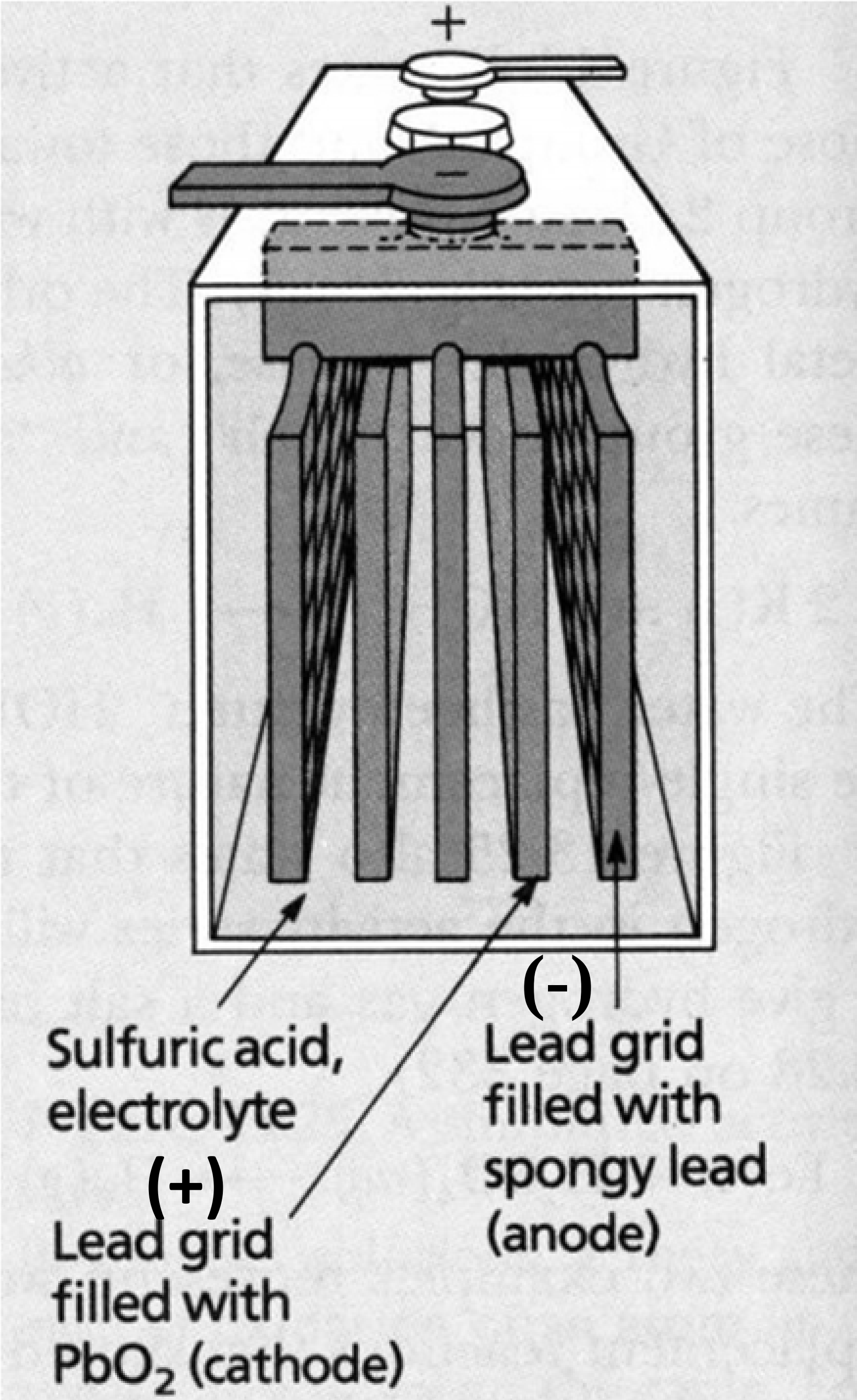
Chemical Reaction of Lead- Acid Batteries

(Charged) (Discharged)

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

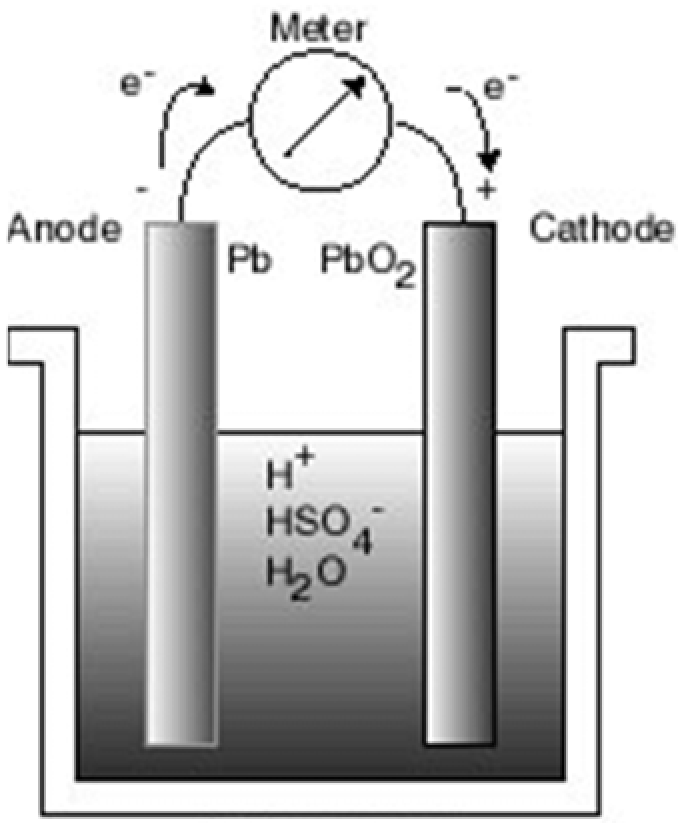
Lead Acid Electrolysis

- Water breaks down to produce oxygen at positive plate
- Hydrogen is produced at negative plate
- Grid Corrosion
  - Oxygen from water reacts with lead in the positive grid

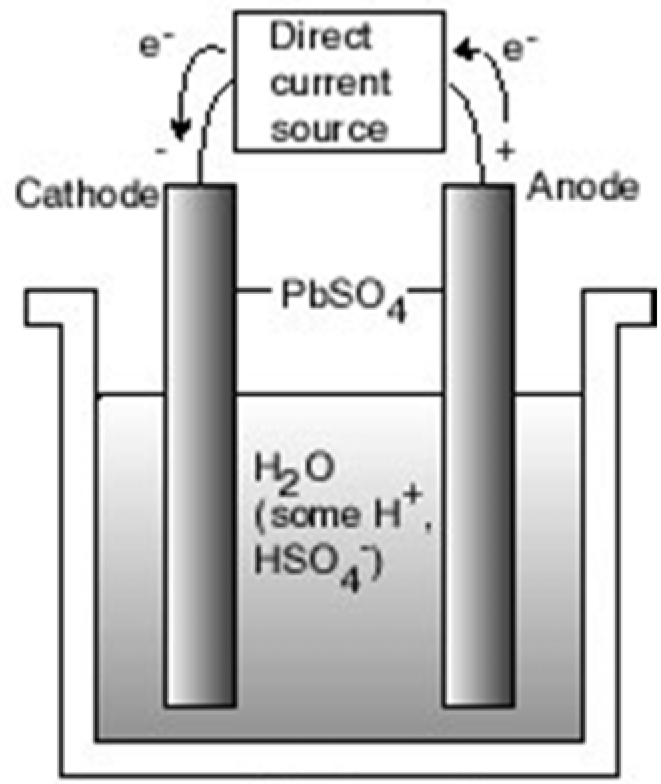


Flooded Lead Acid Battery Construction

Flooded Lead Acid Battery Operation



Discharging cell



Charging cell

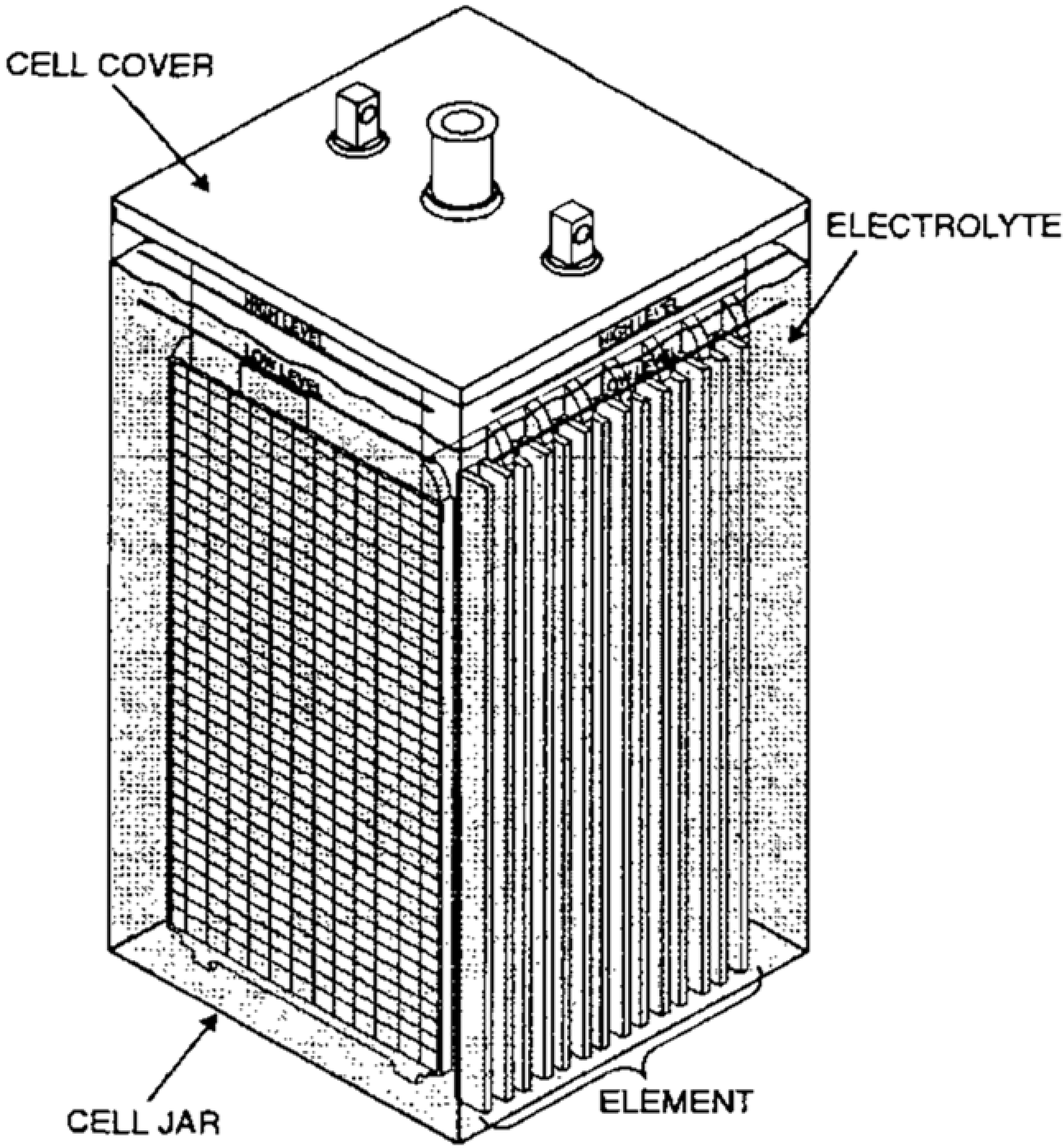
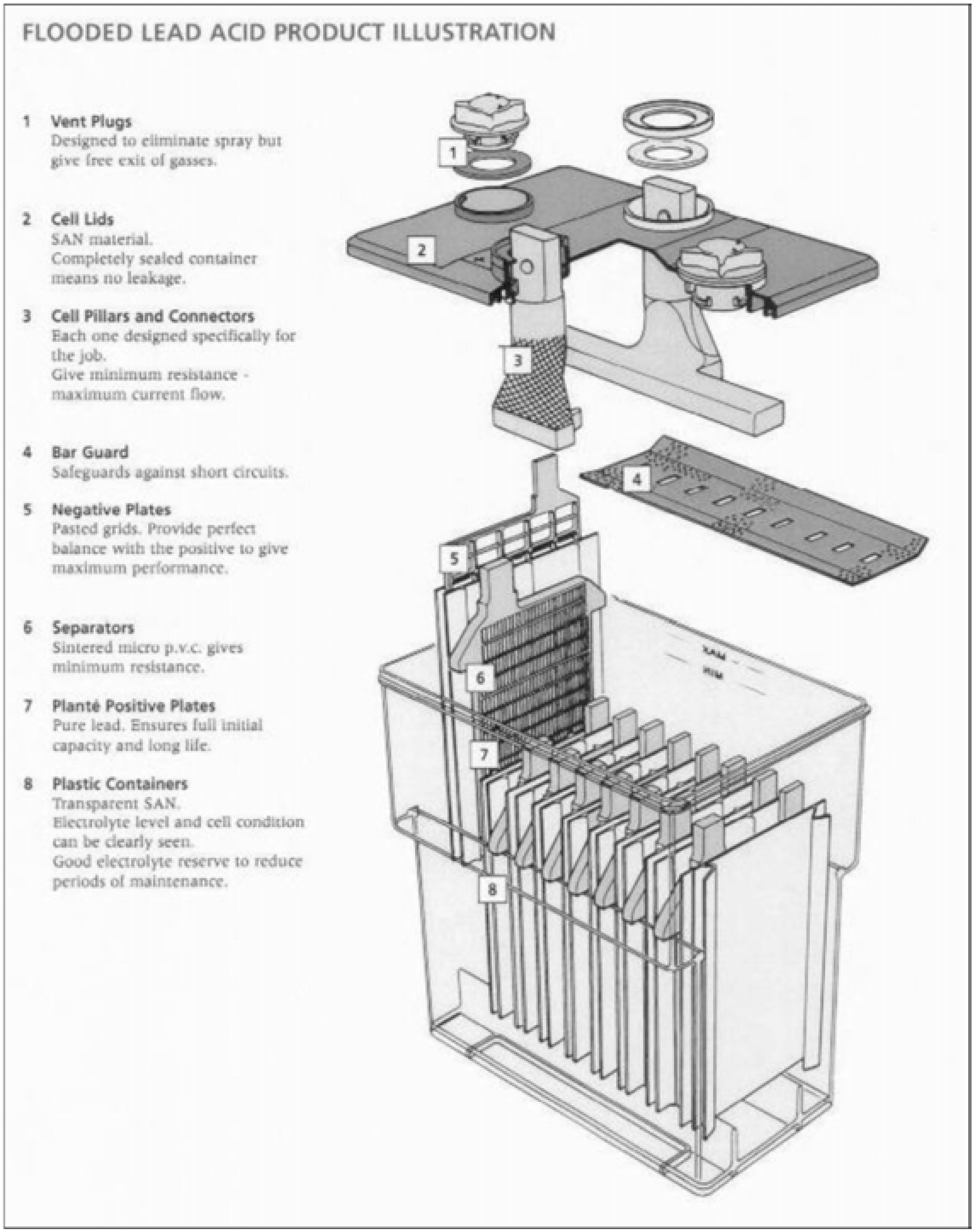


Figure 1
Basic Components of a Lead-Acid Cell



Flooded Lead Acid Battery

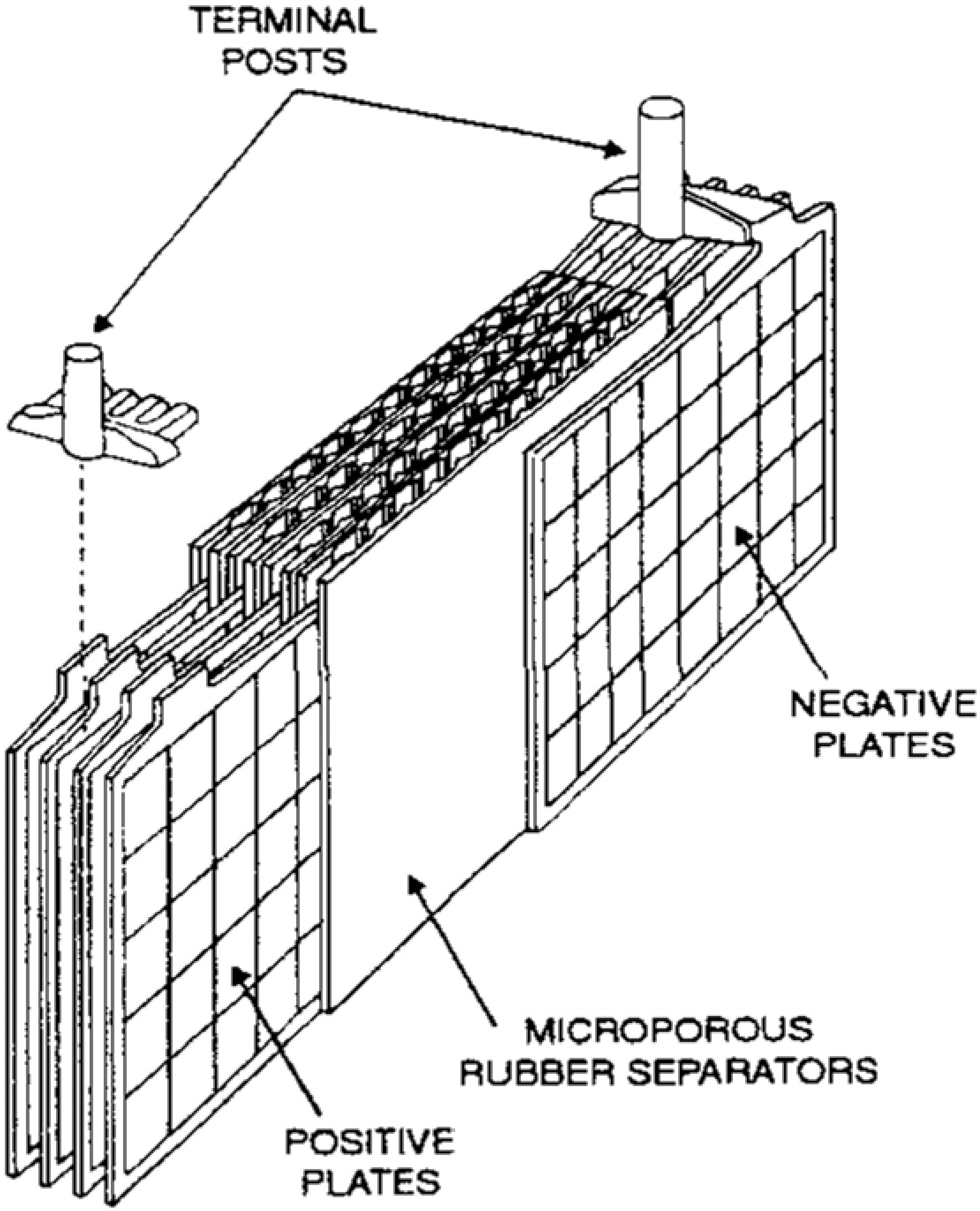


Figure 2
Battery
Element

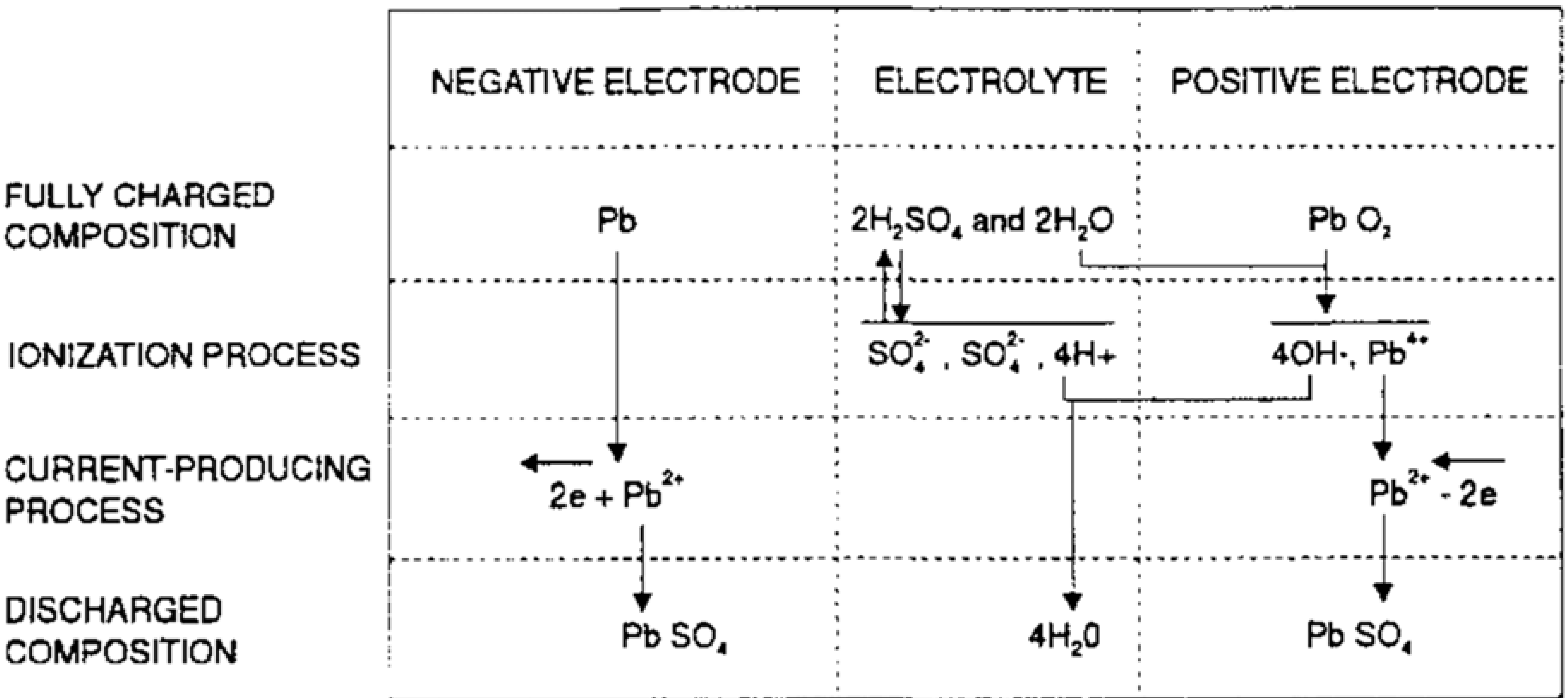


Figure 9

Discharge Electrochemical Reaction

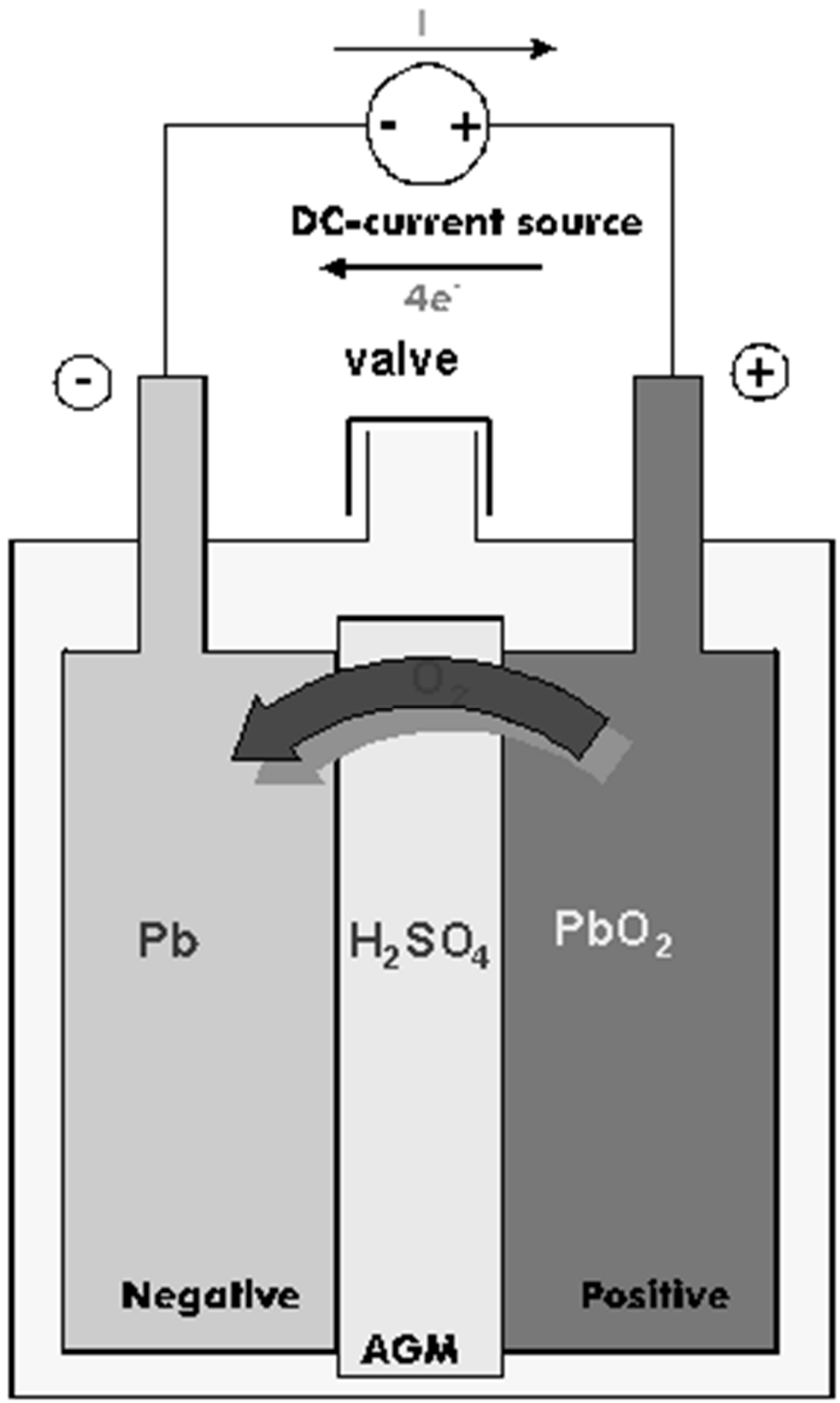

I
- +
DC-current source
4e⁻
valve
-
+
O2
Pb
H2SO4
PbO2
Negative
Positive
AGM

Plate Types for Lead Acid

- There are various types of electrodes (plates), which are used in lead-acid batteries. Each offers different characteristics, which makes it suitable for specific application

Plate Construction

- Lead Acid
  - Pasted Grid Plate
  - Tubular Plate
  - Rod Plate
  - Planté Plate
  - Modified Planté Plate

Pasted Flat Plate

- Can be used as positive or negative electrodes
- Used for automotive and standby float applications
- Active material pasted to a lead or lead alloy grid
- Advantages
  - Low cost
  - Good performance
  - High energy density
- Disadvantage
  - Limited life
  - Limited cycling capability
    - Cycling can be improved with positive plate retainers

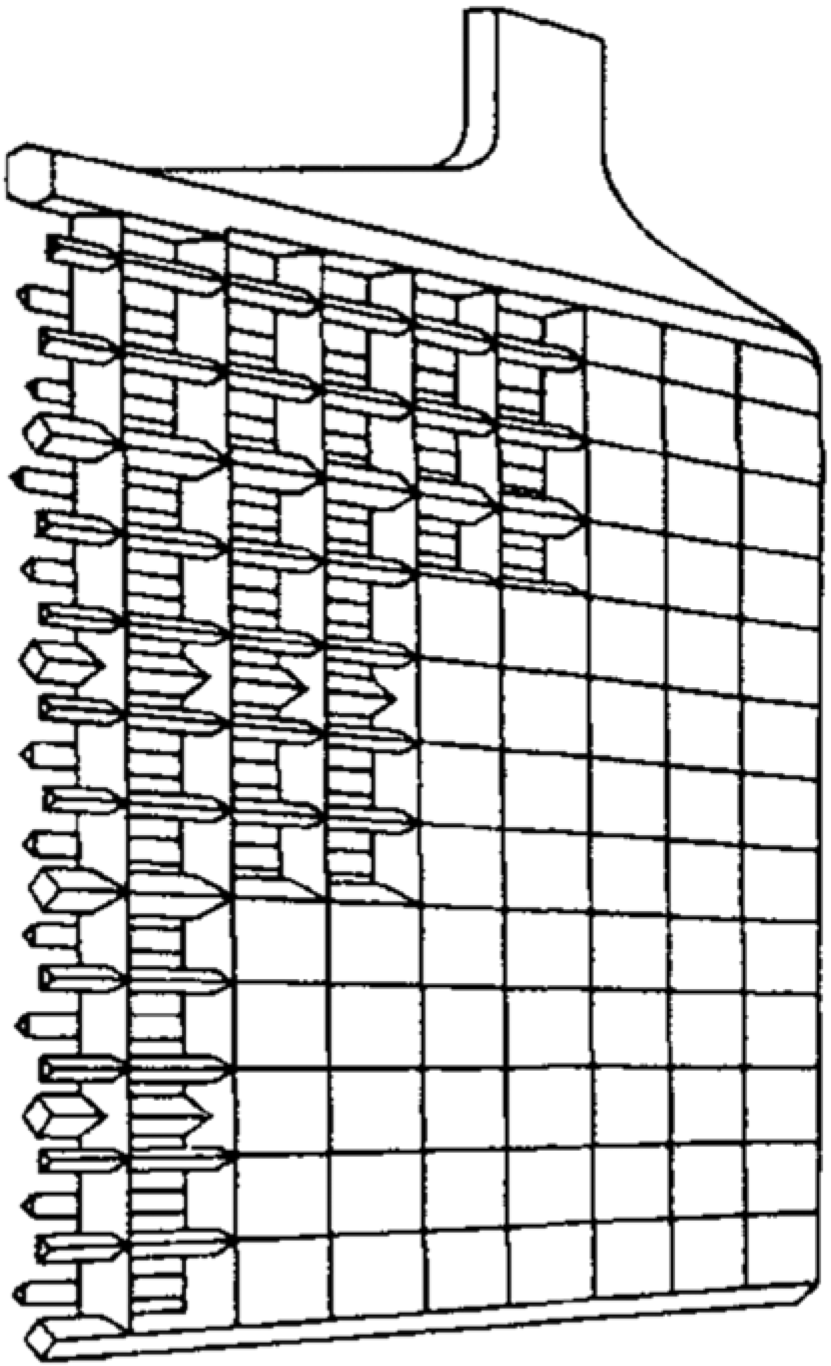
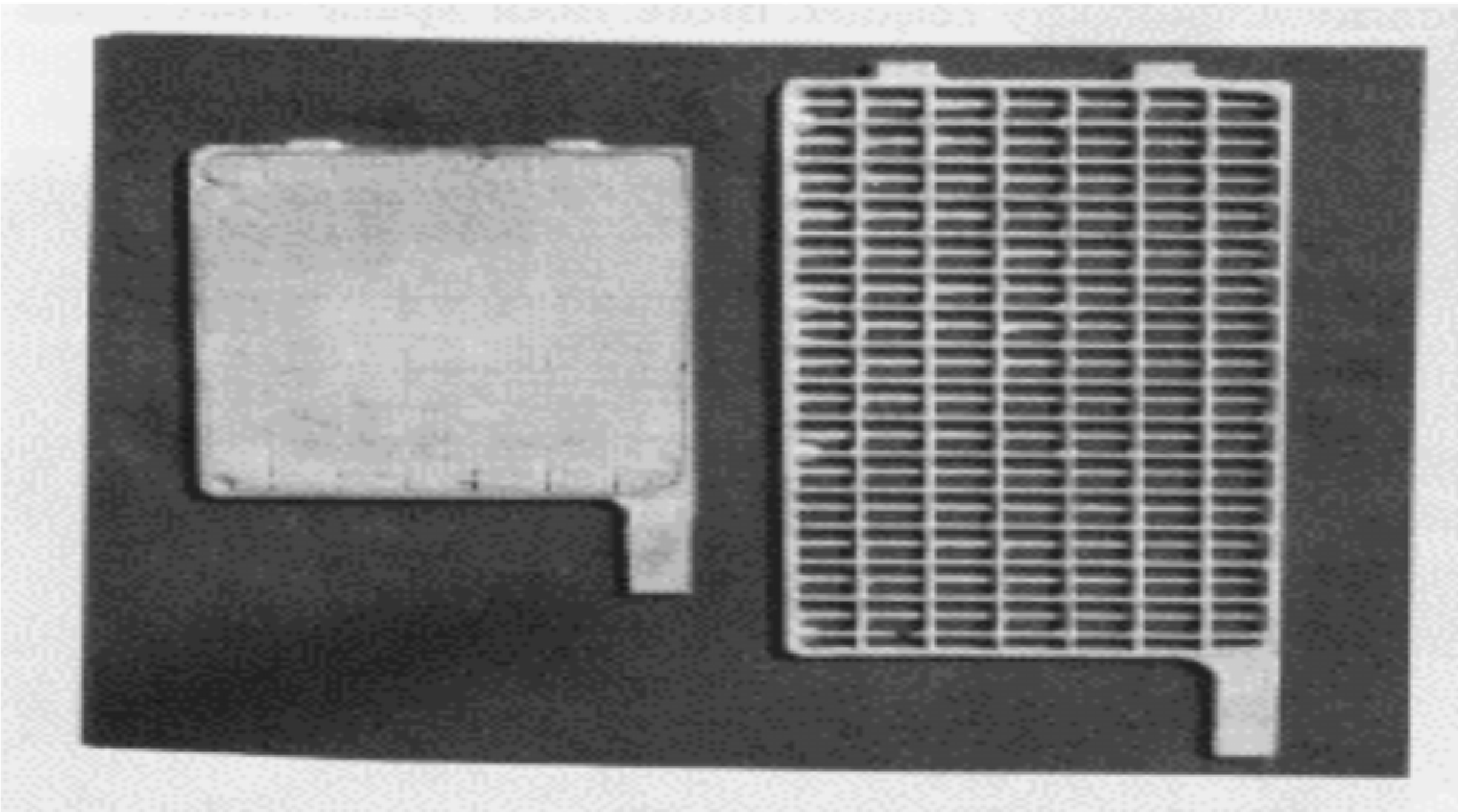


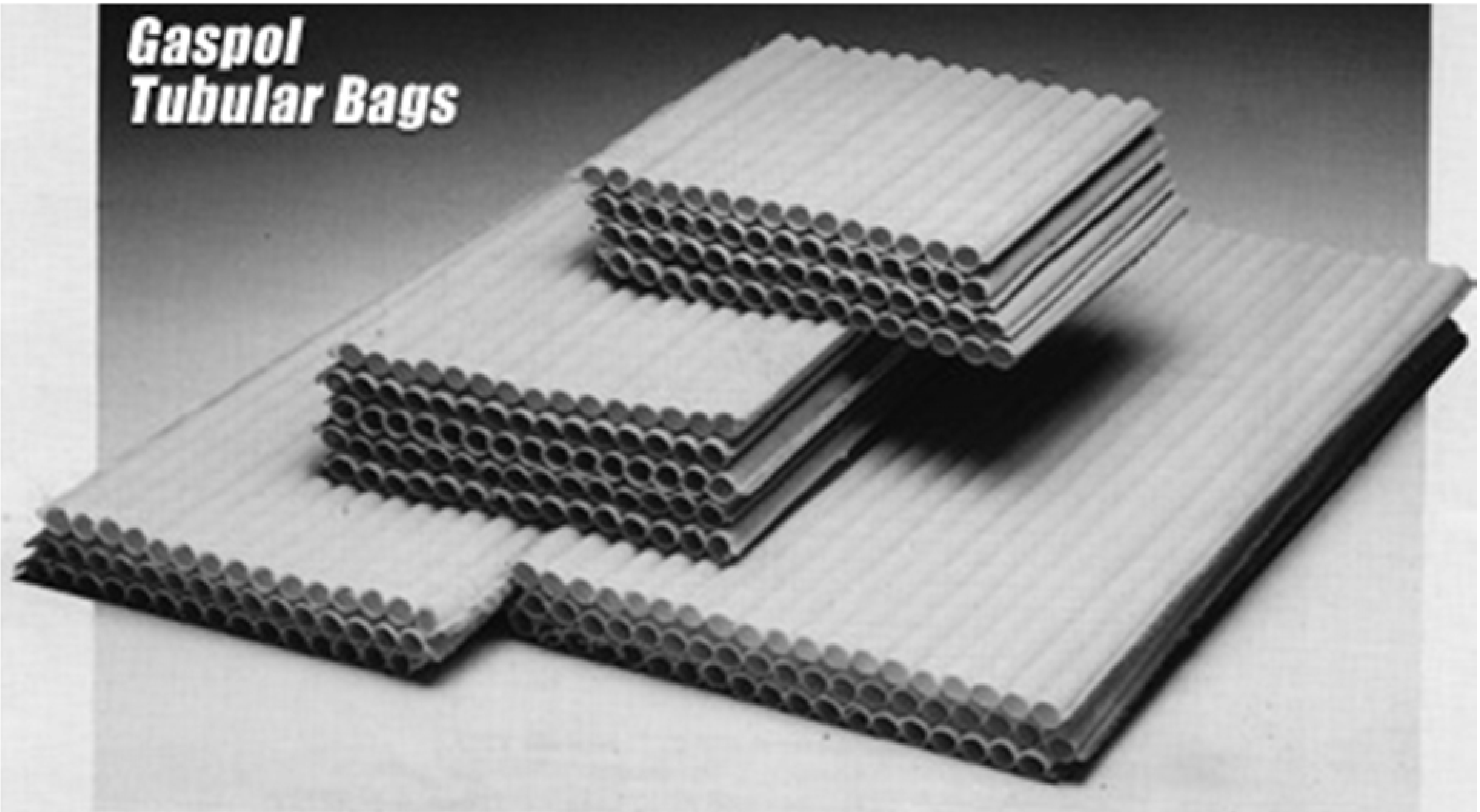
Figure 4

Typical Pasted Plate Grid

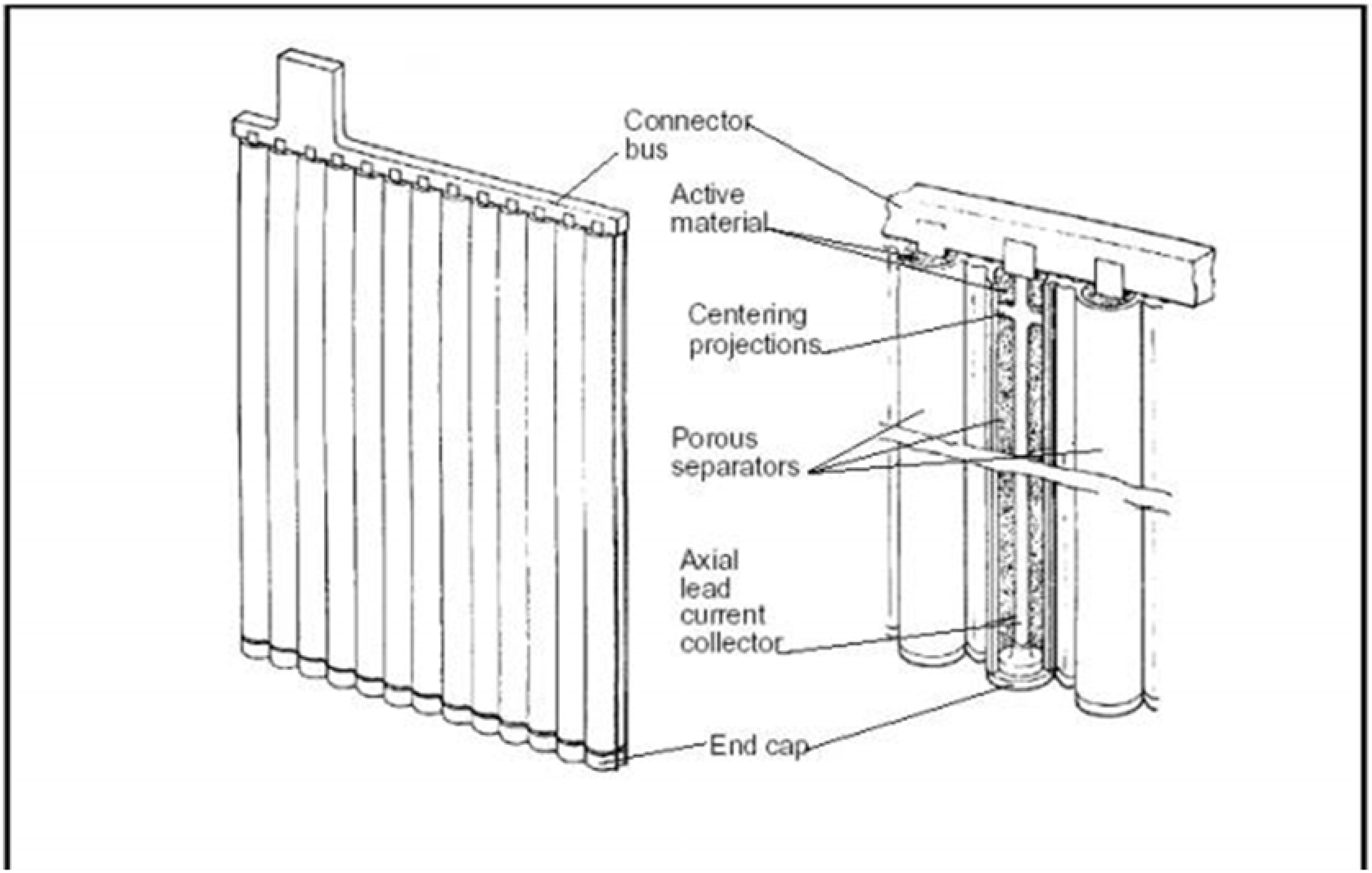
Pasted Plate



Tubular Plate



Tubular Plate



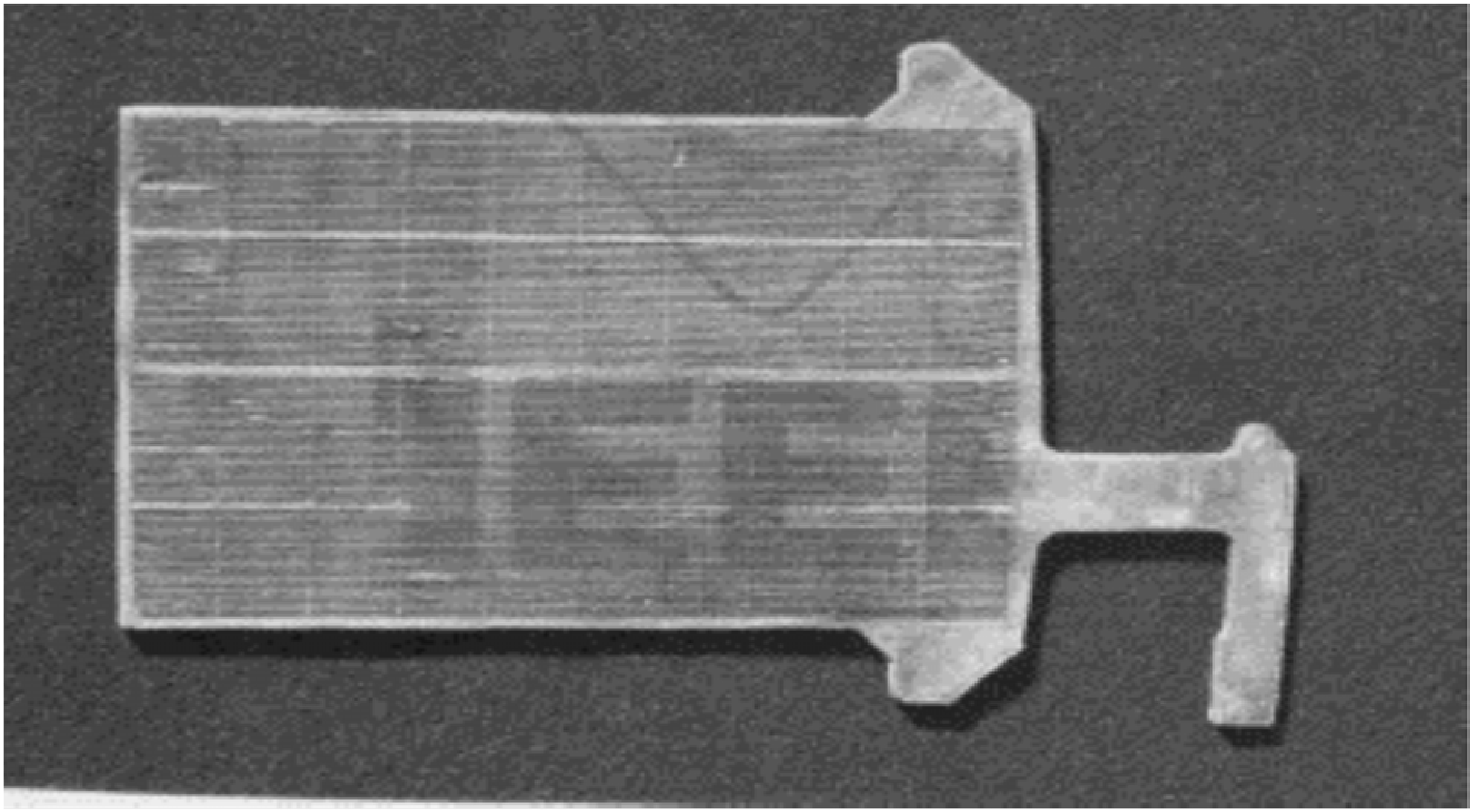
Rod Plate

- Can be used as positive or negative electrode
- Used in standby float applications
- Advantages
  - Robust
- Disadvantages
  - Limited high-rate (short discharge) performance
  - Moderate service life
  - Moderate energy density

Planté Plate

- Can be used as positive electrode only
- Used for standby float application
- Plates configured to increase surface area
- Advantages
  – Extremely reliable
  – Low maintenance
  – Long service life
- Disadvantage
  – High initial cost
  – Moderate energy density

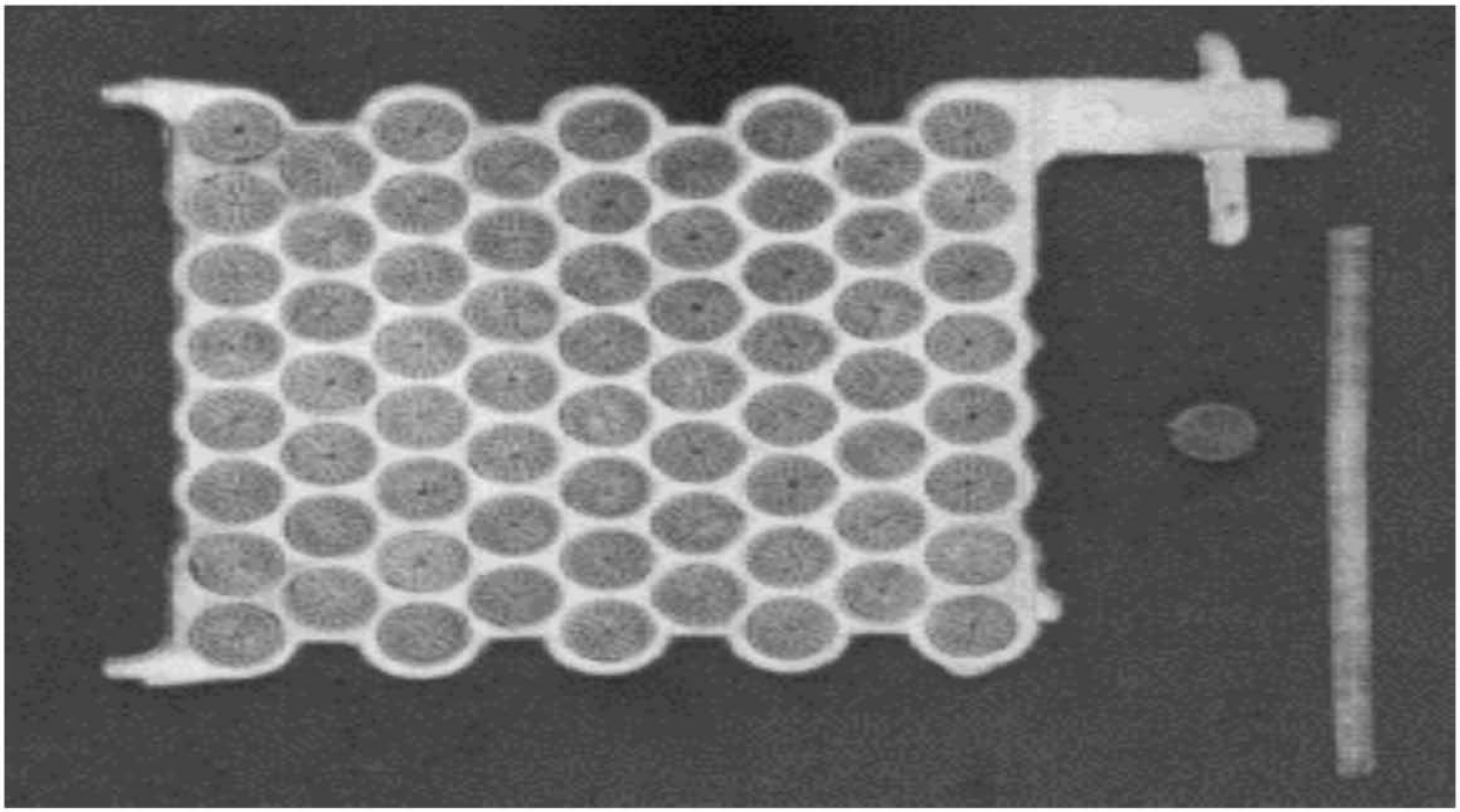
Planté Plate



Modified Planté Plate

- Can be used as positive electrode only
- Uses lead antimony grid with holes and corrugated pure lead strips
- Advantages
  - Long service life
  - High cycling capability
  - Good for high-rate (short discharge)
- Disadvantages
  - High initial cost
  - Low energy density

Modified Planté



Grids

- Support the active material
- Conduct current
- Pure lead grids are mechanically weak
- Alloyed grids are stronger
- Alloying improves the electrical & mechanical properties

Grid Materials

Lead is the primary component of lead-acid battery grids. However, since pure lead is a soft material, the grid are generally alloyed with hardening materials such as:

- Lead calcium
- Lead antimony
- Lead antimony selenium

Pure Lead Grid

- Advantages
  - High energy density
  - Low water consumption (gassing)
- Disadvantages
  - Poor cycling performance
  - Very short life due to material retention properties due to softness
  - Mechanically weak

Lead Calcium Grid

- Advantages
  - Stable (low) float current
  - Low water consumption (gassing)
- Disadvantages
  - Unpredictable aging
  - Poor cycling capability
    - Excessive testing should be avoided

Lead Antimony Grid

- Advantages
  - Mechanically robust
  - Predictable aging
  - Excellent cycling
- Disadvantages
  - Antimony poising
    - Migration of antimony from positive to negative
    - Contamination of electrolyte with antimony with aging
  - High float current (10 times)
  - High water consumption (gassing)

Lead Antimony Selenium

- Low lead-antimony grid with a slight amount of selenium
- Less than 2% antimony
  - Eliminate antimony poisoning
  - Maintain benefits of antimony
    - Predictability
    - Cycling capability
  - Low, stable float current

Negative Plate Construction

- Mostly pasted flat plate, with the exception of round positive plate design

Thick Plate Design

- The conversion of lead to lead sulfate occurs slowly.
- 8 hour/low rate batteries have thick plates

Thin Plate Design

- The conversion of lead to lead sulfate occurs fast
- High rate UPS demand is met by providing many thinner plates
- Thinner plates tend to fail from positive plate corrosion sooner than thicker plates.

Separators & Retainers

- Porous non-conducting inert separator keeps the plates separated & prevents bridging.
- Porous retainers between plates or wrapped around the positive plate
  - Adv: Minimize shedding of active material during charge/discharge
  - Disadv: Increase battery impedance
    - Reduce short rate discharge capability

Nickel Cadmium Batteries

Electrochemistry of Batteries

Nickel Cadmium:

- **Positive Plate:** Nickel Hydroxide, $Ni(OH)_2$
- **Negative Plate:** Spongy Cadmium (Cd)
- **Electrolyte:** Potassium Hydroxide (KOH)

  (KOH does not take part in the chemical reaction)

Chemical Reaction of Nickel-Cadmium Batteries

- <u>At negative plate:</u>

$Cd(OH)_2 + 2e \rightarrow Cd + 2OH^-$

- <u>At positive plate:</u>

$2Ni(OH)_2 + 2OH^- \rightarrow NiOOH + 2H_2O + 2e$

- <u>Overall reaction:</u>

(Charged) KOH (Discharged)

$Cd + 2NiOOH + 2H_2O \rightarrow Cd(OH)_2 + 2Ni(OH)_2$

Plate Construction for Nickel Cadmium

- Active Materials:
  - Positive: Nickel Hydroxide
  - Negative: Cadmium Hydroxide
- Plates:
  - Pocket Plate
  - Sintered Plate
  - Fiber Plate
  - Plastic Bonded Plate

Nickel Cadmium Batteries

- Advantages
  - Tolerant to temperature extremes
  - Resistant to mechanical and electrical abuse
  - High cycling capability
- Disadvantages
  - Lower cell voltage
  - Memory effect
  - More need for equalization
  - Higher cost
  - Electrolyte contamination (carbonation)
    - KCO4 is formed in the electrolyte when exposed to air
      - Frequent replacement of electrolyte (every 5-6 years)

Pocket Plate

- Active material interlocked in pockets of perforated nickel-plated steel strips
- All mechanical parts and connections are made of steel

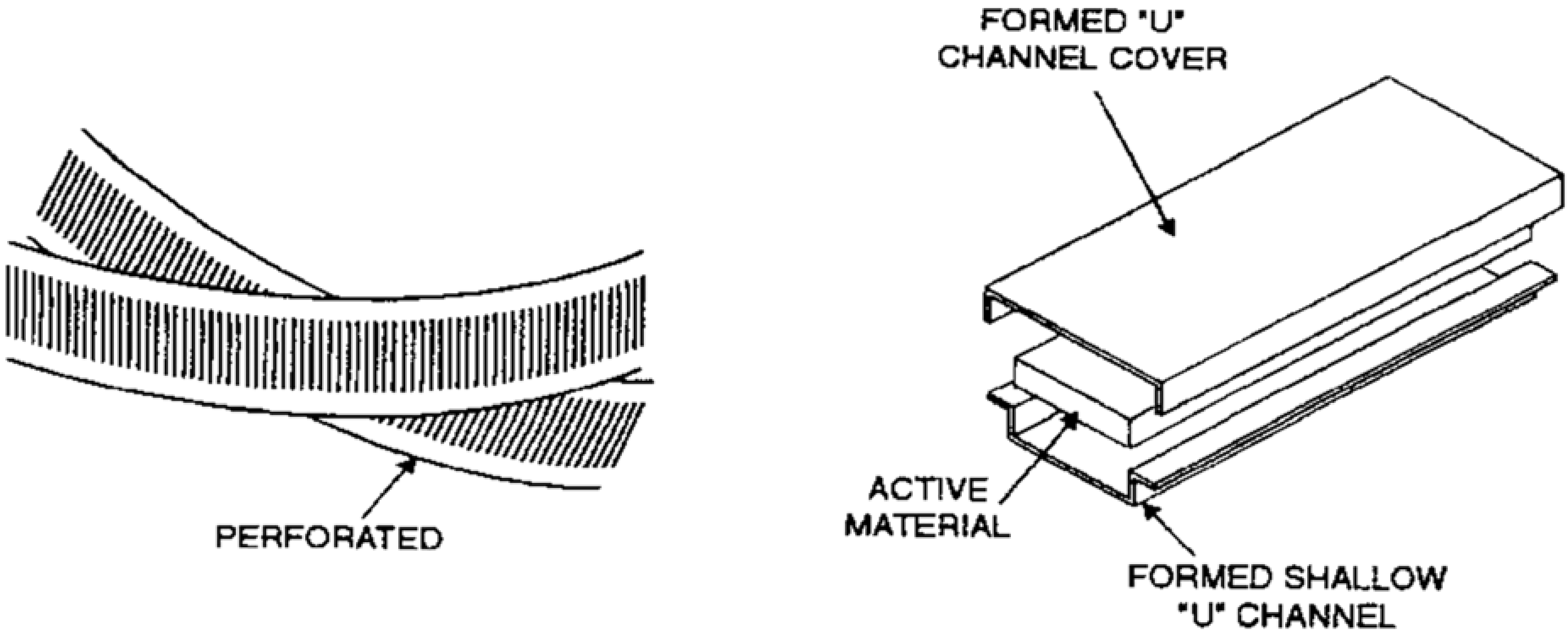
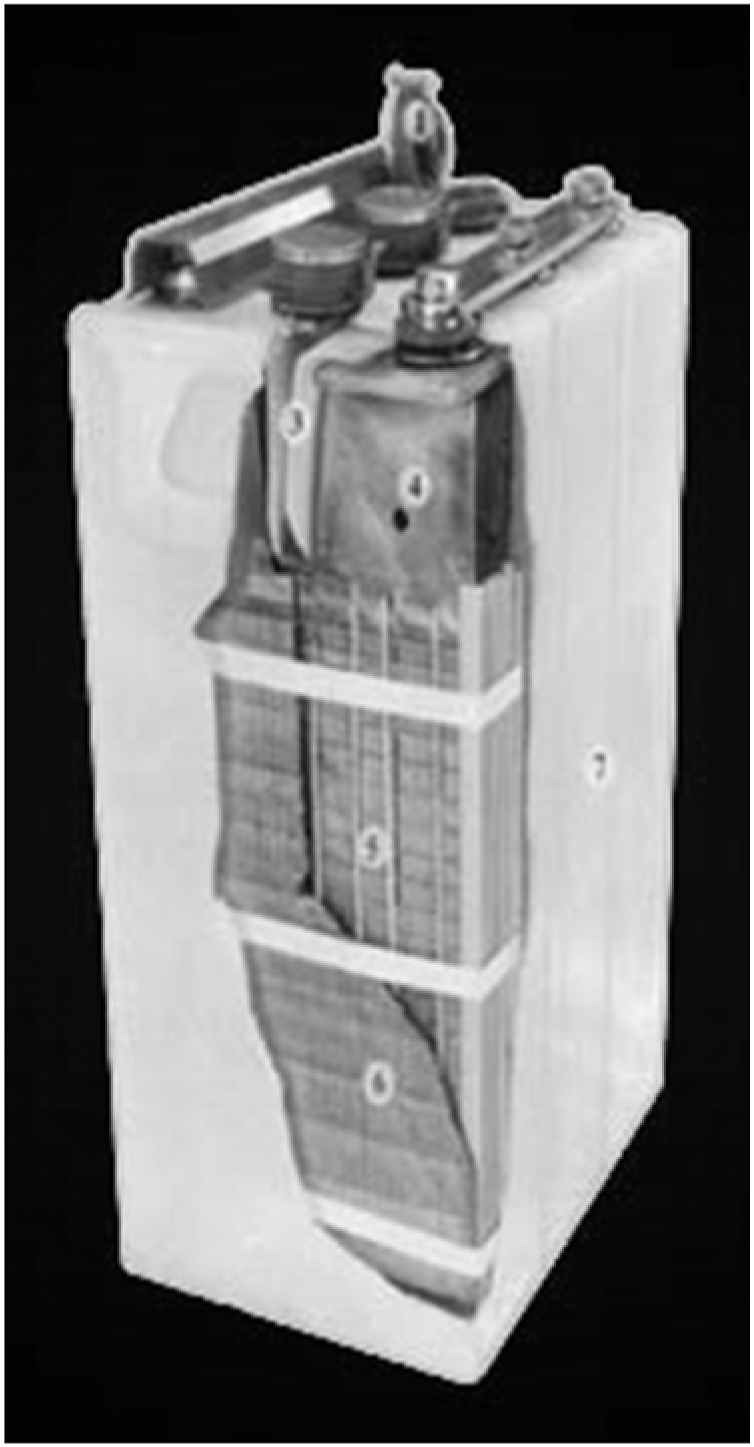
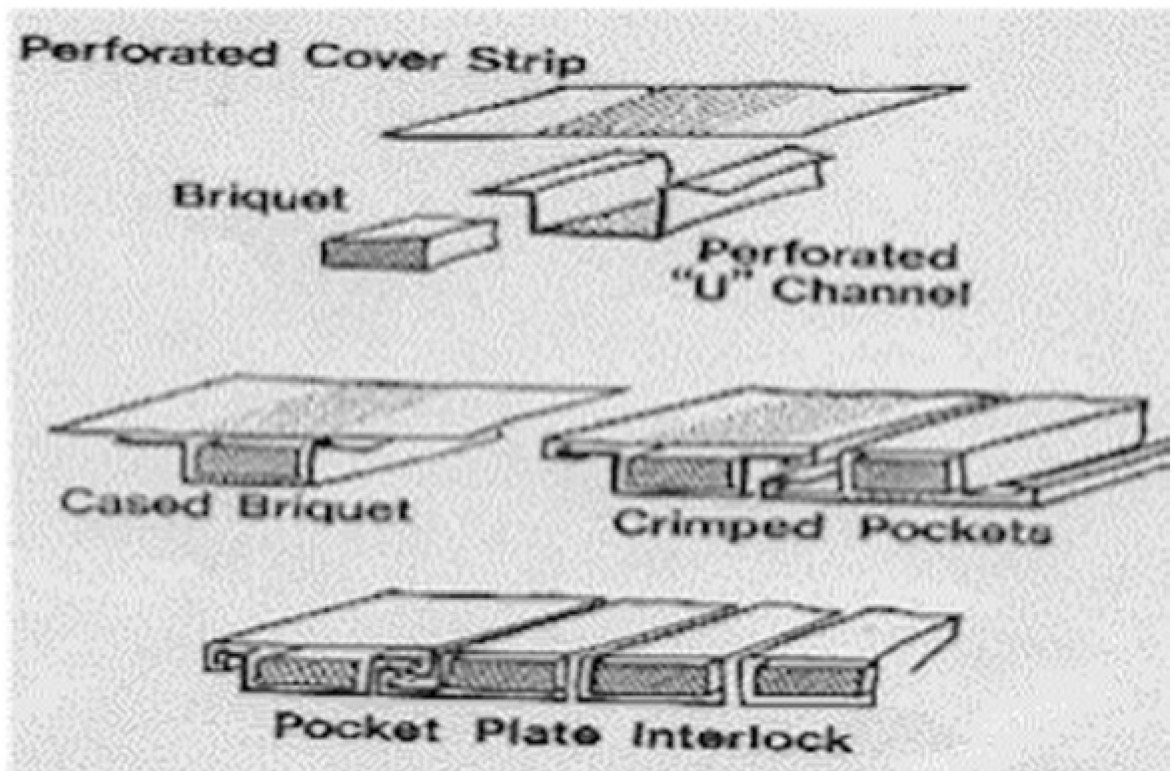


Figure 5

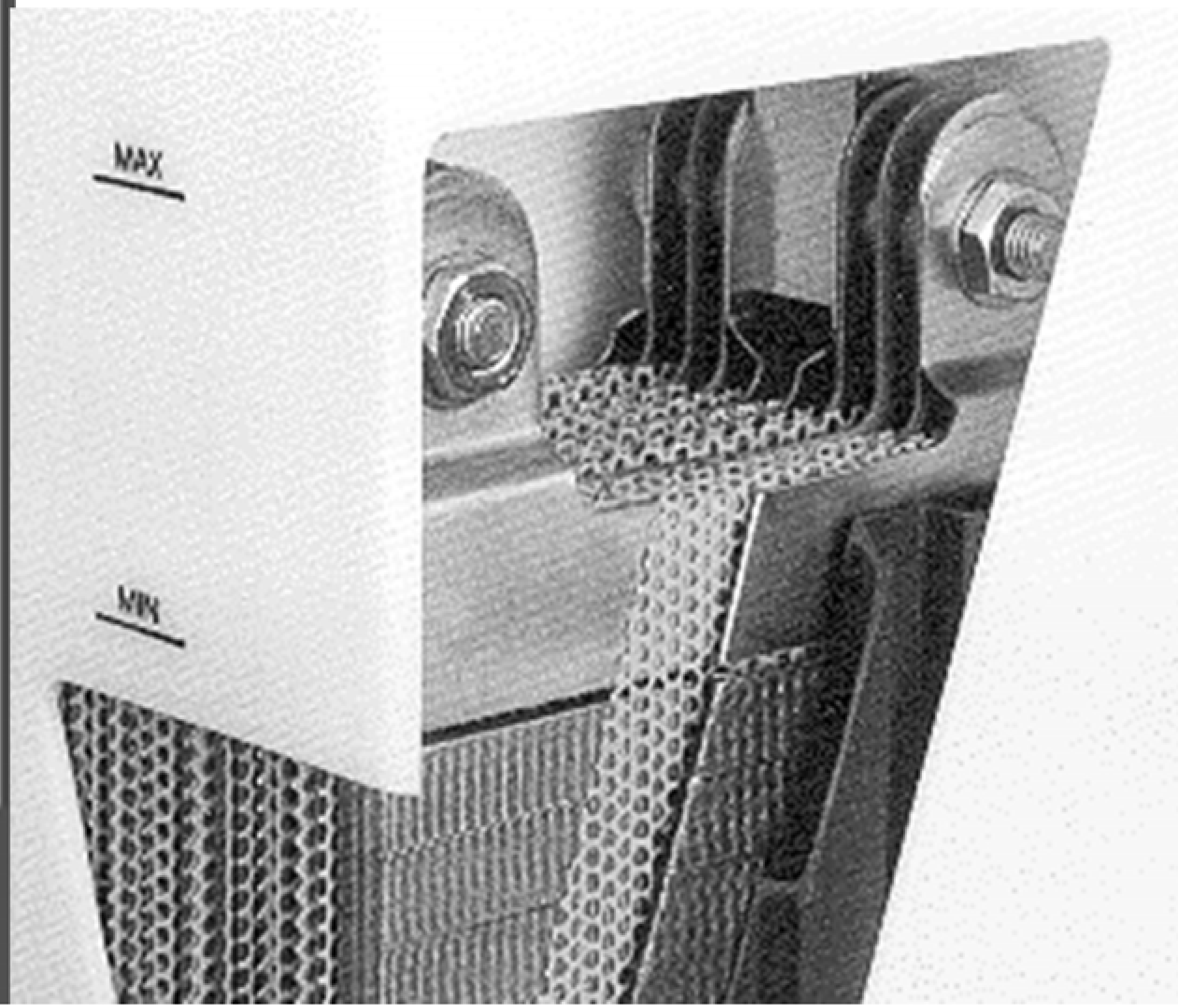
Pocket Plate Construction

Pocket Plate





Pocket Plate



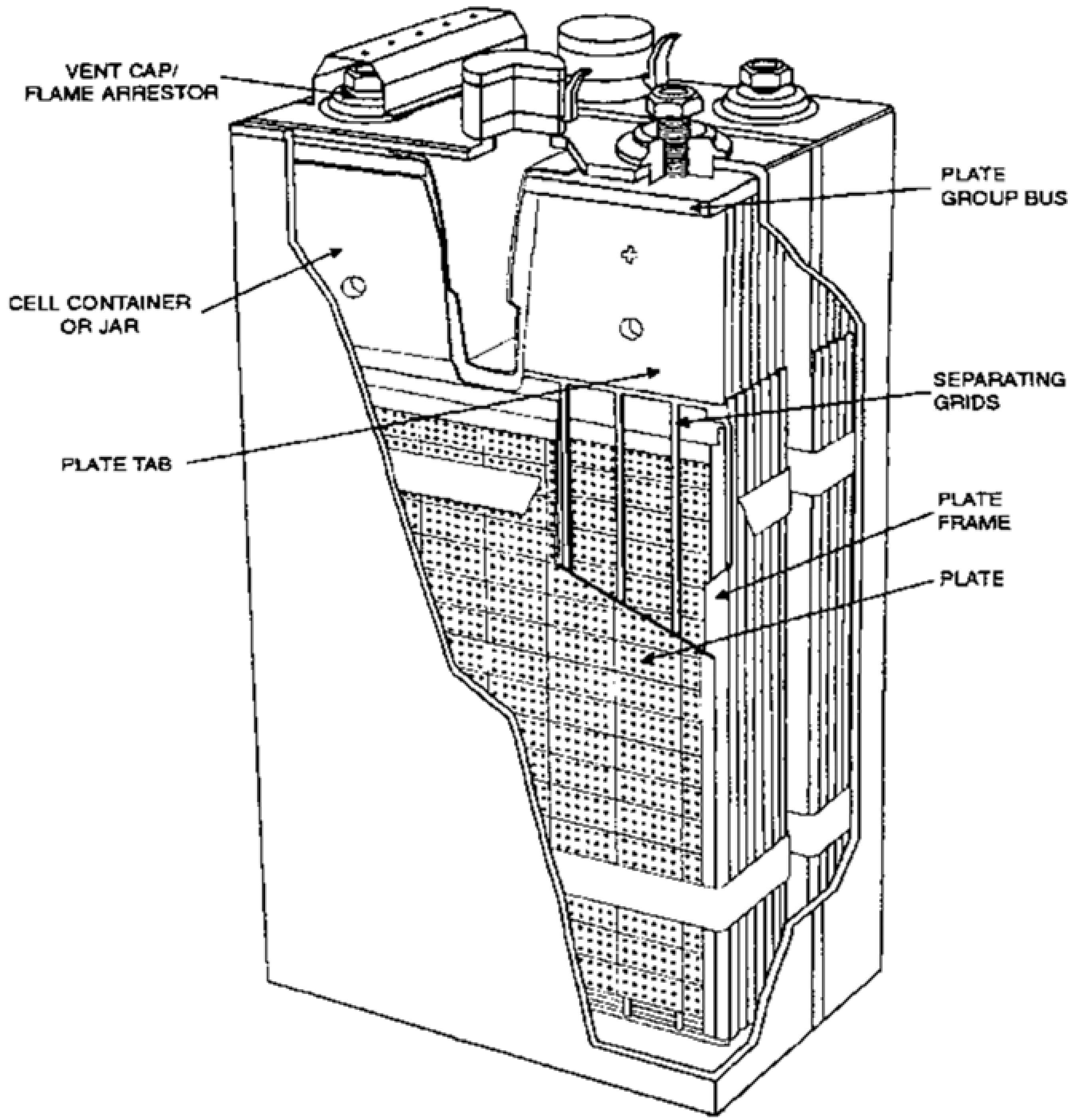


Figure 6

Typical Pocket Plate Nickel-Cadmium Battery

Sintered Plate

- Sintered plates utilize nickel powder to form a highly porous metal sponge. The pores of this material are impregnated with the active material
- High discharge performance
- Very long life.
- Excellent energy density

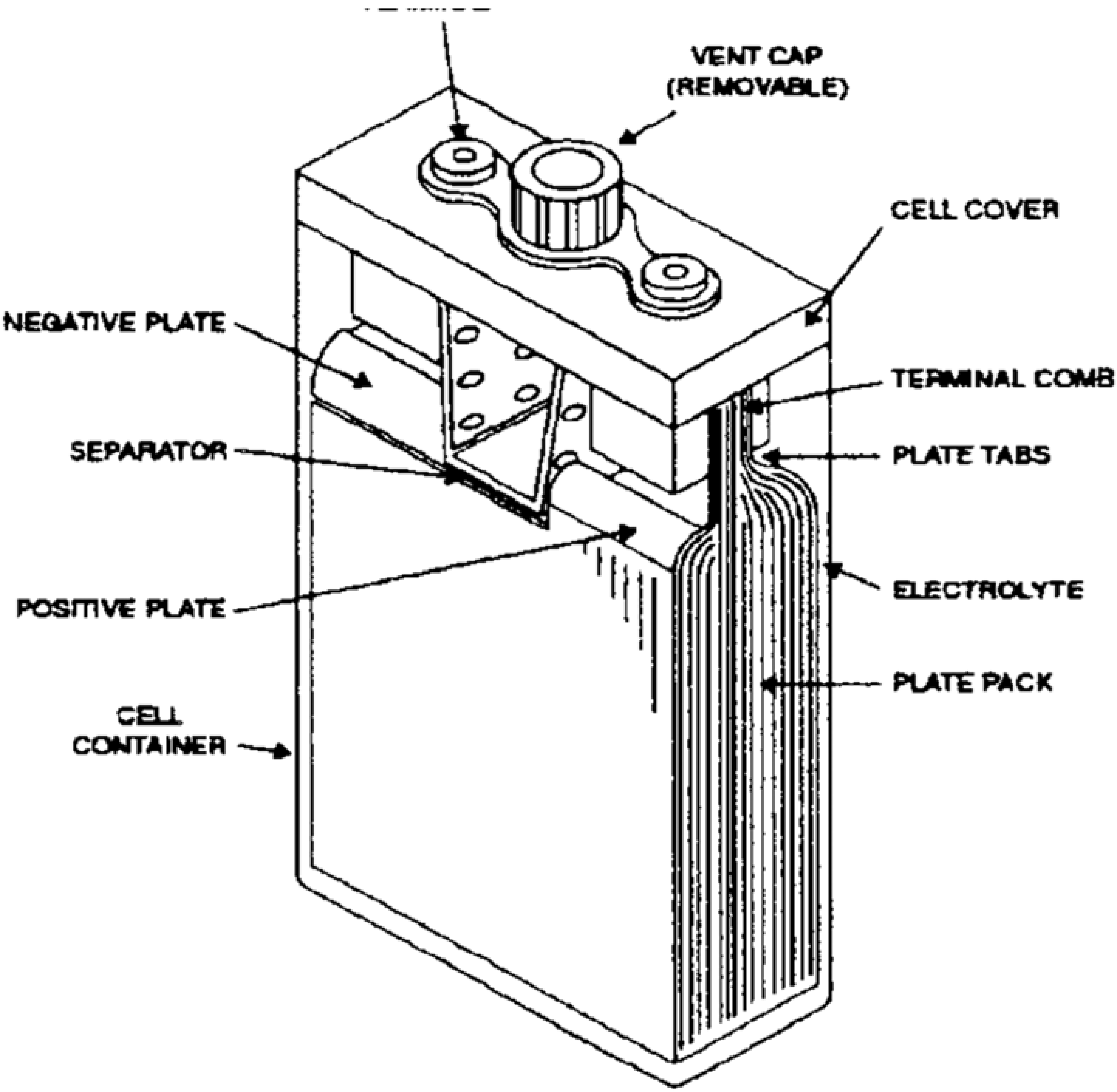


Figure 7

Typical Sintered-Plate Ni-Cad. Battery

Sintered Plate Ni-Cad Battery

Valve Regulated Lead Acid Batteries

- Types
  - Gelled Electrolyte
  - Absorbed Glass Mat (AGM)
- Recombination Principle
  - **Gas Recombination** - Gas formed within the cell is recombined within the cell rather than being vented to atmosphere

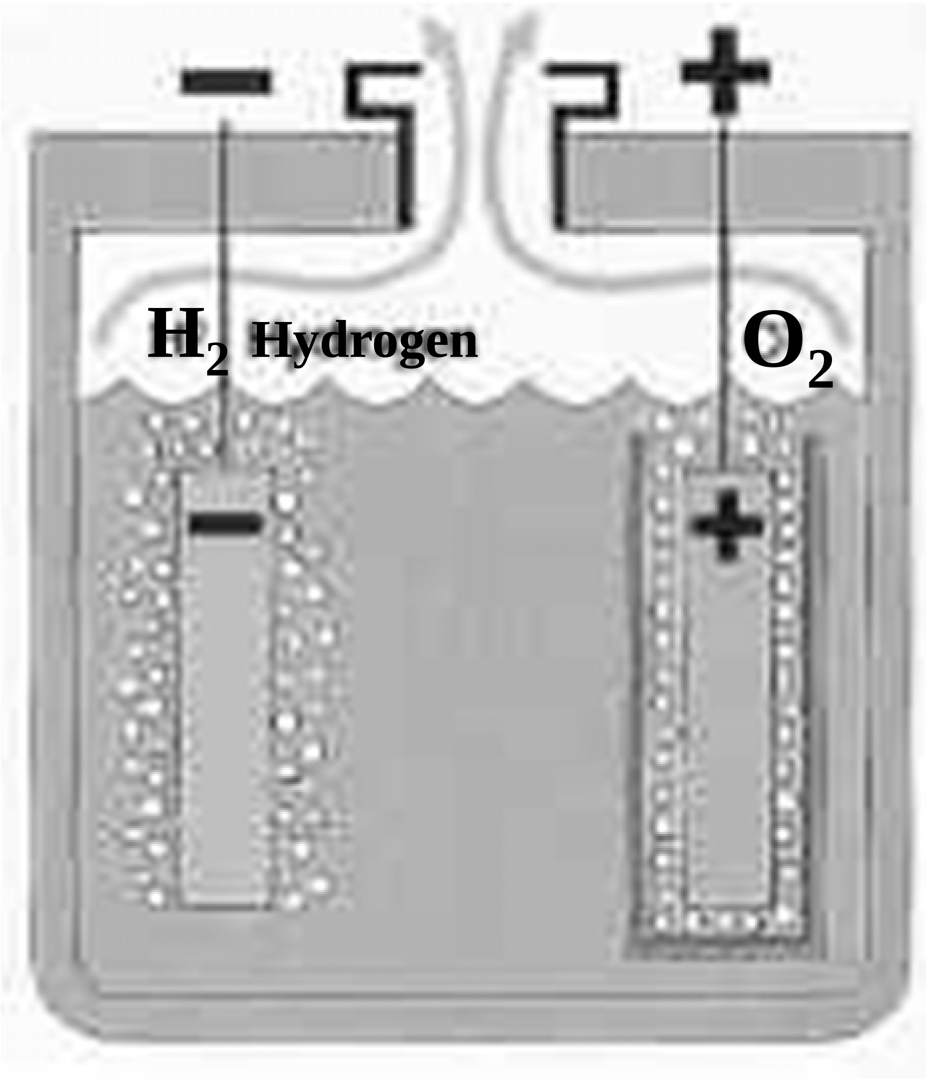
What is VRLA Battery?

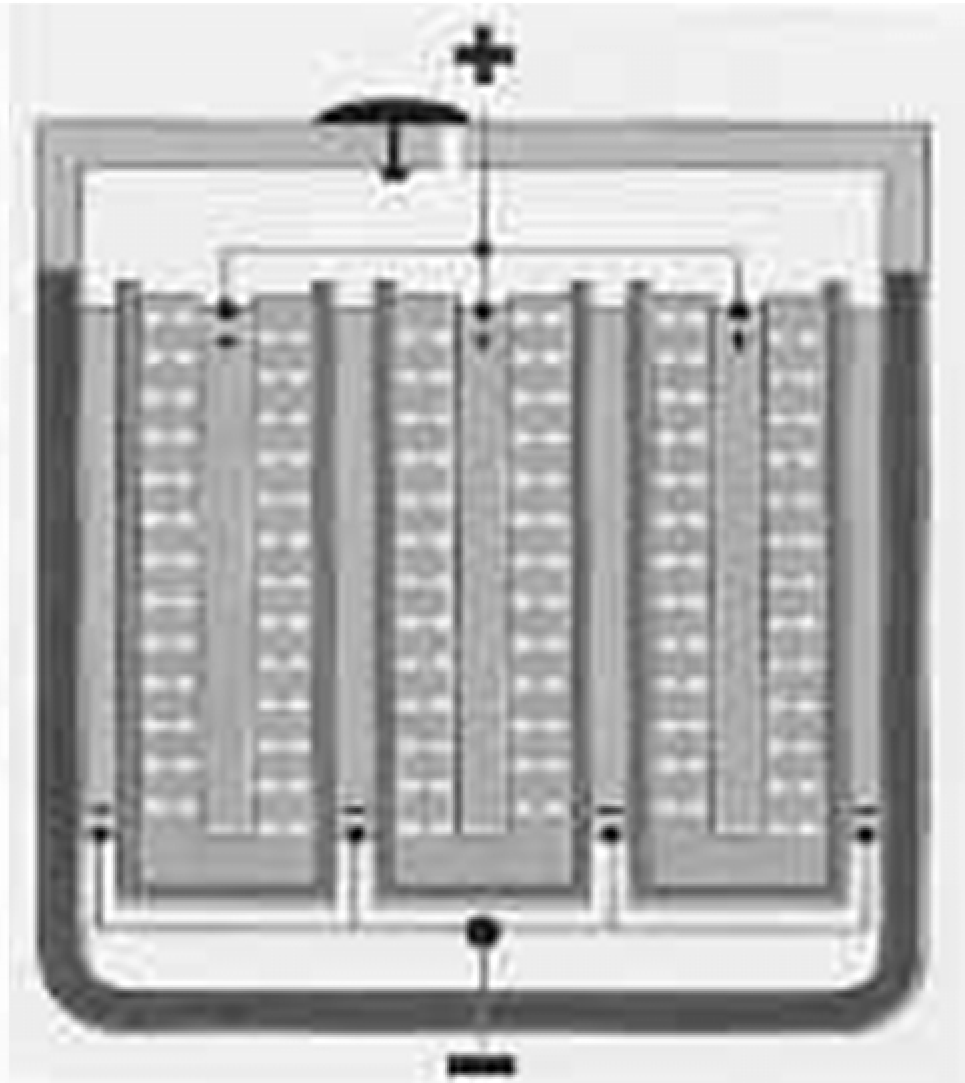
Valve-regulated lead-acid (VRLA) battery is:

A cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds atmospheric pressure by a pre-selected amount. VRLA cells provide a means for recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

(IEEE-1188)

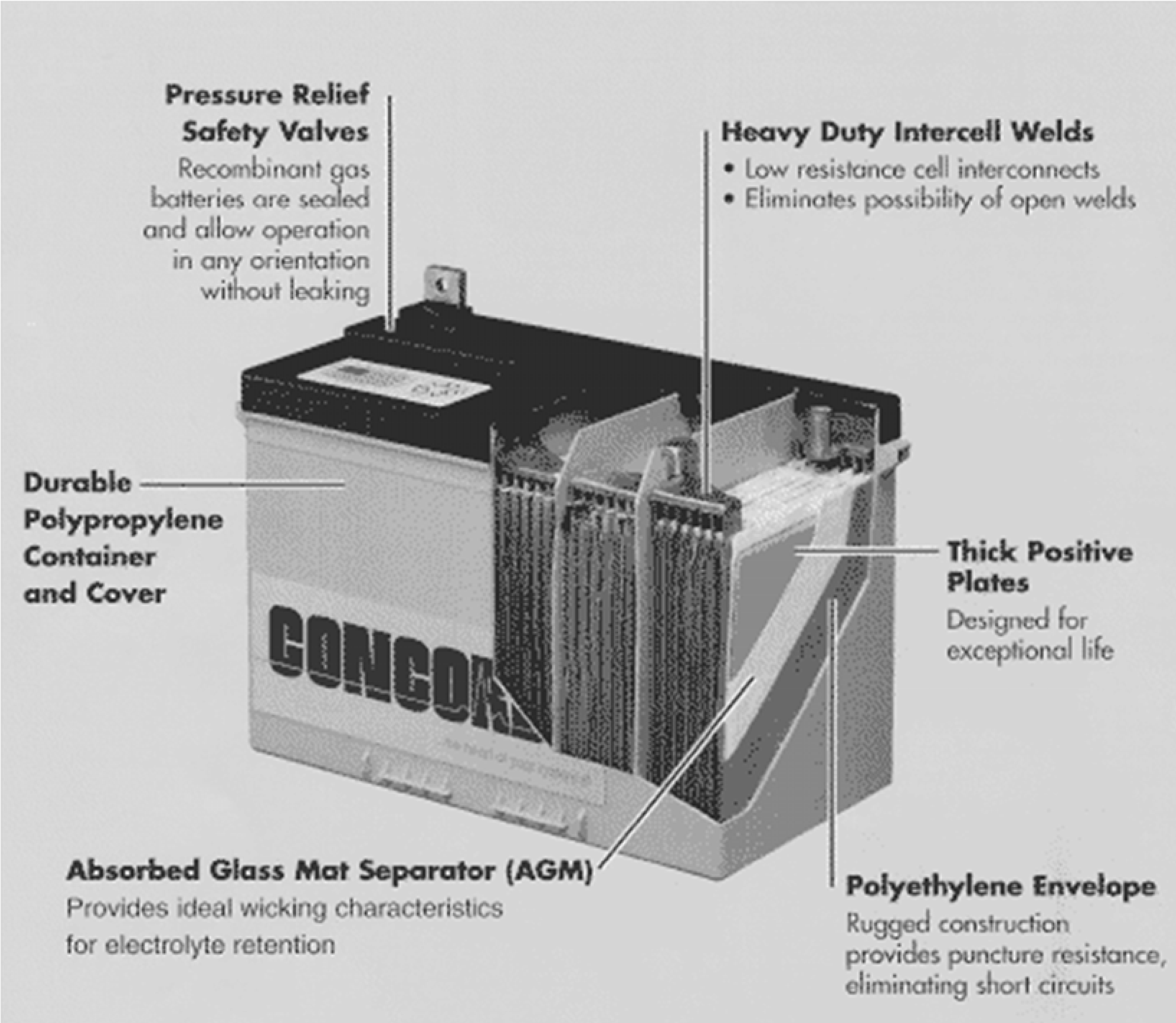
Flooded vs. VRLA



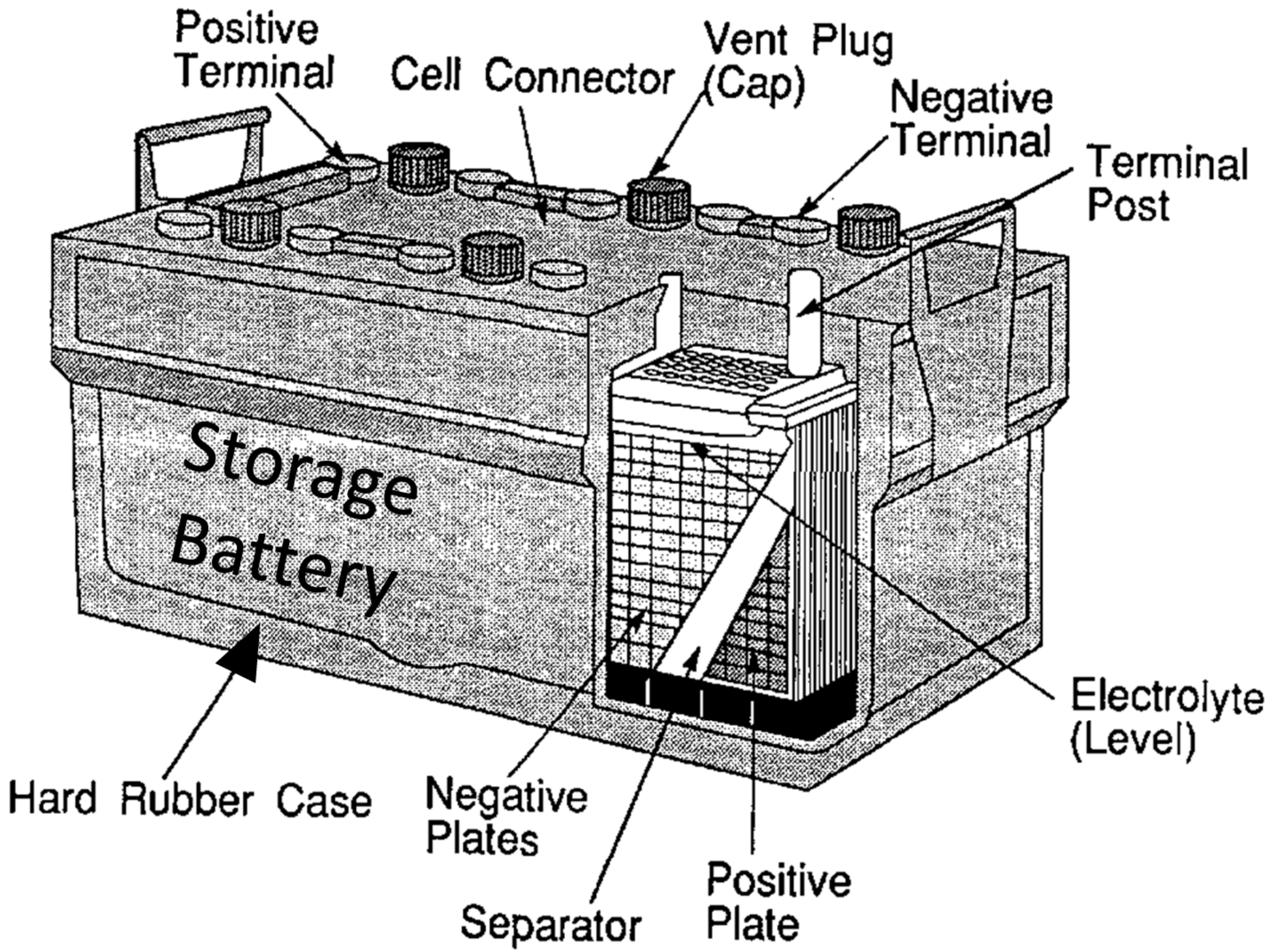


Advantage and Disadvantages of VRLA

Advantages	**Disadvantages**
Low initial cost	Short life
Less gassing	Dry-out
High energy density	Thermal runaway
Clean	Sensitive
No water addition	Negative strap corrosion
Low maintenance	Faster loss of high-rate capability



VRLA BATTERY


Positive
Terminal
Cell Connector
Vent Plug
(Cap)
Negative
Terminal
Terminal
Post
Storage
Battery
Electrolyte
(Level)
Hard Rubber Case
Negative
Plates
Separator
Positive
Plate

DC/UPS SYSTEMS

(Emergency Backup Systems)

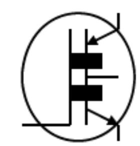
BATTERY CHARGERS

Power Electronics Basic Components

- Diode: *Semiconductor Device that conducts current in one direction*

- Thyristor or SCR (Silicon Controlled Rectifier): *Semiconductor Device that switches ON to conduct current when gate signal is applied*

- IGBT (Insulated Gate Bipolar Transistor) : *Semiconductor Device that switches current ON and OFF by a control gate signal*



Battery Charger (Rectifier)

- A device that changes AC to DC
- It provides DC power to
  – Charge battery
  – Load (Inverter in case of UPS)

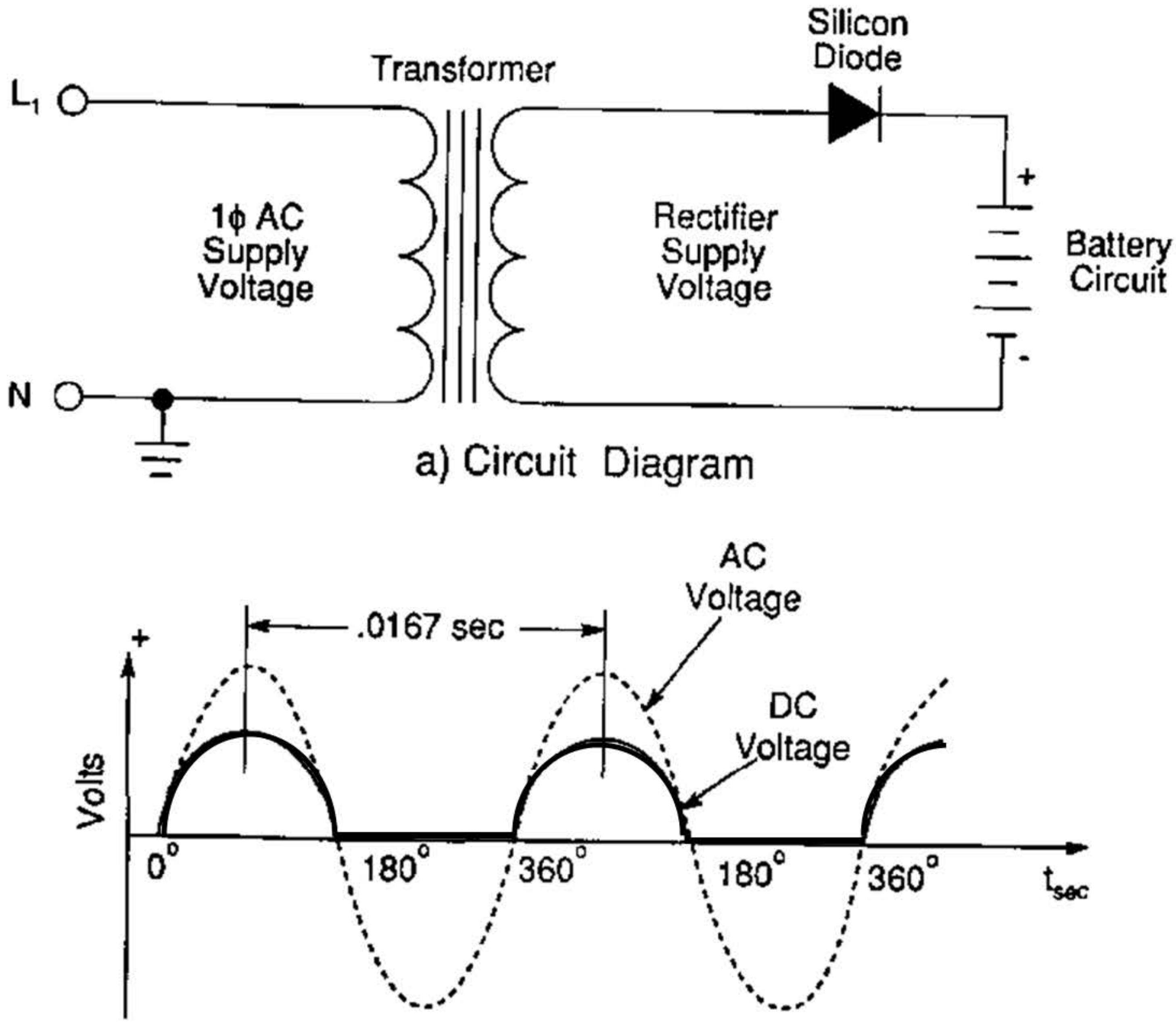
Types of Rectifiers

1. Simple Half-Wave Rectifier
2. Center-Tap Full-Wave Rectifier
3. Full-Wave Bridge Rectifier
4. Three-Phase Half-Wave Rectifier
5. Three-Phase Full-Wave Rectifier (6 pulse)
6. Double 3ϕ Full-Wave Rectifier (12 pulse)

Simple Half-Wave Rectifier

1. Single diode
2. Ripple frequency the same as fundamental frequency, 60 Hz
3. Not used for battery charging

Simple Half-Wave Rectifier

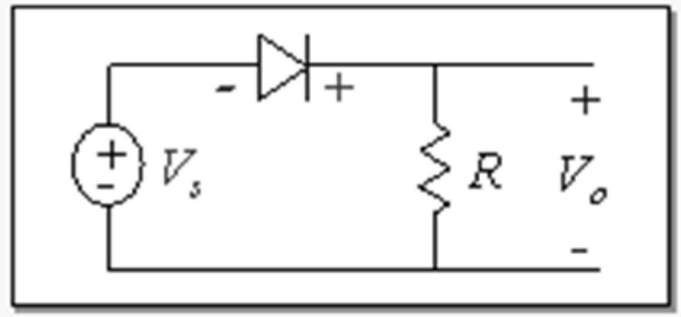


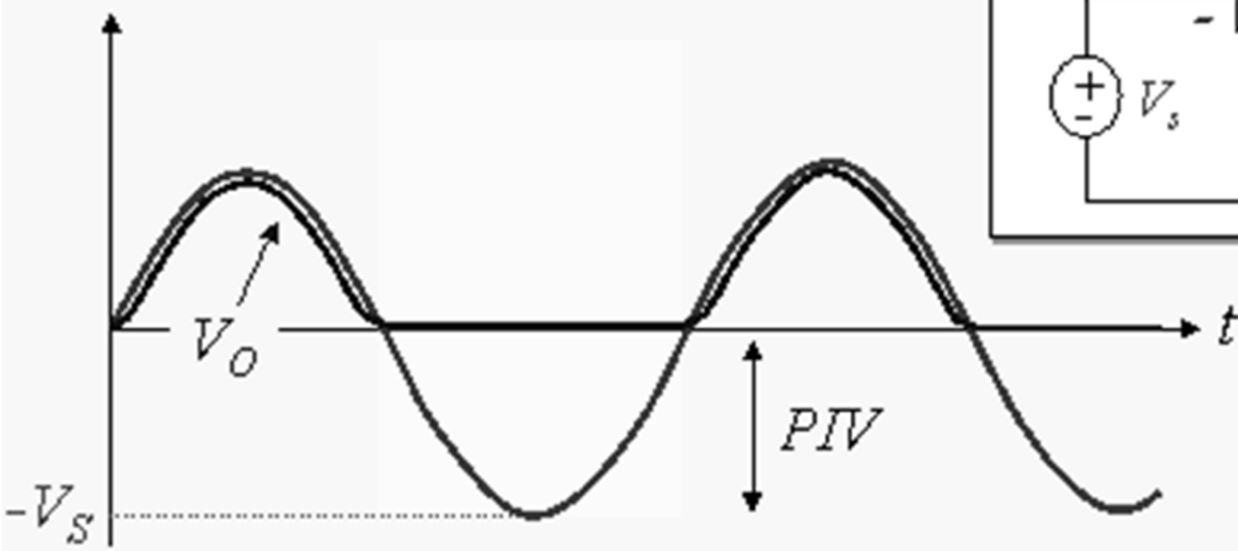
b) Voltage Profile

Source: I. Lazar

HALF-WAVE RECTIFIERS

(Peak Inverse Voltage)



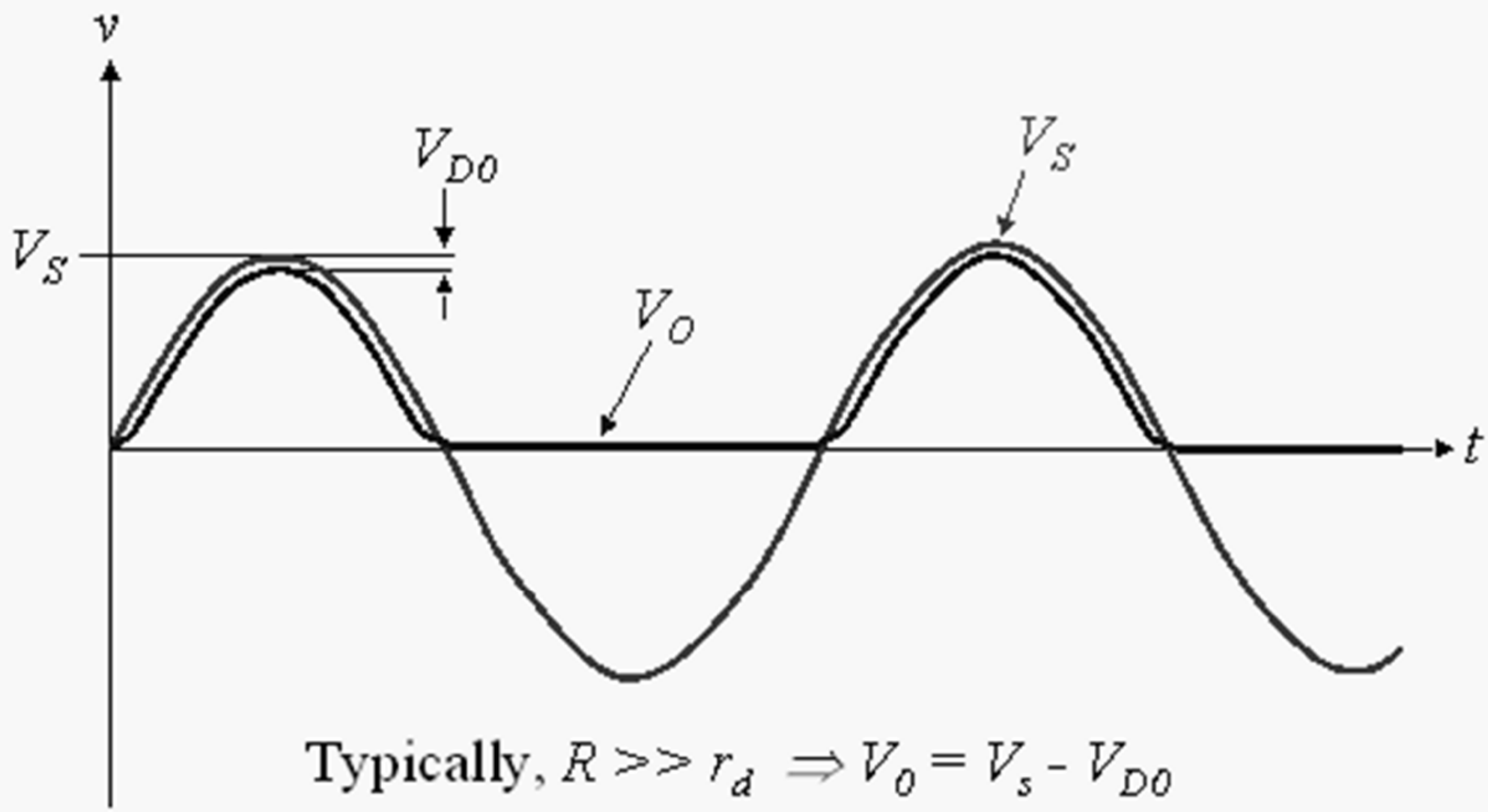


PIV (Peak Inverse Voltage): *The maximum reverse voltage the diode must be able to withstand without breakdown.*

For half-wave rectifiers: $PIV = V_s$

HALF-WAVE RECTIFIERS

(Waveforms)

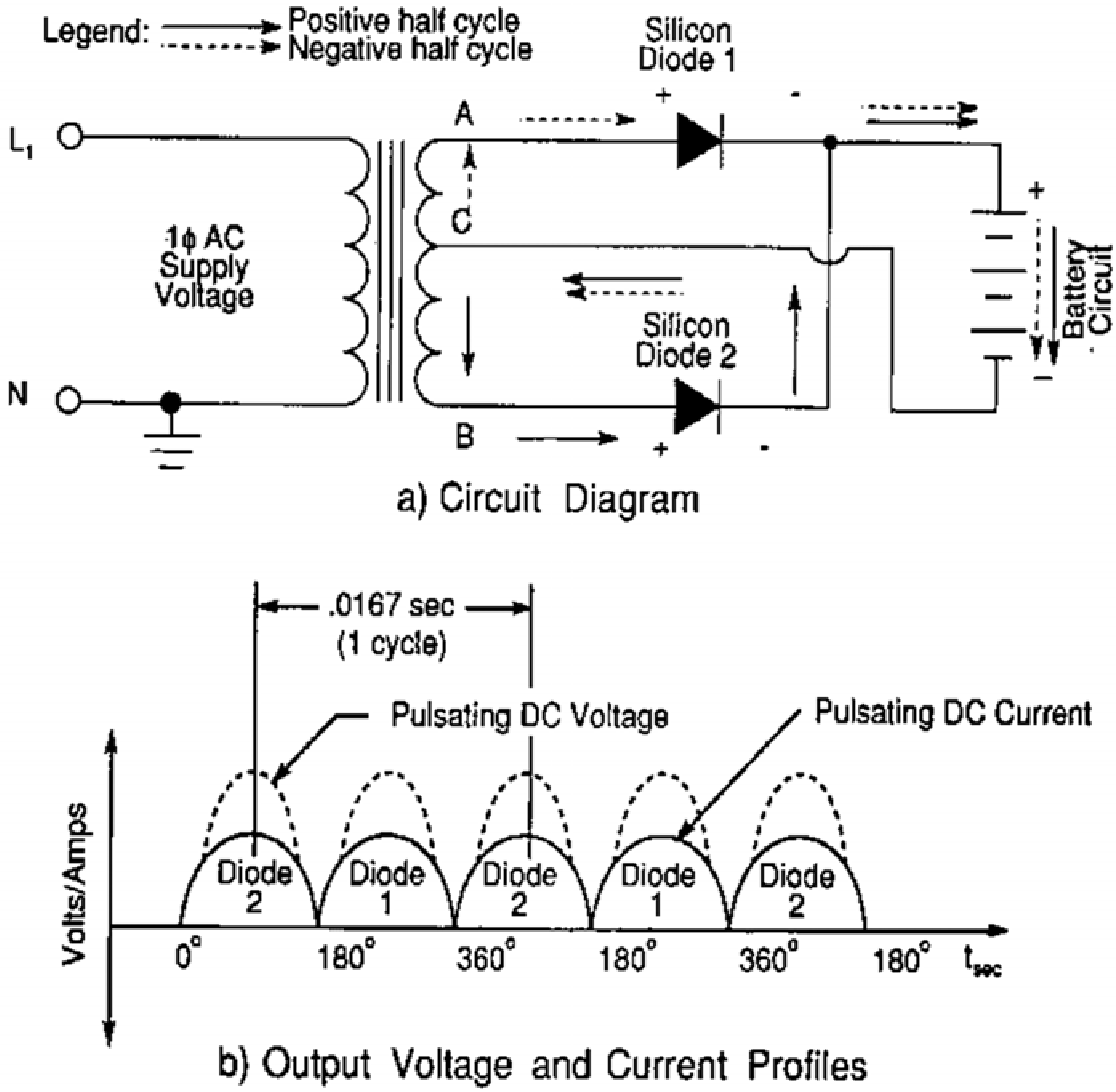


Typically, $R >> r_d \Rightarrow V_0 = V_s - V_{D0}$

Center-Tap Full-Wave Rectifier

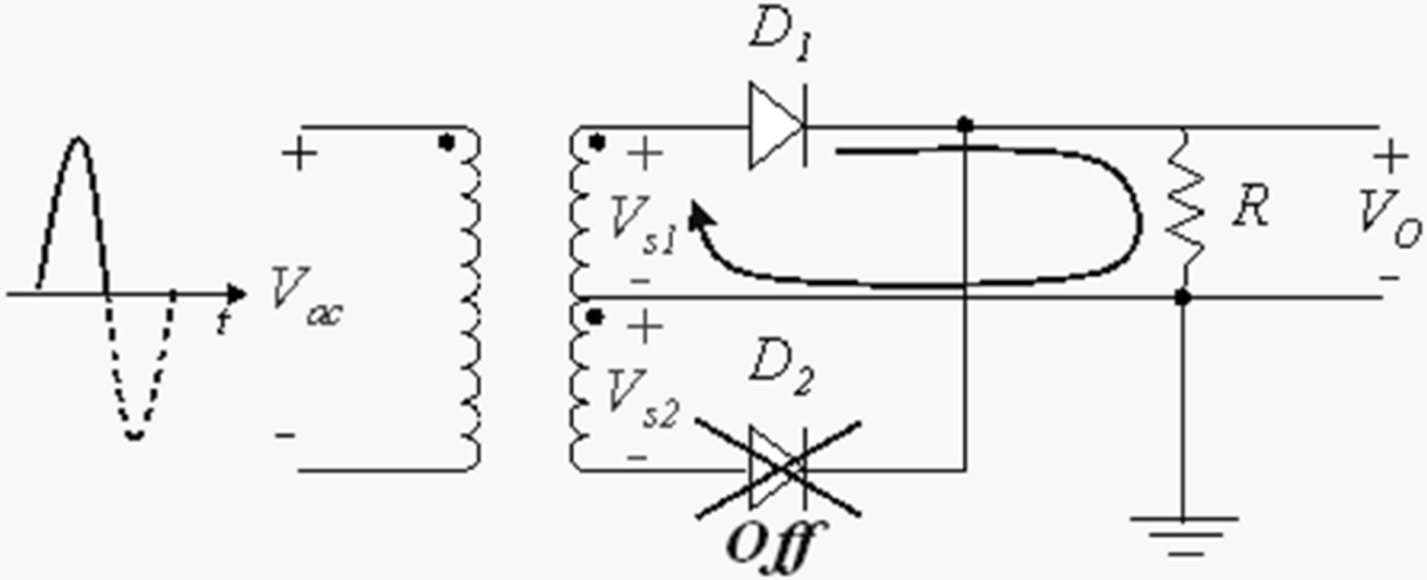
1. Two diodes: one diode connects during the positive half-cycle and the other connects during the negative half-cycle
2. The ripple frequency is twice the fundamental frequency, 120 Hz
3. Extensively used in 1-phase chargers

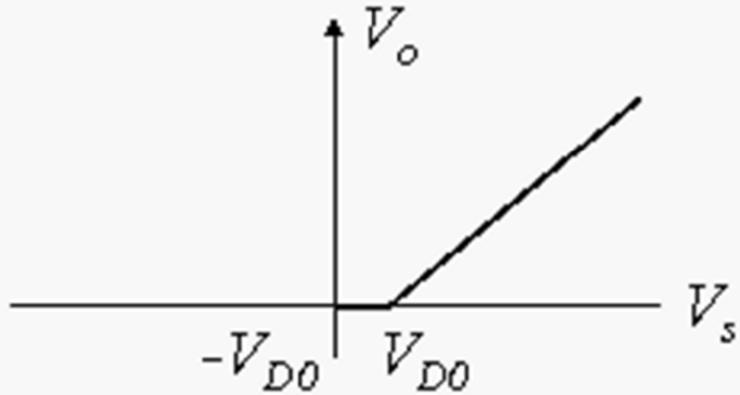
Center-Tap Full-Wave Rectifier



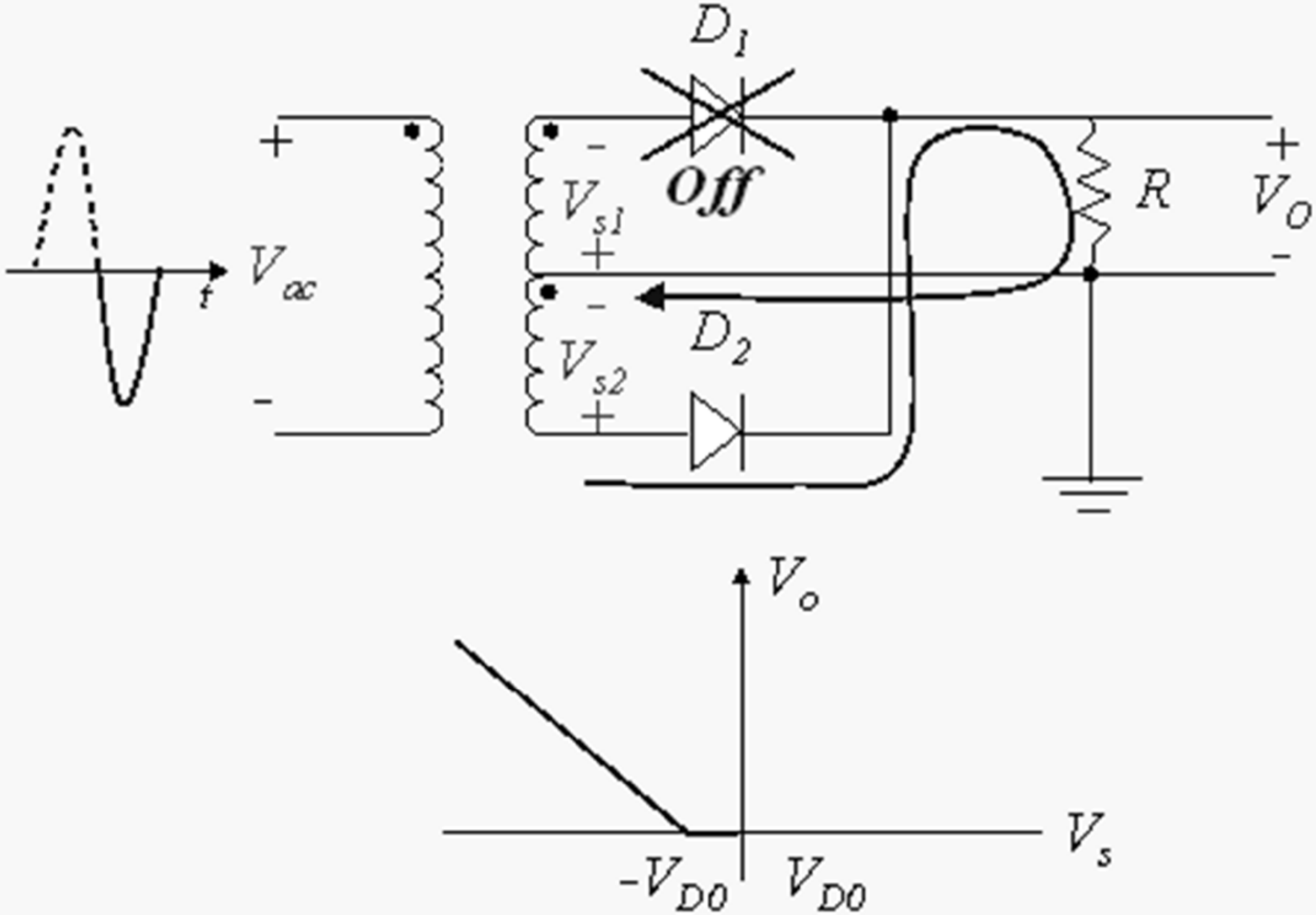
Source: I Lazar

FULL-WAVE RECTIFIER

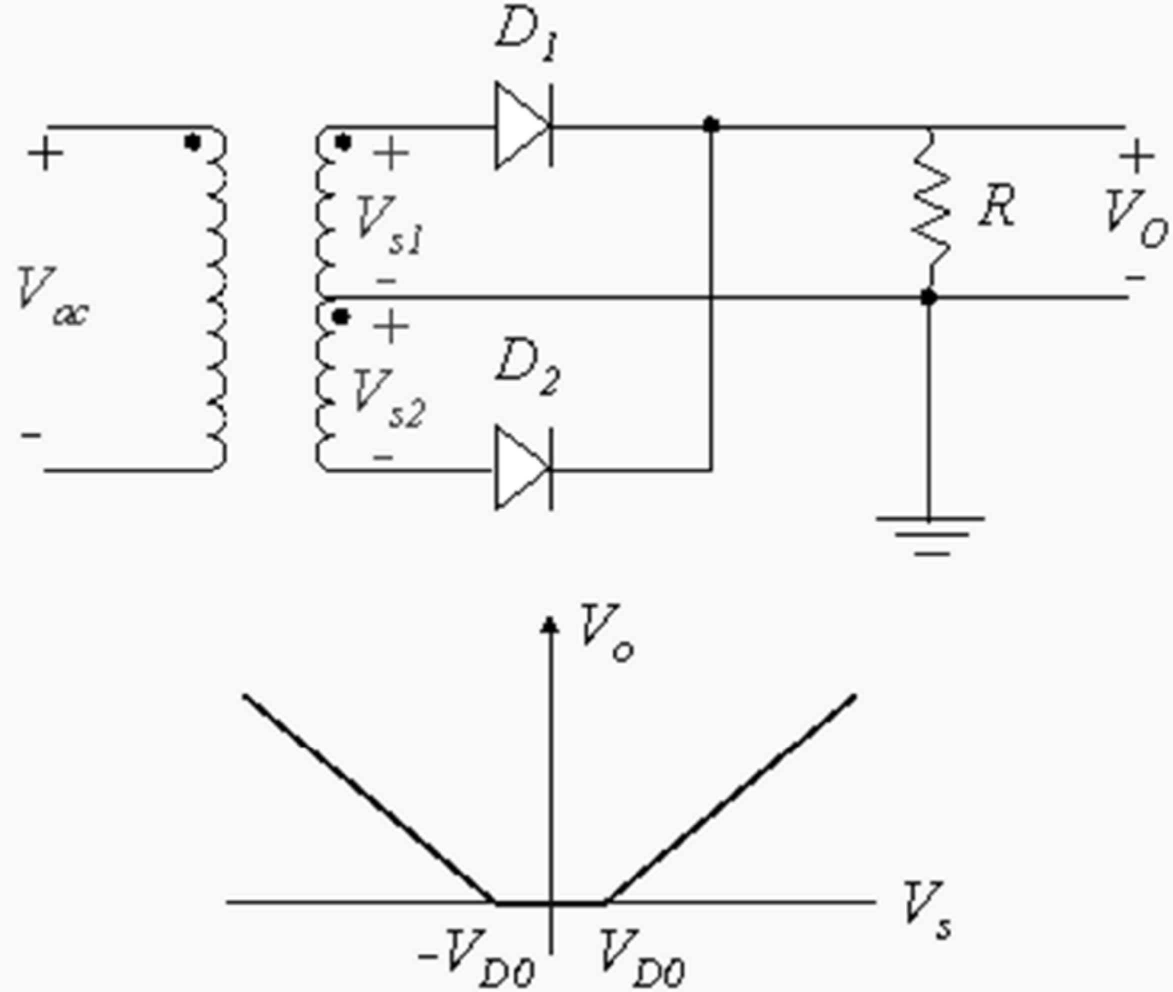




FULL-WAVE RECTIFIER

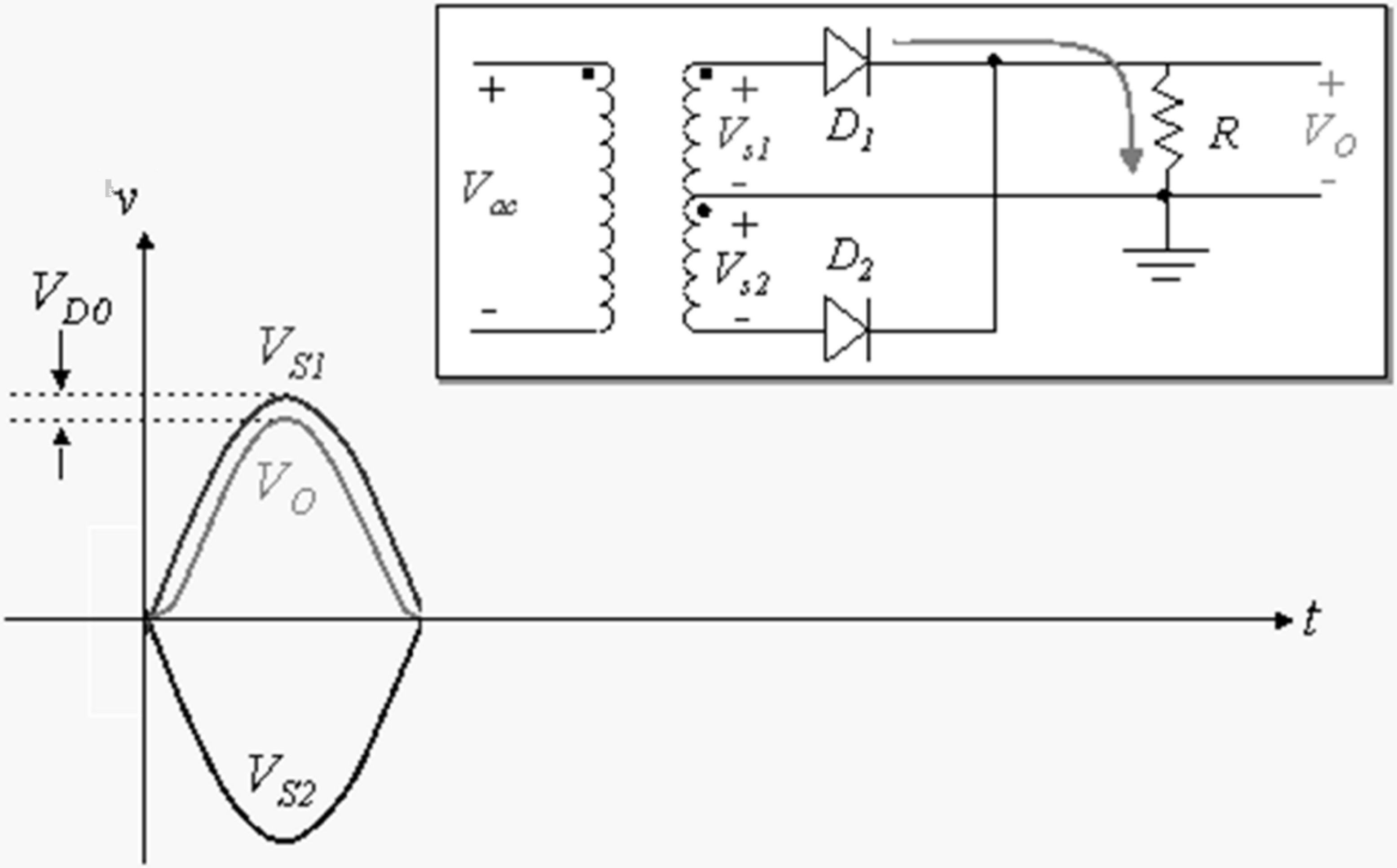


FULL-WAVE RECTIFIER



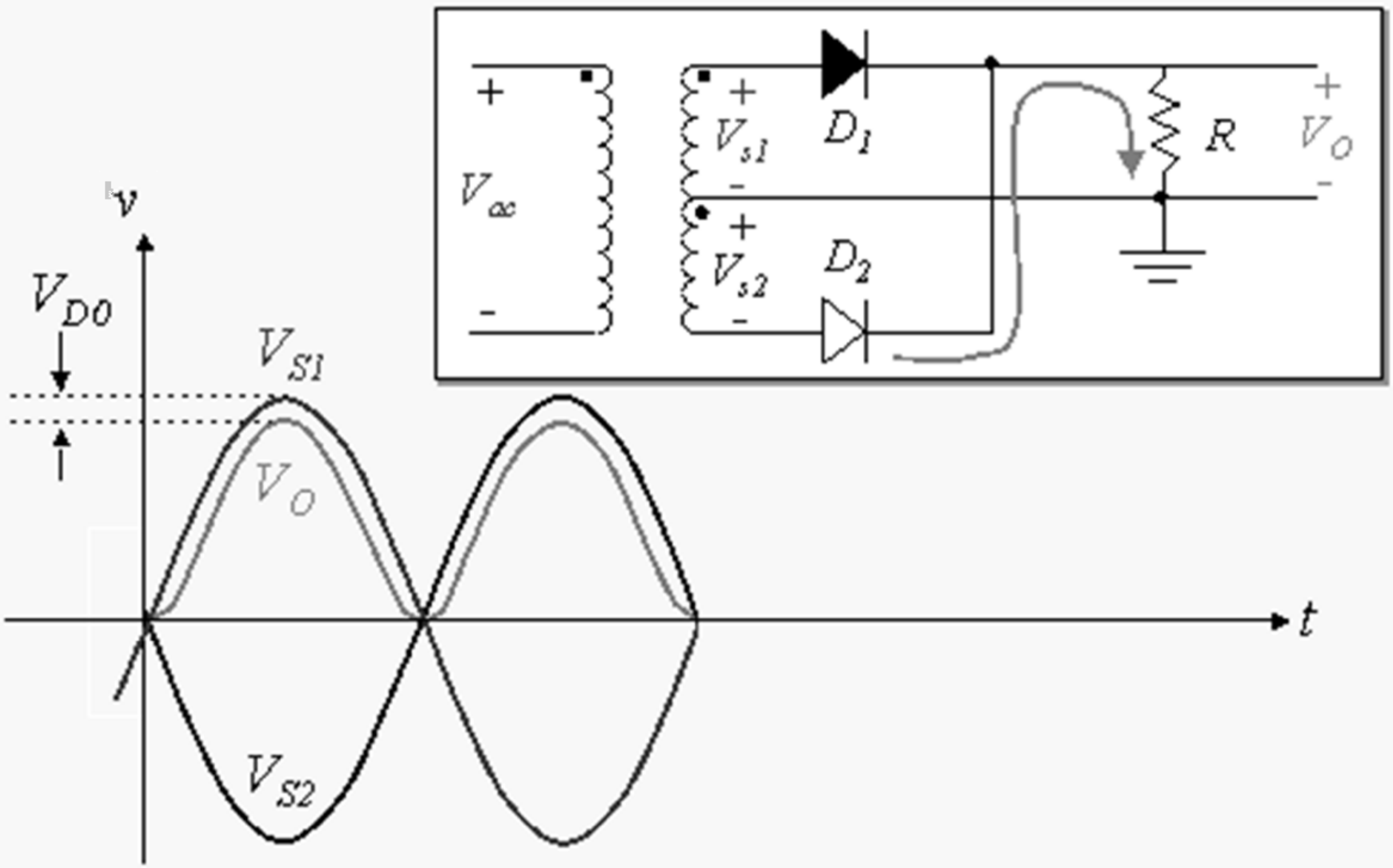
FULL-WAVE RECTIFIER

- Waveforms -



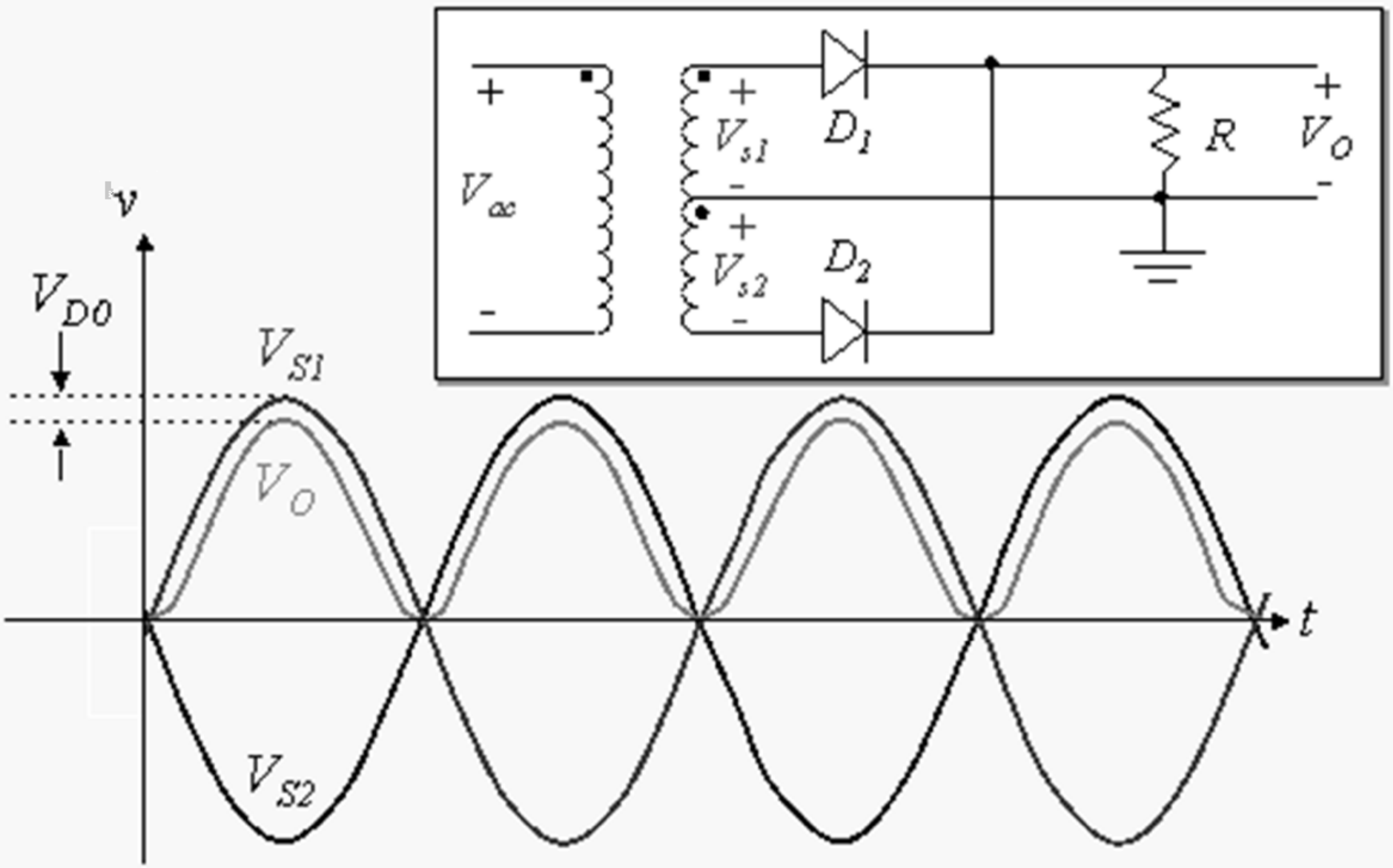
FULL-WAVE RECTIFIER

- Waveforms -



FULL-WAVE RECTIFIER

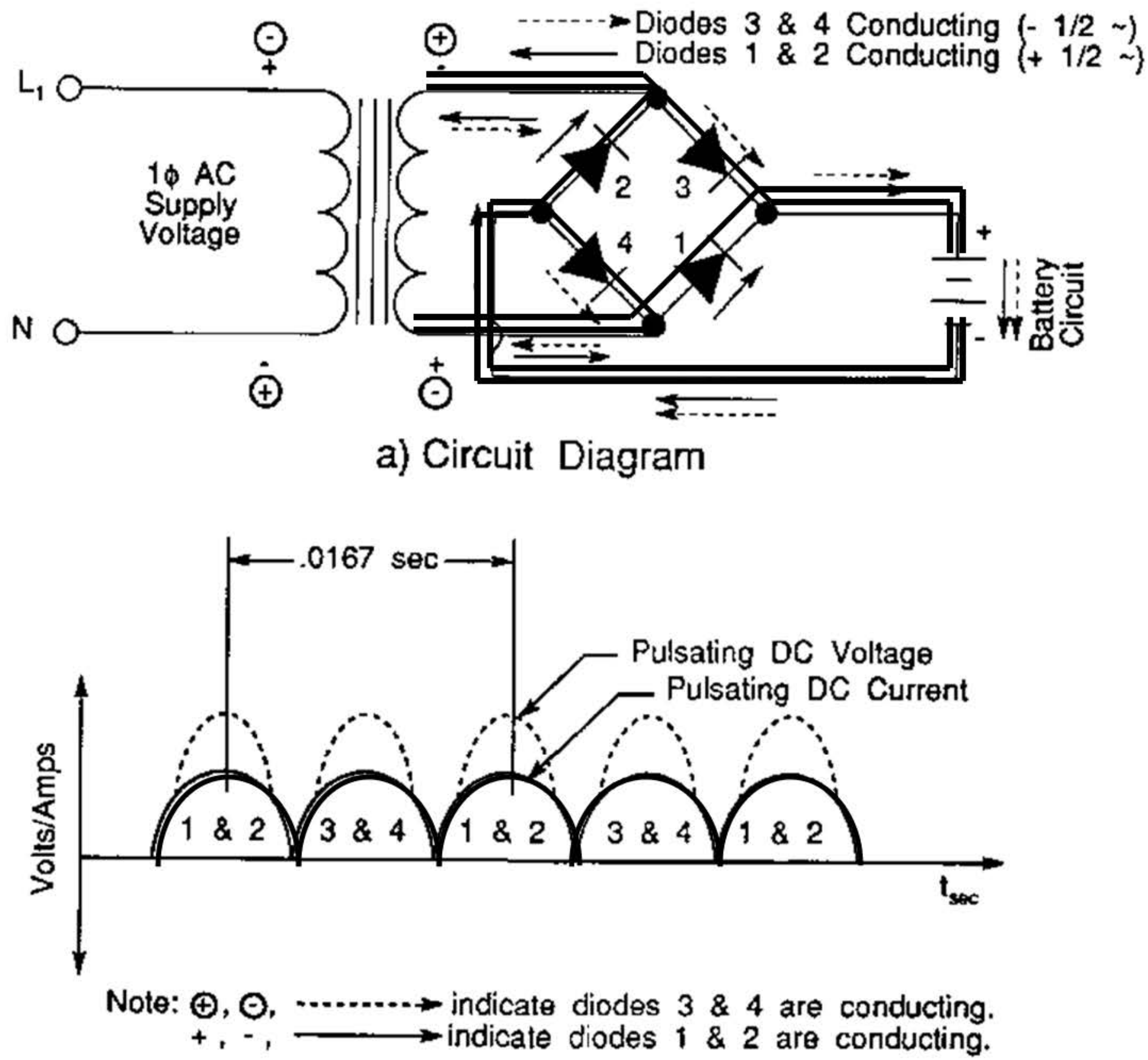
- Waveforms -



Full-Wave Bridge Rectifier

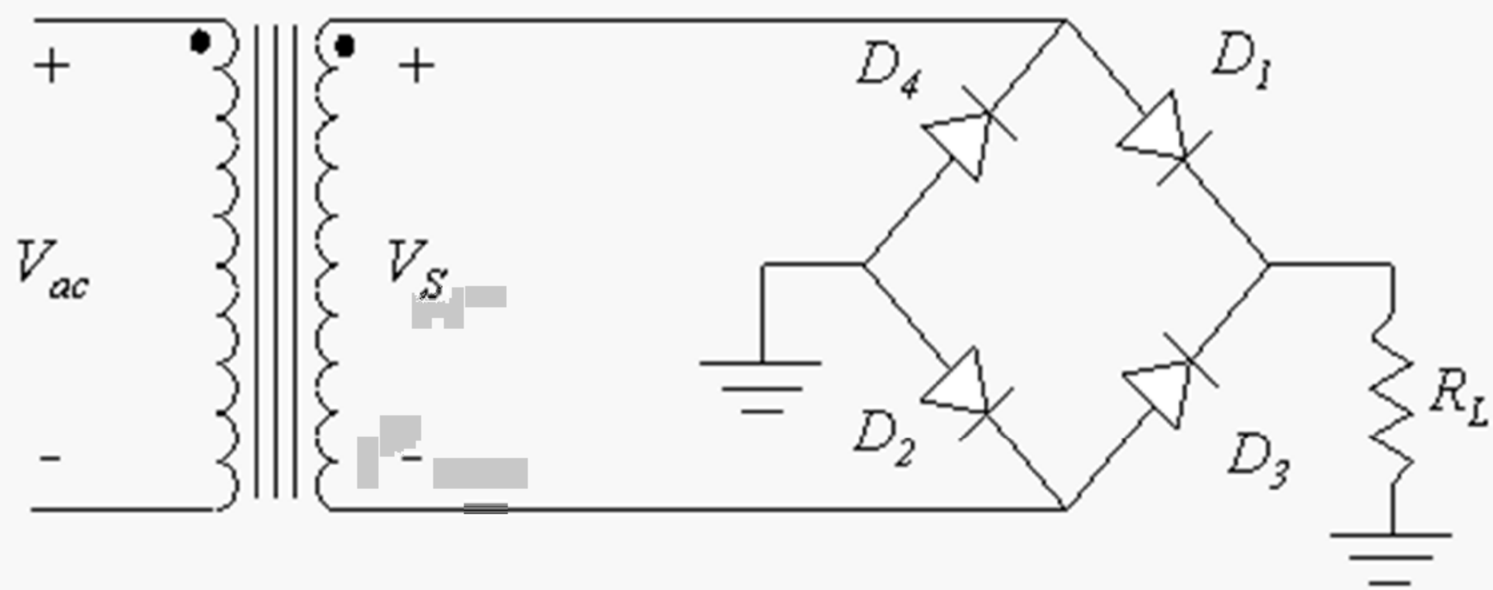
1. Bridge circuit requires no input transformer
2. Allows operating voltage higher than center-tap
3. The ripple frequency is twice the fundamental frequency, 120 Hz
4. Most common type

Full-Wave Bridge Rectifier



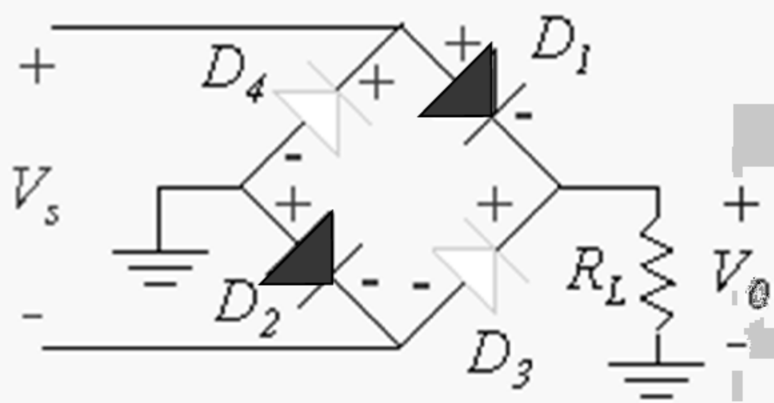
b) Output Voltage and Current Profiles

BRIDGE RECTIFIER



BRIDGE RECTIFIER

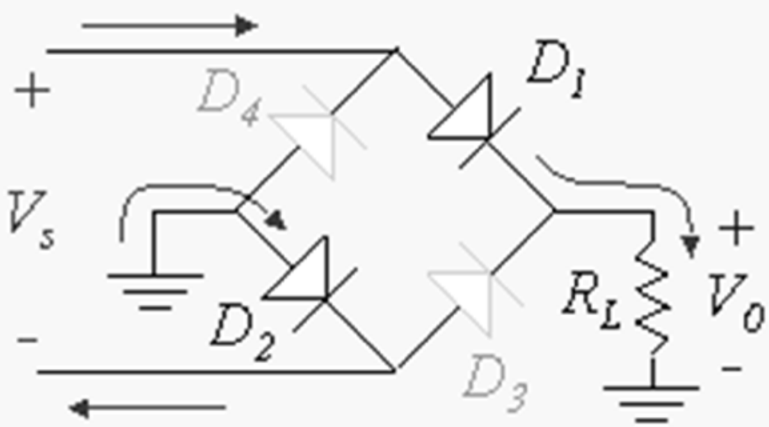
- Positive Cycle -



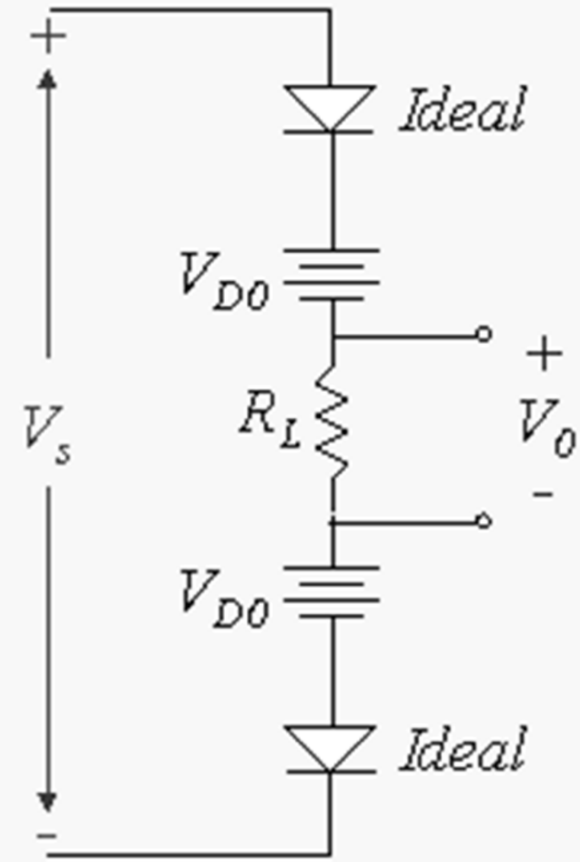
D_1 is ON
D_4 is OFF
D_2 is ON
D_3 is OFF

BRIDGE RECTIFIER

- Positive Cycle -

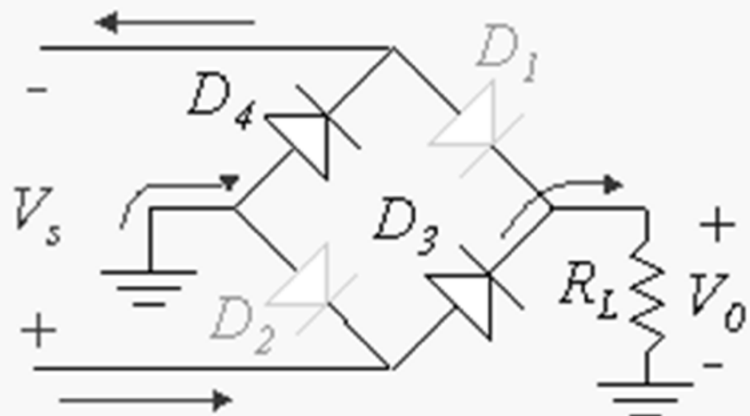


$$V_0 \le V_s - 2V_{D0}$$

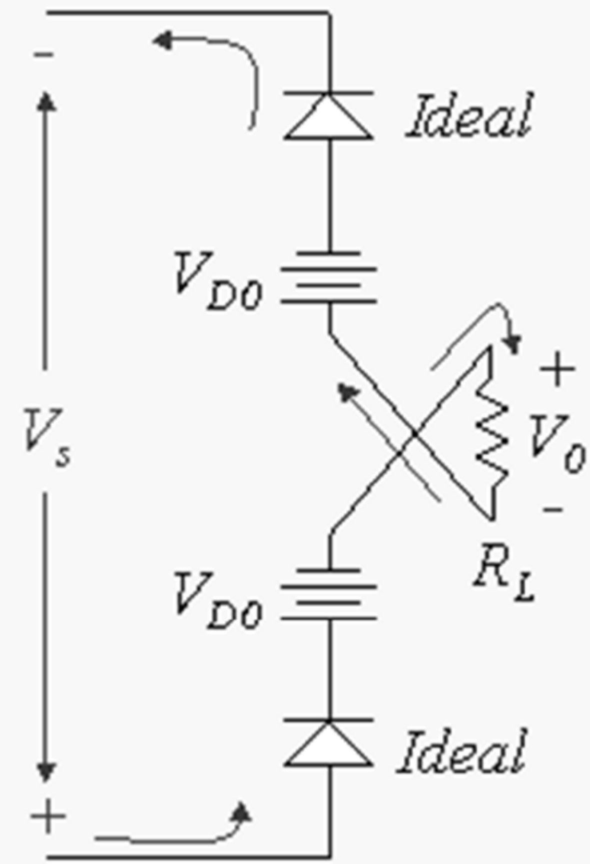


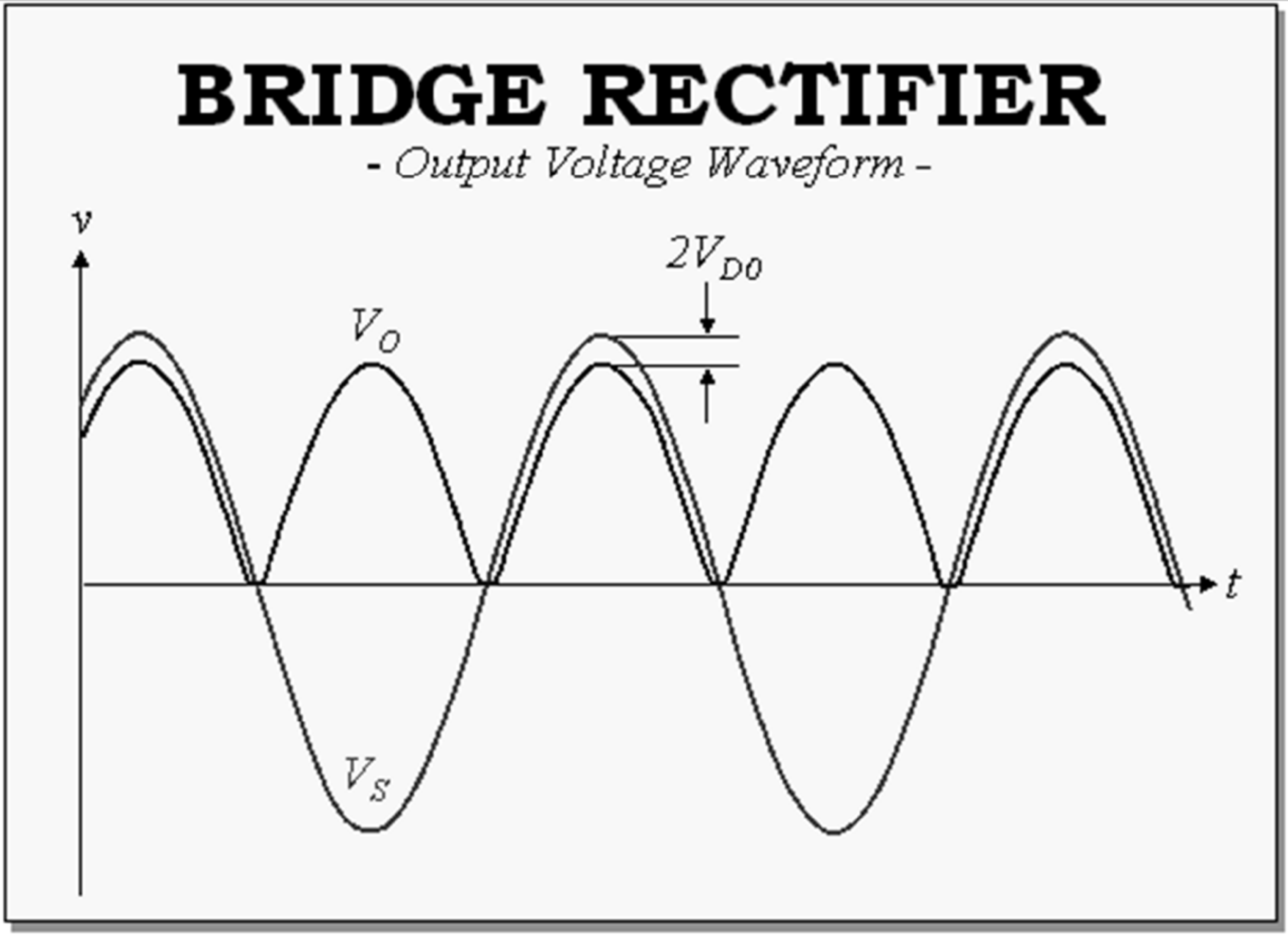
BRIDGE RECTIFIER

- Negative Cycle -



$$V_0 \leq V_s - 2V_{D0}$$

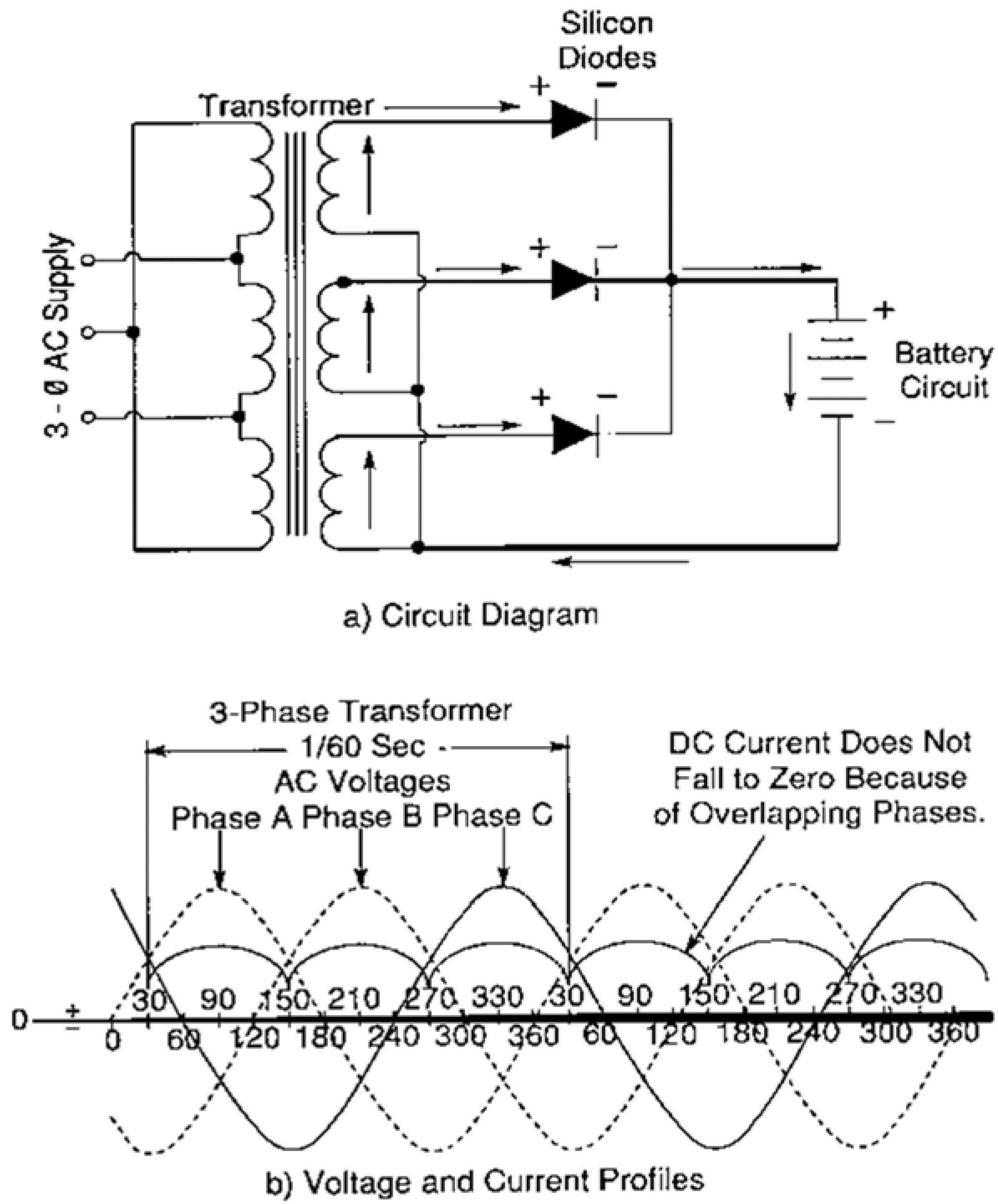



BRIDGE RECTIFIER
- Output Voltage Waveform -
v
2V_D0
V_O
V_S
t

Three-Phase Half-Wave Rectifier

1. Ripple frequency is three times the fundamental frequency, 180 Hz
2. Smoother (less ripple) than single phase half-wave rectifier

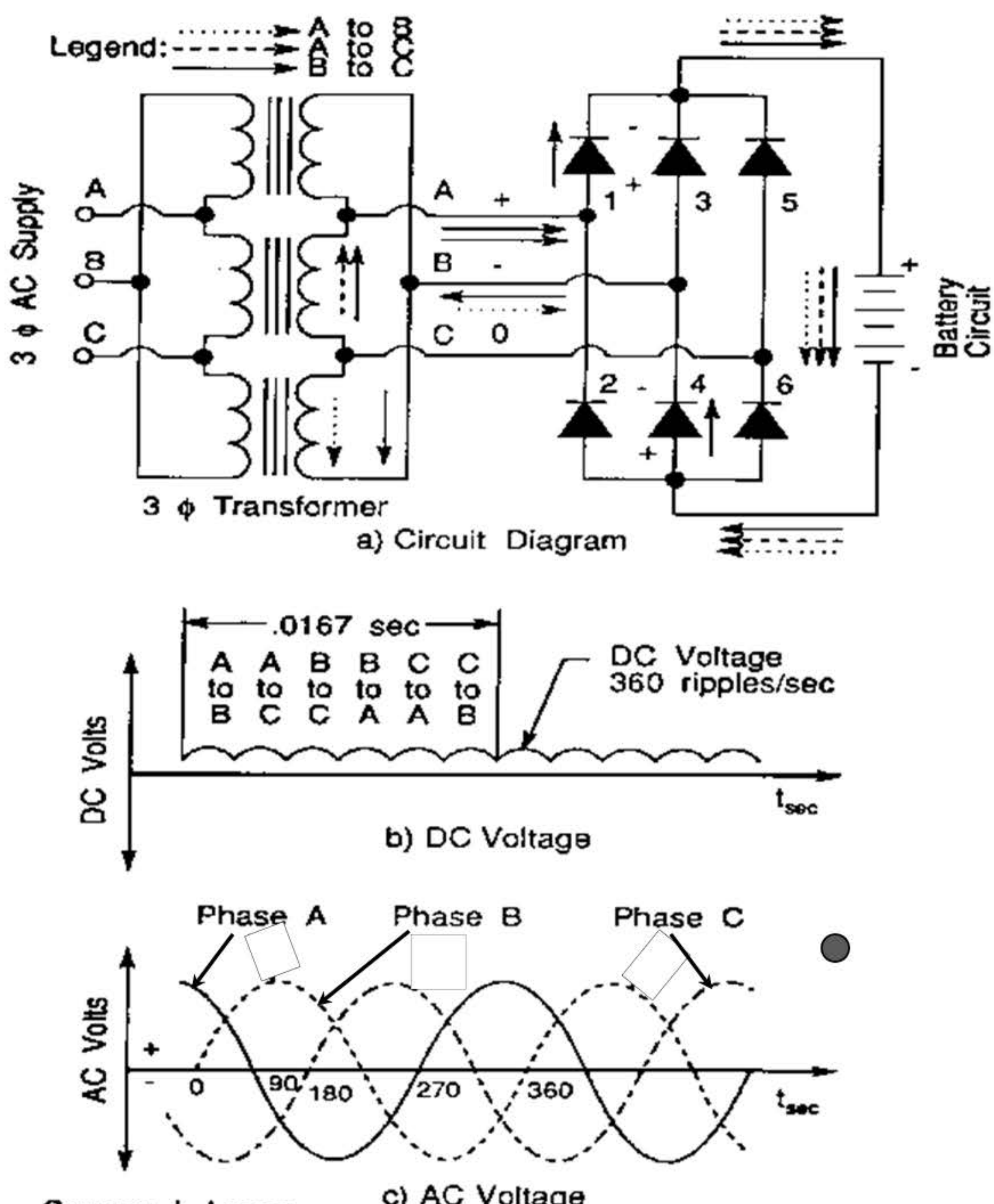
Three-Phase Half-Wave Rectifier



Three-Phase Full-Wave Rectifier

1. Bridge connection
2. Most commonly used for 3-phase industrial-size UPS
3. 6-pulses per cycle $\Rightarrow$ Ripple frequency = 360 Hz

Three-Phase Full-Wave Rectifier

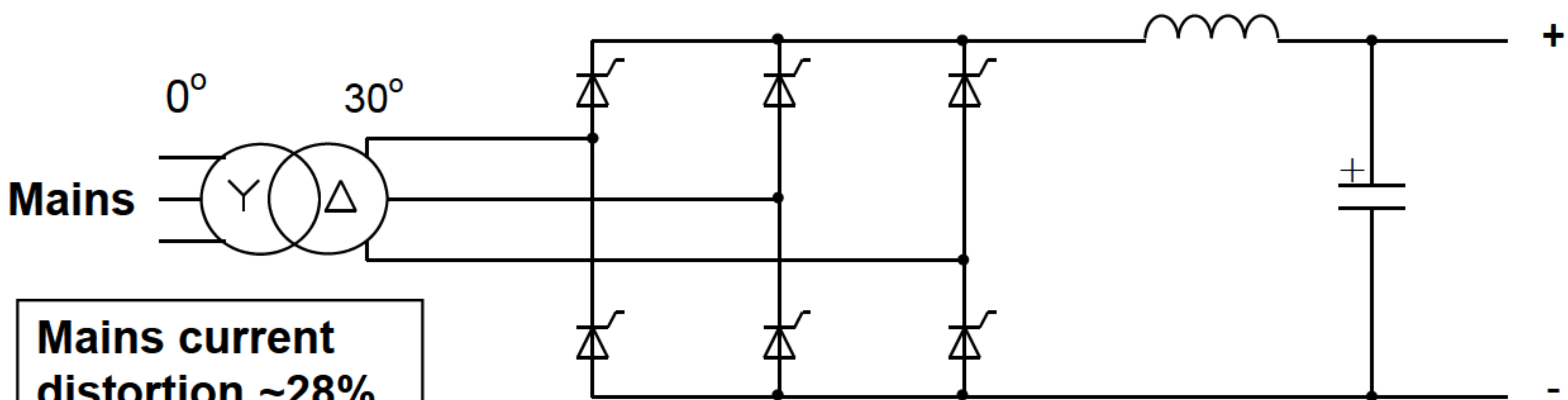


Source: I. Lazar

Rectifier Types

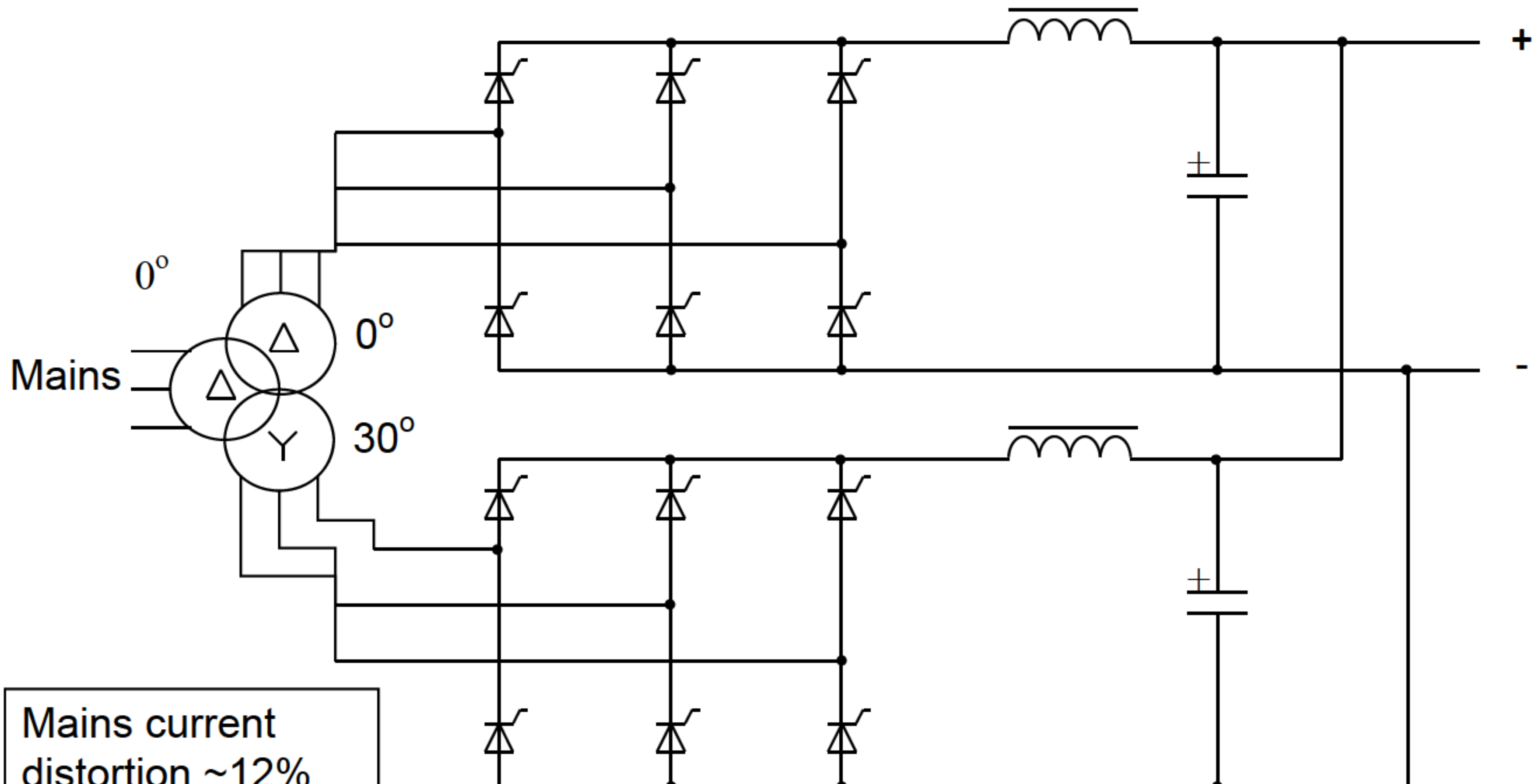
- 6 Pulse
- 12 Pulse

6-Pulse Rectifier Configuration



Mains current distortion ~28%

12-Pulse Rectifier Configuration



Mains current distortion ~12%

Harmonic content of the ideal input current for 6 pulse and 12 pulse rectifiers in [%]

	I_{ni} / I_{1i} x 100%									
n	1	5	7	11	13	17	19	23	25	Total
p=6	100	20	14.3	9.1	7.7	5.9	5.25	4.35	4	~28%
p=12	100	-	-	9.1	7.7	-	-	4.35	4	~12%
Harmonic Filter	100	-	-	-	-	-	-	4.35	4	~5%

How can the harmonic current be reduced?

Measures	**Achieved reduction of harmonic current in %**
6-pulse up to 12-pulse Rectifier	from 28% down to 10-12%
Additional filter for the 11^{th} and 13^{th} harmonics (12-pulse rectifier)	Down to ~5%
Additional active harmonic filters	Down below 5 %

Type of Rectifiers

- Fully Regulated
- Inherently Regulated
- Non-regulated

Fully Regulated Battery Chargers

- ± 0.5% Voltage Regulation from no load to full load
- Advantage:
  - Suitable for varying loads
  - Charge battery at the maximum available current
- Disadvantage
  - High initial cost

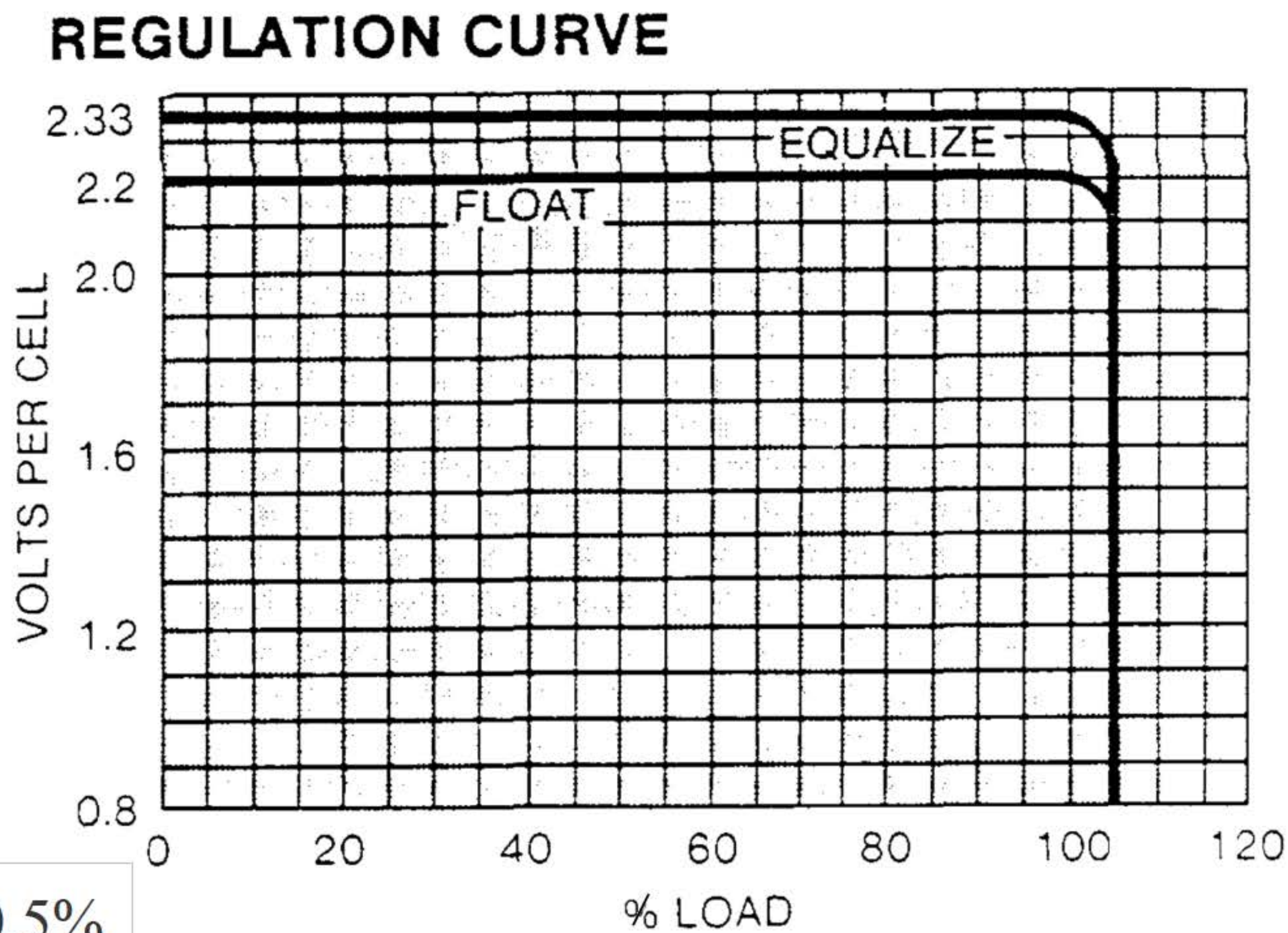
Inherently Regulated Battery Chargers

- ± 1% voltage regulation from 10% loaded to full load
- Advantage:
  - Suitable for normally fixed loads
  - Charge battery at the maximum available current
  - Less expensive
  - Less maintenance
  - More reliable (less components)
- Disadvantage
  - Not suitable for varying loads

Non-regulated Battery Chargers

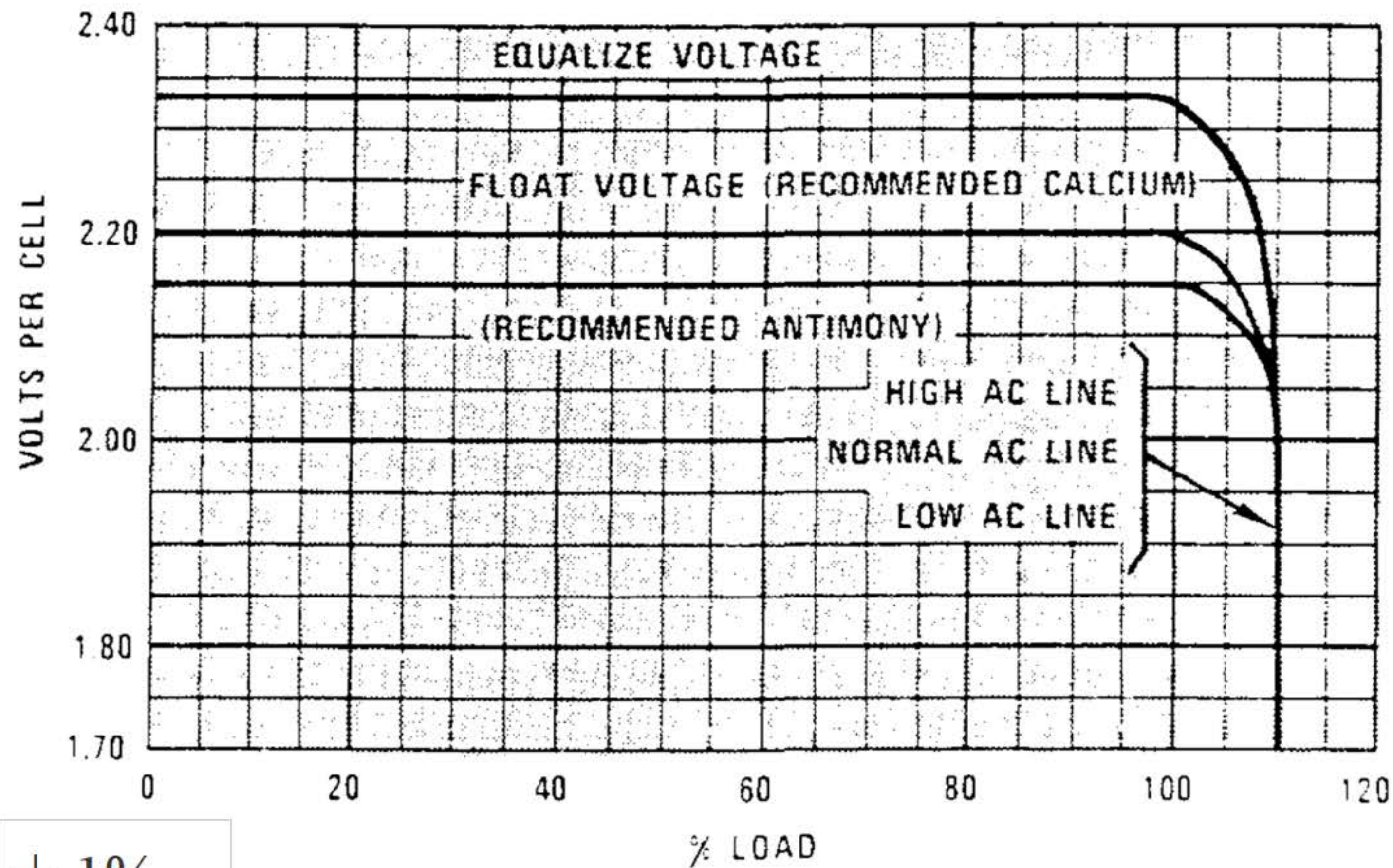
- Drooping voltage with increasing load
- <u>Advantage:</u>
  - Low cost
  - Simple
- <u>Disadvantage</u>
  - Battery recharge is slower
  - Frequent adjustment to maintain the desired floating voltage
  - Reduced battery life due to usually high settings
  - Not suitable for varying loads

Voltage Regulation (Fully Regulated)



$\pm$ 0.5%

Voltage Regulation (inherently Regulated)



± 1%

Battery Charger Sizing

$$A = \frac{SF \times L + \left(\frac{AH \times BIF}{RT}\right)}{Kt}$$

<u>Where:</u>

1. A = Ampere rating of charger
2. SF = Service factor 1.1
3. L = Sum of continuous DC loads (amperes)
4. AH = Ampere-hour rating of the battery
5. BIF = Battery inefficiency factor (1.15 for lead acid and 1.4 for Ni-Cad)
6. RT = Recharge time (8 hours for all applications)
7. Kt = Temp. compensation (1.00 for at or below 40°C, 0.83 from 40 to 50°C)

Charger/Rectifier Specifications

- Input voltage: 120, 208, 240, or 480 V ± 10%
- Input phases: (1 or 3ϕ)
- Input frequency: 50 or 60 Hz ± 5%
- Output voltage regulation: ± 0.5% (float), ± 1% (equalize)
- Output ripple: See next slide
- Current limiting: factory set at 105% of the rated DC output current.
- Dynamic Response: ± 6% (for 10-90% and 90-10% step loads)
- Float/Equalize
- Temperature compensation

Specifications (Cont.)

Step Load Change

- Dynamic Response with the battery connected: Voltage transients due to sudden changes in load current over the range of 10 to 90% or 90 to 10% within 2 milliseconds shall not cause a change in the output voltage of more than ± 6% of the initial voltage setting.

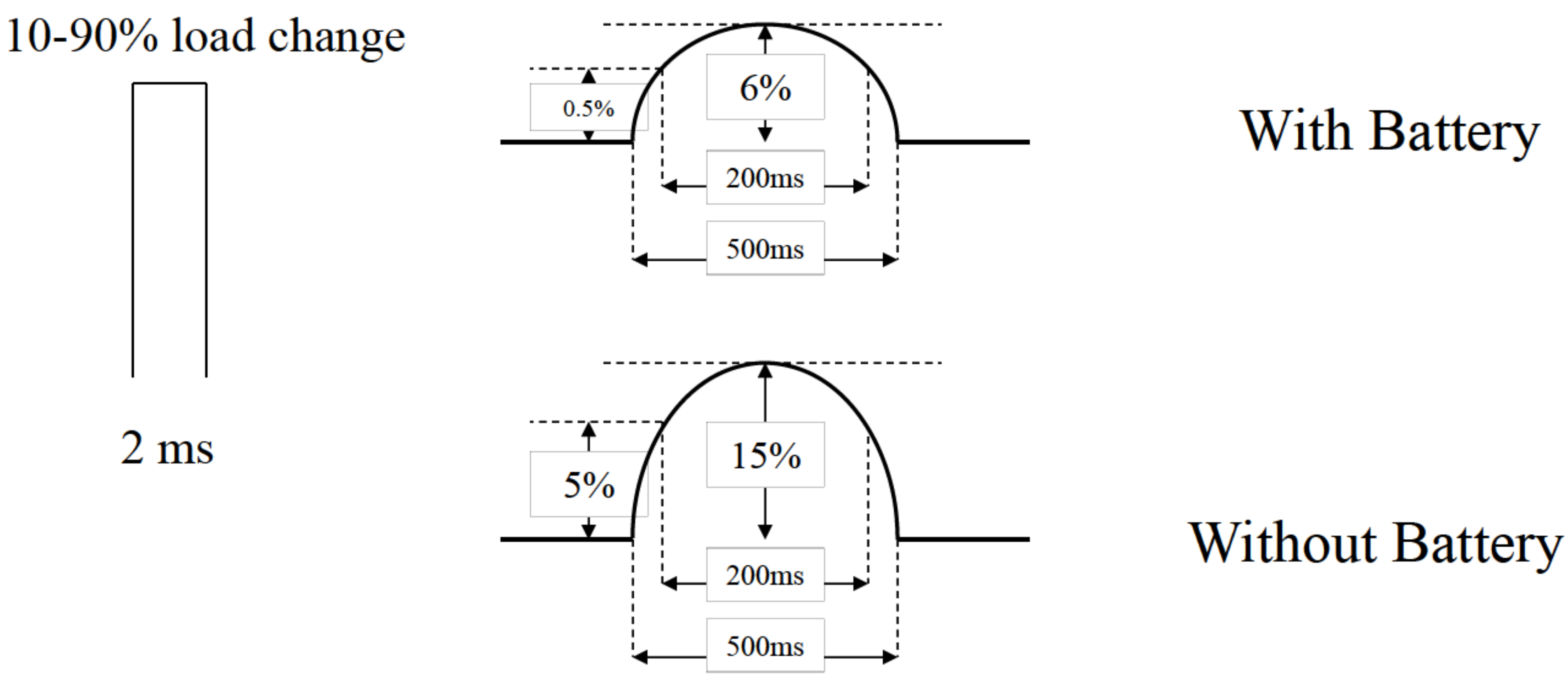
Specifications (Cont.)

- Recovery to within the steady state voltage regulation range shall not exceed 200 milliseconds, and the transients shall be overcome within 500 milliseconds.

Specifications (Cont.)

- Dynamic Response with the battery disconnected: voltage transients shall not cause a change in the output voltage of more than ± 15% of the initial voltage setting.
- Recovery: within 200 milliseconds to ±5%. The transient shall be overcome within 500 milliseconds.

Dynamic Response



Specifications (Cont.)

- Start-up Behavior: With the battery connected and a load equal to 10% of the rated output, energizing the charger shall not result in an output voltage greater than 110% of the voltage setting, and the high voltage shutdown shall not be activated. The voltage shall stabilize to ± 5% of the nominal voltage setting within 200 milliseconds.

Float/Equalize Voltage Settings

- Float Voltage:
  - Lead-Acid: 2.15 to 2.35 V/cell
  - Nickel-Cadmium: 1.35 to 1.45 V/cell
- Equalize Voltage:
  - Lead-Acid: 2.20 to 2.45 V/cell
  - Nickel-Cadmium: 1.50 to 1.60 V/cell

Parallel Operation of Two Chargers

- The battery charger shall be designed to allow parallel operation and load sharing between two chargers connected to a common battery and load.

DC/UPS SYSTEMS

BATTERY INSTALLATION

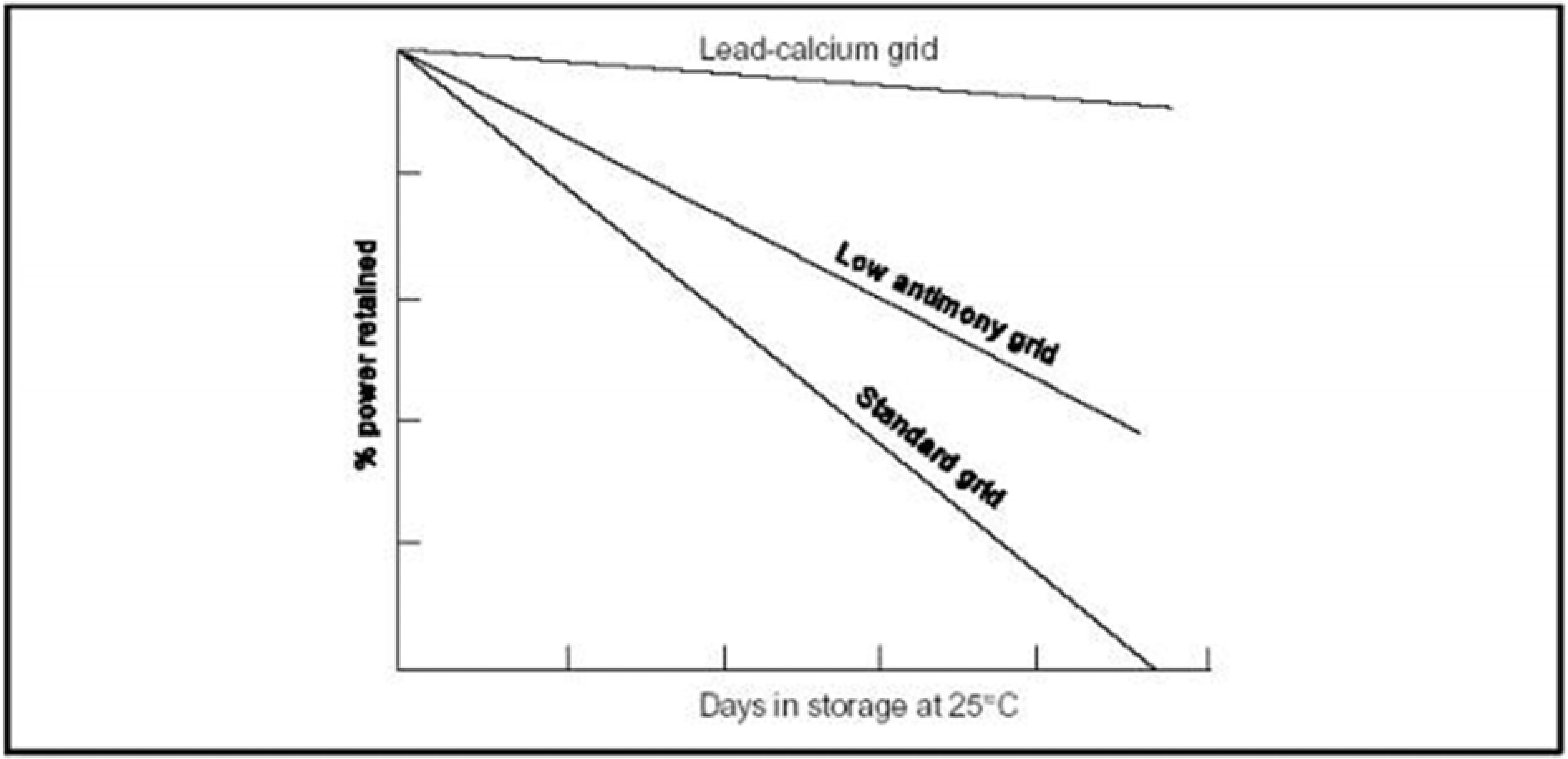
Battery Shipment

- Dry charged
- Dry uncharged
- Moist charged
- Wet charged
- Wet uncharged (X)

Battery Storage

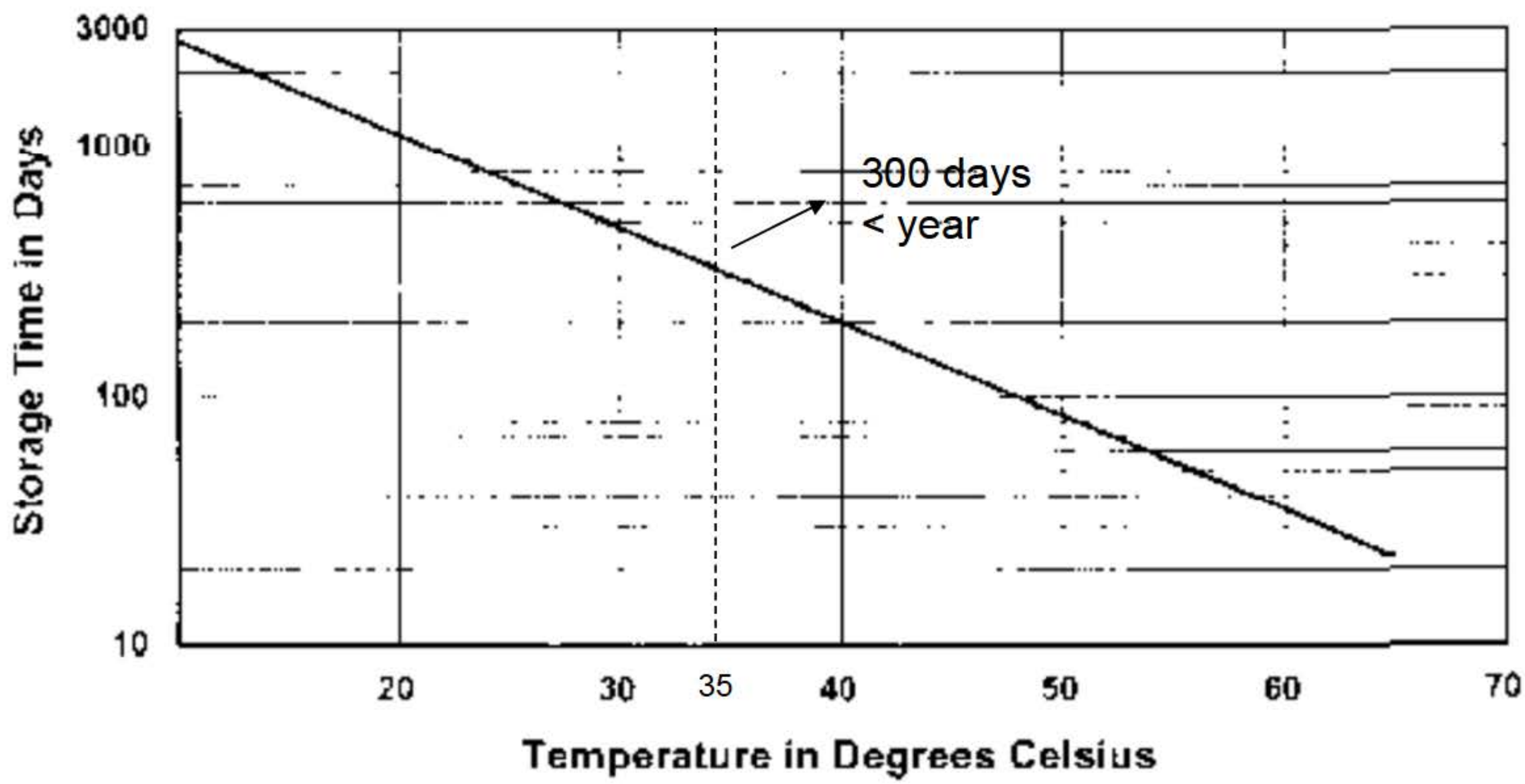
- Shelf Life
  - Sealed Batteries
  - Vented
- Storage Environment
  - Temperature (shortens service life)
  - Humidity (corrosion of plates)

Self Discharge Rate



Typical Storage Period vs. Storage Temperature

STORAGE TIME AS A FUNCTION OF TEMPERATURE FOR GENESIS BATTERIES
(FULLY CHARGED BATTERY)



Shelf Life

Storage Condition	**Shelf Life @ 35 ^{0}C**	**Remarks**
Sealed Batteries	6 months	Self discharge
Dry-charged	2 years	Highly recommended
Dry-uncharged	4 years	Difficult to charge
Wet-charged	3 months	Short shelf life
Moist-charged	2 years	Corrosion/cheaper
Wet Uncharged	Not recommended	Sulphation

Parallel Strings

- Advantages
  - Maintenance convenience
  - Redundancy
  - Smaller and lighter cells for handling
- Disadvantage
  - Higher cost
  - More space
  - Increased maintenance

Low Voltage Disconnect

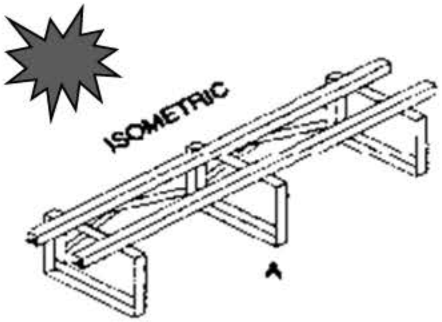
- Fused disconnect switch
- Circuit breaker with undervoltage release feature
  - Rated for short circuit (Battery volt/internal resistance or 20 x AH)
  - Provision of alarm for battery circuit breaker open condition (or fused disconnect switch open or blown fuse condition)

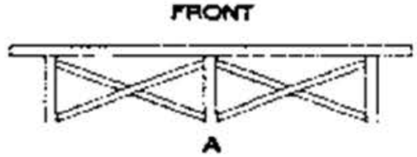
Battery Racks

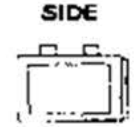
- Maximum Height 170 cm
- Work space 1 m
- Acid/alkali resistant paint

Battery Racks

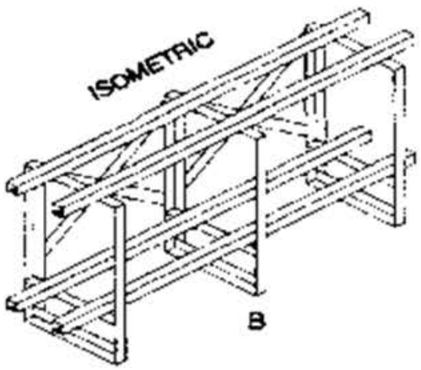
- Single Tier
- Two Tier
- Three Tier
- Two Step
- Three Step

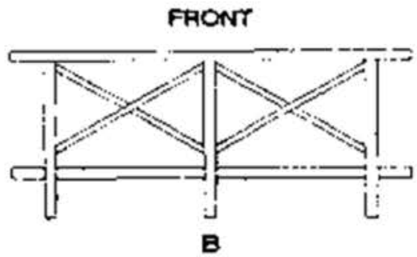


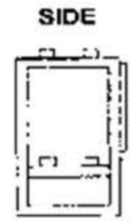




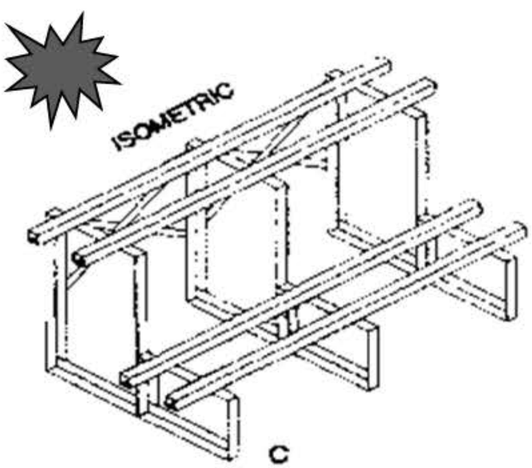
Single Tier

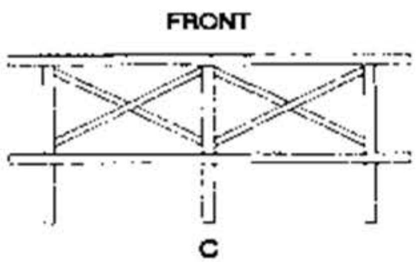






Two Tier

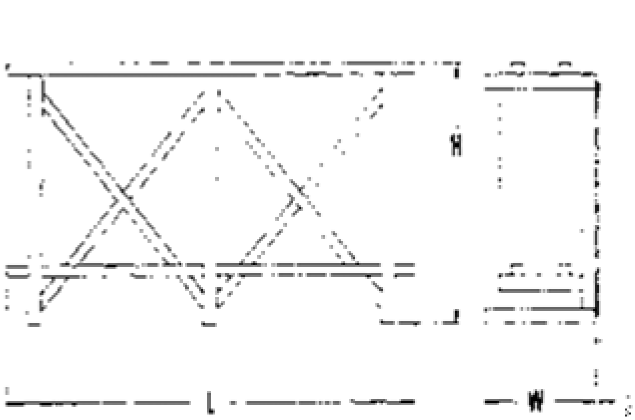




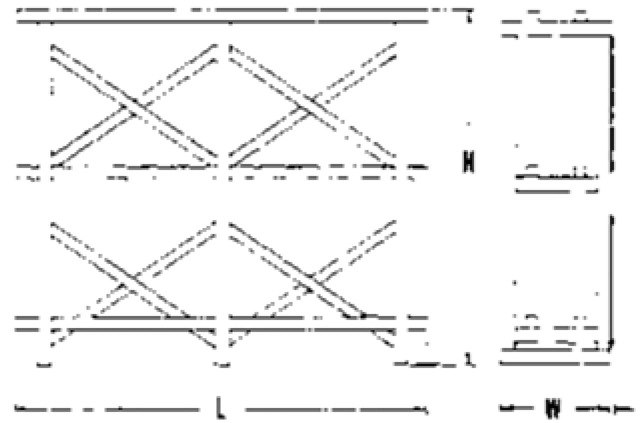
Two Step

Figure 1
Battery Rack Configurations

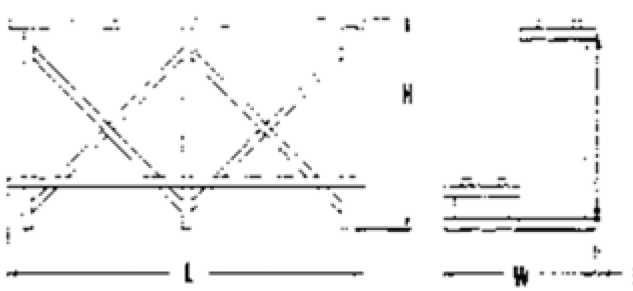
Typical Battery Racks



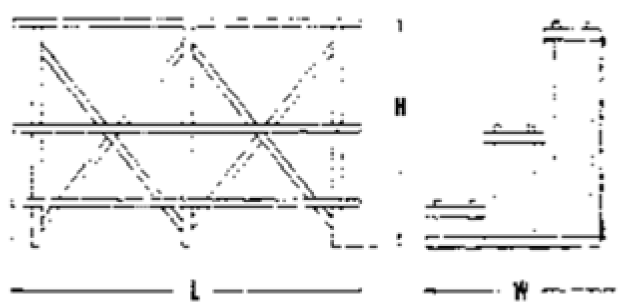
TWO TIER



THREE TIER



TWO STEP



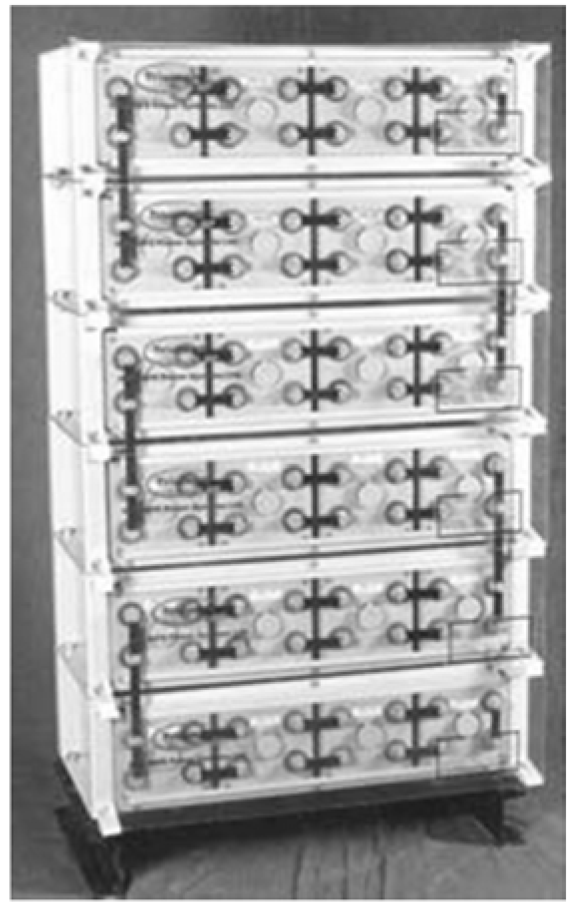
THREE STEP

Three Step Rack

4-Step 4-Tier
Rack

Three Step Rack

VRLA Modular Rack



Battery Room Safety

- Lighting
  - Vapor tight fixtures
  - 300 lux illumination level
- Safety signs
- Safety tools
  - Fire extinguisher
  - Eyewash
  - Apron, goggles, etc
- Room Door
  - Panic hardware
  - Outside the building
  - Opens outward

DC/UPS SYSTEMS

BATTERY MAINTENANCE

Typical Battery Problems

- Manufacturing/Design Defects
- Bad Operation/Maintenance Practices
- Incorrect Sizing and Selection Methods
- Misconception

Manufacturing/Design Defects

- Post leak
- Vent leak (VRLA)
- Jar cover seal failure
- Deformation of the battery jar
- Flame arrestor failure
- High post/copper insert resistance
- Electrolyte dry-out (VRLA)
- Bad storage conditions


Post Seal
Cover Seal
Jar Deformation
max
min
max
min

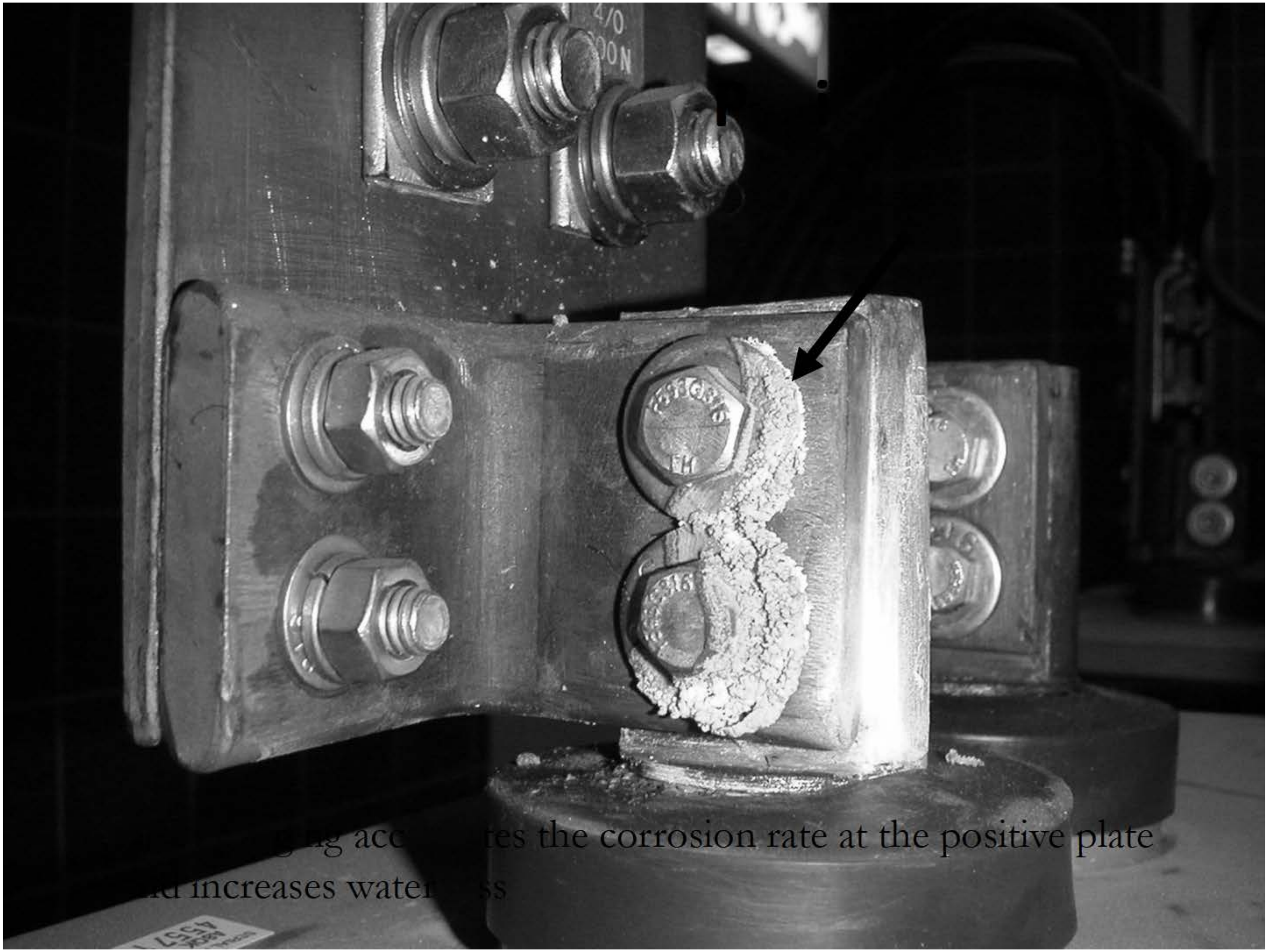
Single Cell / Multicell

Bad Operating and Maintenance Practices

- Overcharging
- Undercharging
- Inadequate cooling
- Lack of scheduled maintenance
- Lack of test records
- Reluctance to carry a load test *(non redundant)*

Lead Acid Battery Failure Modes

- Positive grid corrosion (plate growth)
  - Lead alloy becomes lead oxide (bigger crystals)
  - Caused by aging, cycling, temperature and overcharging
- Sediment buildup (shedding)
  - Fall down of active material > white lead sulfate > short circuit
  - Caused by overcharging
- Top lead corrosion
  - Manufacturing defect, fails at high discharge current
- Plate sulphation
  - Negative (sometimes positive) plates become lead sulfate ($PbSO_4$)
  - Caused by undercharging (low SOC for extended periods)


4/0
00N
ng ac tes the corrosion rate at the positive plate
d increases water ss

VRLA Battery Failure Modes

- Dry-out (loss of compression)
  - Glass mat is no longer in contact with plates
  - Caused by excessive heat and can be detected by high impedance
- Plate Sulphation (see above)
- Post leakage
  - Caused due to horizontal orientation
- Thermal runaway
  - See next slide
- Positive grid corrosion (see above)

Thermal Runaway

When the VRLA battery is being charged, it exhibits significantly higher temperature. If the generated heat is not dissipated properly, the battery temperature will rise and more charging current will be required. The additional current will further generate more heat to a point of dry-out and melting of the battery and a fire may start.

The possibility of thermal runaway can be avoided or minimized by proper ventilation, air circulation, cooling and use of temperature-compensated charging techniques.

What is Thermal Runaway?

Heat → Charging Current→ Heat → Damage

Ni-Cad Battery Failure Modes

- Carbonation
  - Caused by CO_2 (in air) contaminating the electrolyte, thus reduces battery capacity
  - Replacement of electrolyte and oil film, oversizing
- Floating effects
  - Gradual loss of capacity
  - Caused by lack of deep-cycling
- Iron poisoning of positive plates
  - Corroding plates (design failure mode for pocket plates)
- Memory effect
  - Battery adjust its capacity to a daily load cycle (depth of discharge)
  - Design defect of sintered plates, eliminate by routine cycling

Types of Load Tests

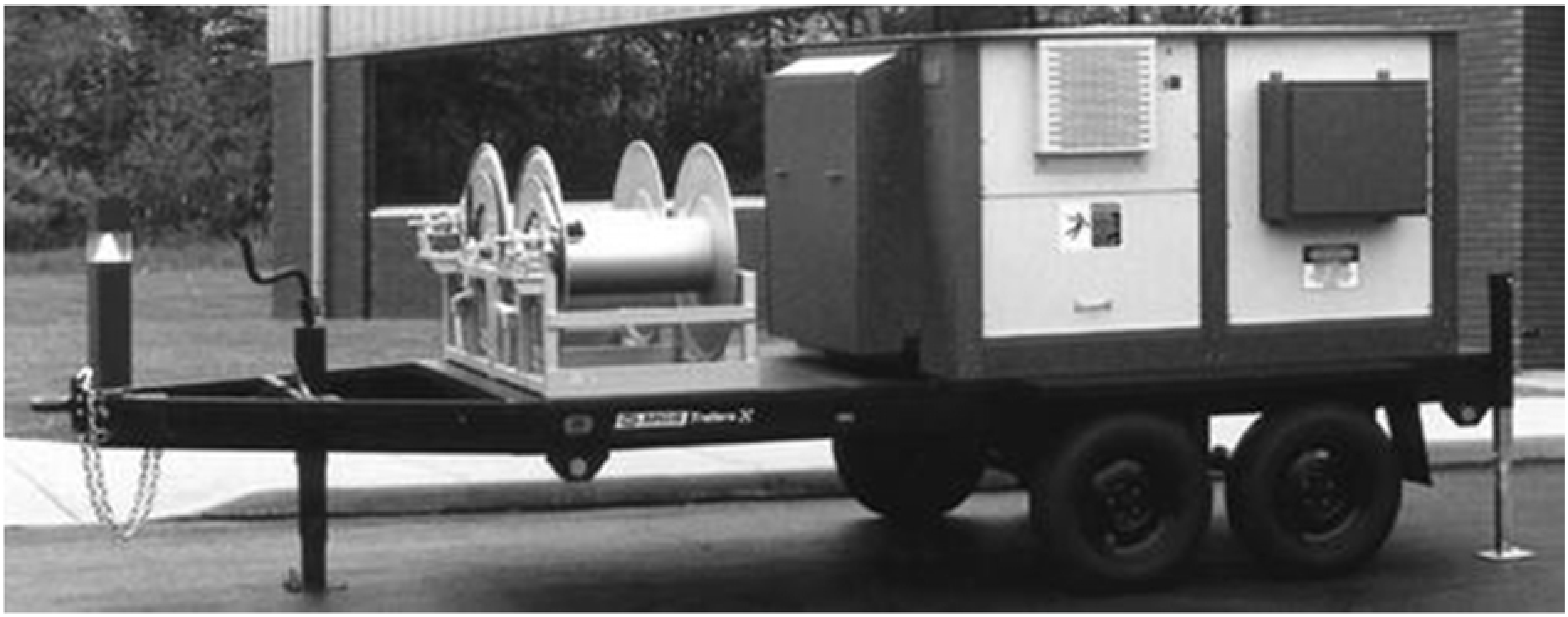
- Initial acceptance test
- Performance test
- Service test “as found”

Battery Test Load Bank

Battery Test Load Bank

Load Bank

Load Bank
Trailer Mounted



Battery Room Problems

- Inadequate ventilation and cooling
- Insufficient space
- Electrolyte spillage handling
  - Drain
  - Neutralization tank
  - Eyewash
- Battery enclosures/racks

DC/UPS SYSTEMS

BATTERY PERFORMANCE

Definitions

- **AH capacity**: The capacity (in Ampere Hour) assigned to a cell by its manufacturer for a given discharge time.
- **Specific gravity:** The ratio of the density of electrolyte to the density of water.
- **State of charge:** The actual capacity of a cell, expressed as a percent of its rated capacity, that would be available if discharge were to occur.
- **Nominal voltage:** The average cell voltage computed in the basis of 2.0 V/cell for lead-acid and 1.2 V/cell for Ni-Cad.

Definitions (cont.)

- **End of discharge voltage:** The cell voltage at which the discharge is terminated. Normally, 1.75 V/cell for lead acid and 1.10 V/cell for Ni-Cad.
- **Float charge:** Charging the cell at low voltage barely higher than the battery terminal voltage to keep the cell fully charged and to compensate for self-discharge losses.
- **Equalize charge:** Charging the cell at elevated voltage to correct inequalities among battery cells.
- **Load test:** The discharge of a battery at a constant current or power to a specified end of discharge voltage.

Ampere Hour (AH) Capacity

- The number of Ampere-hours a battery can deliver during a continuous discharge at a constant current (in Amperes) until the cell end of discharge voltage is reached.

Nominal AH Capacity

- The capacity assigned to a cell by its manufacturer for a given discharge time
- Normally
  - 8 Hours for Lead Acid (American)
  - 10 Hours for Lead Acid (European)
  - 5 Hours for Nickel Cadmium
  - Sometimes designated as C_5, C_8 or C_{10}

State of Charge

- The available capacity of a battery at any given time, expressed as a percentage of battery's rated capacity

Cycle Life

- The total number of cycles (a sequence of a complete discharge followed by a charge, or a charge followed by a discharge) before a battery becomes nonfunctional for a definite usage

Depth of Discharge

- The Ampere-hours (or Watt-hours) removed from a fully charged battery, expressed as a percentage of its rated capacity at the applicable discharge rate.

Battery Efficiency

- The electrochemical efficiency, expressed as a percentage, of the ratio of the Ampere-hour (or Watt-hour) output of the battery, to the Ampere-hour (or Watt-hour) input required to restore the initial state of charge.

- Batt. inefficiency factor: 115% for lead acid
  140% for Ni-Cad

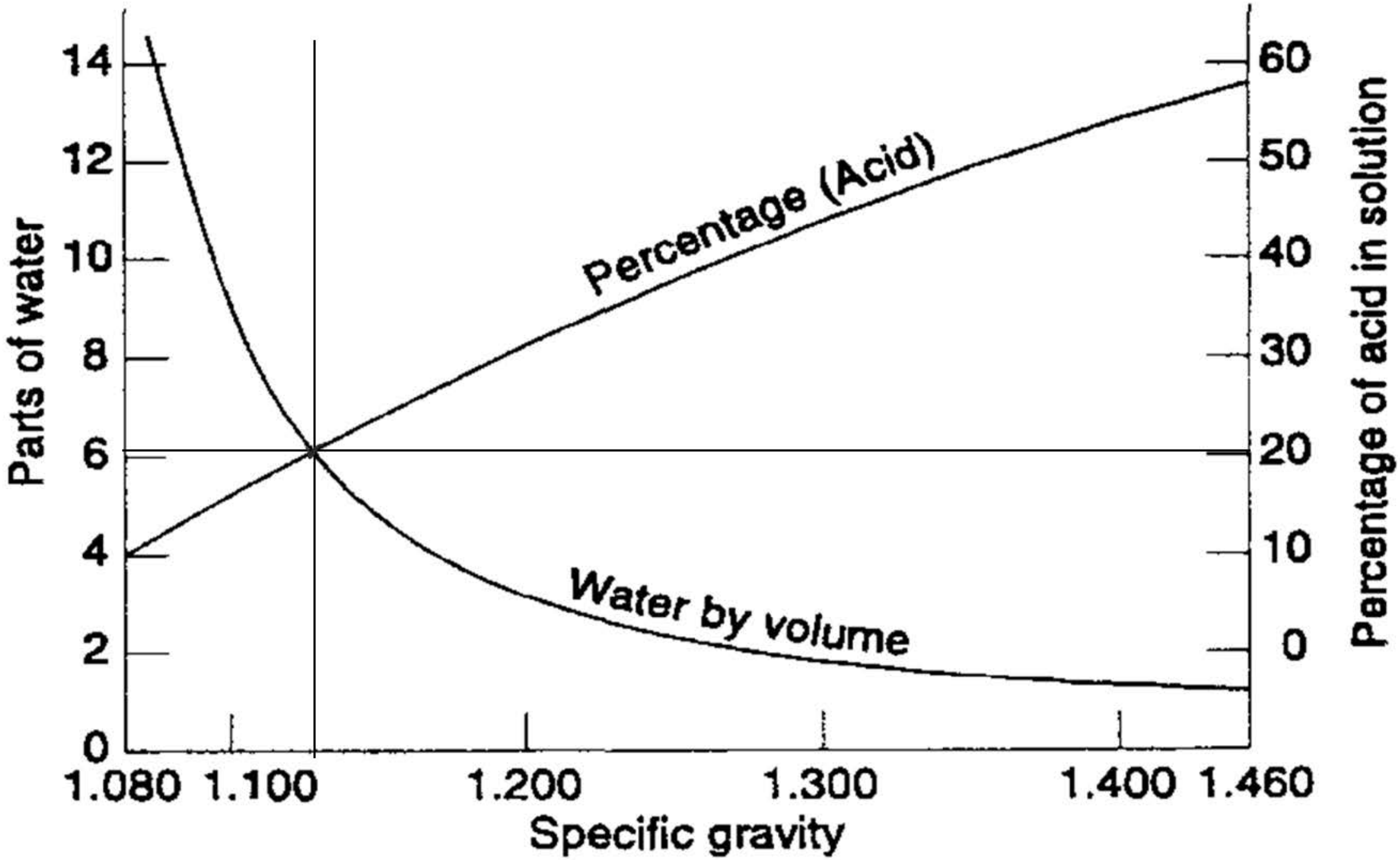
Specific Gravity

- The ratio of the weight of a given volume of electrolyte to the weight of an equal volume of water at a specified temperature (e.g., 25^0C or 77^0F). [electrolyte density]

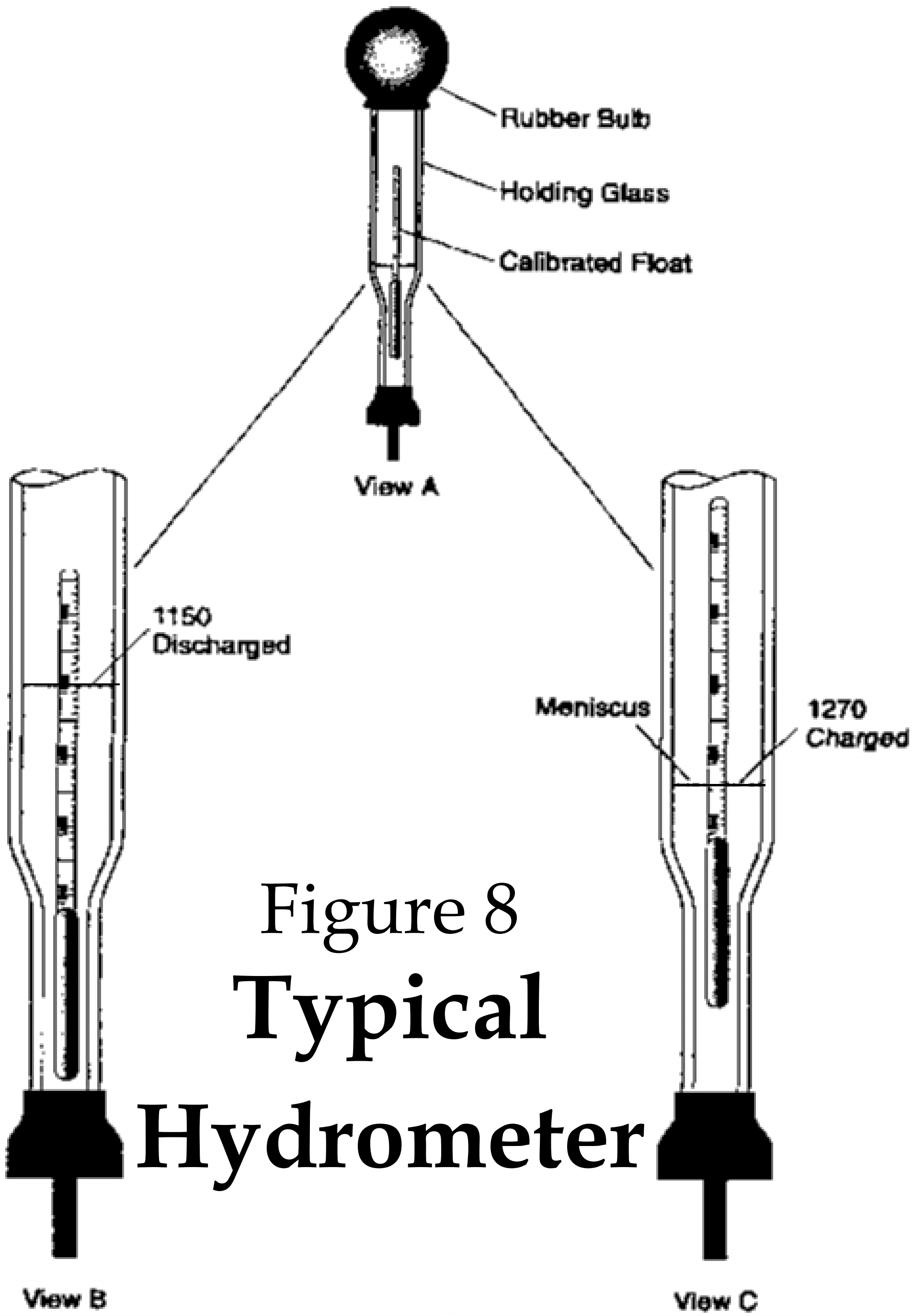
Battery Condition	Lead-Acid	Nickel-Cadmium
Full Charge	1.225	1.300
3/4 Charge	1.185	1.300
1/2 Charge	1.150	1.300
1/4 Charge	1.115	1.300
Discharged	1.080	1.300

Figure 10

Typical Specific Gravity Readings



Sulfuric Acid – Water Concentrations



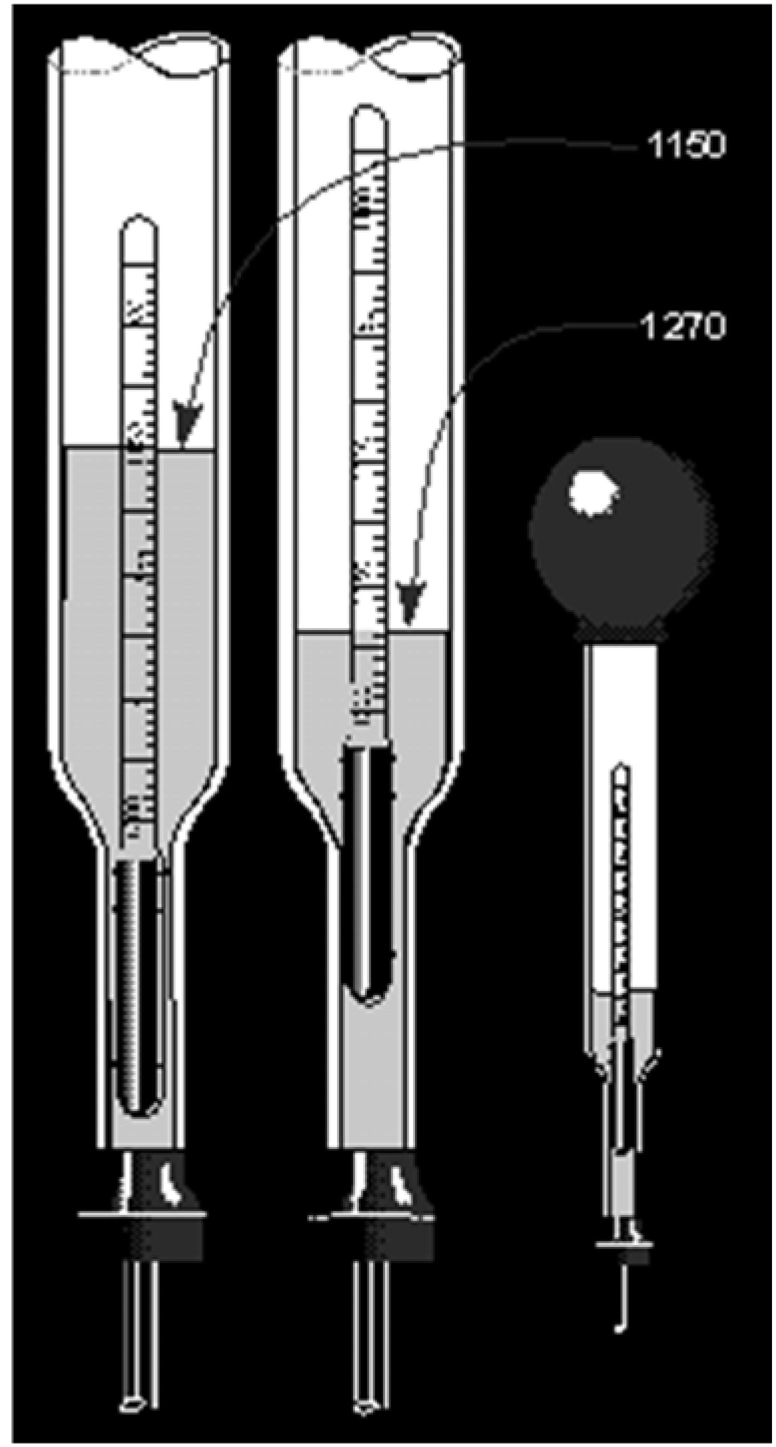
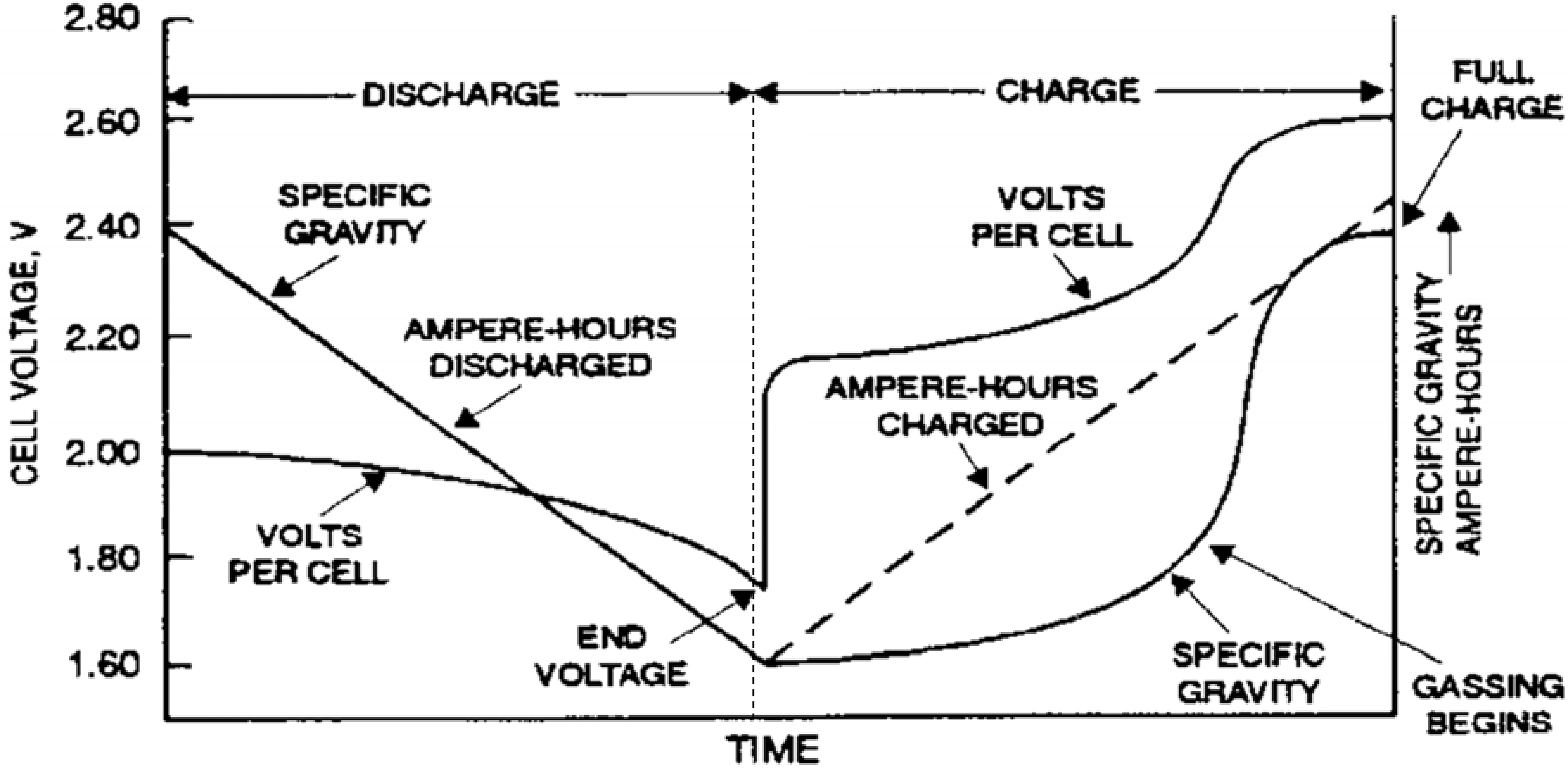


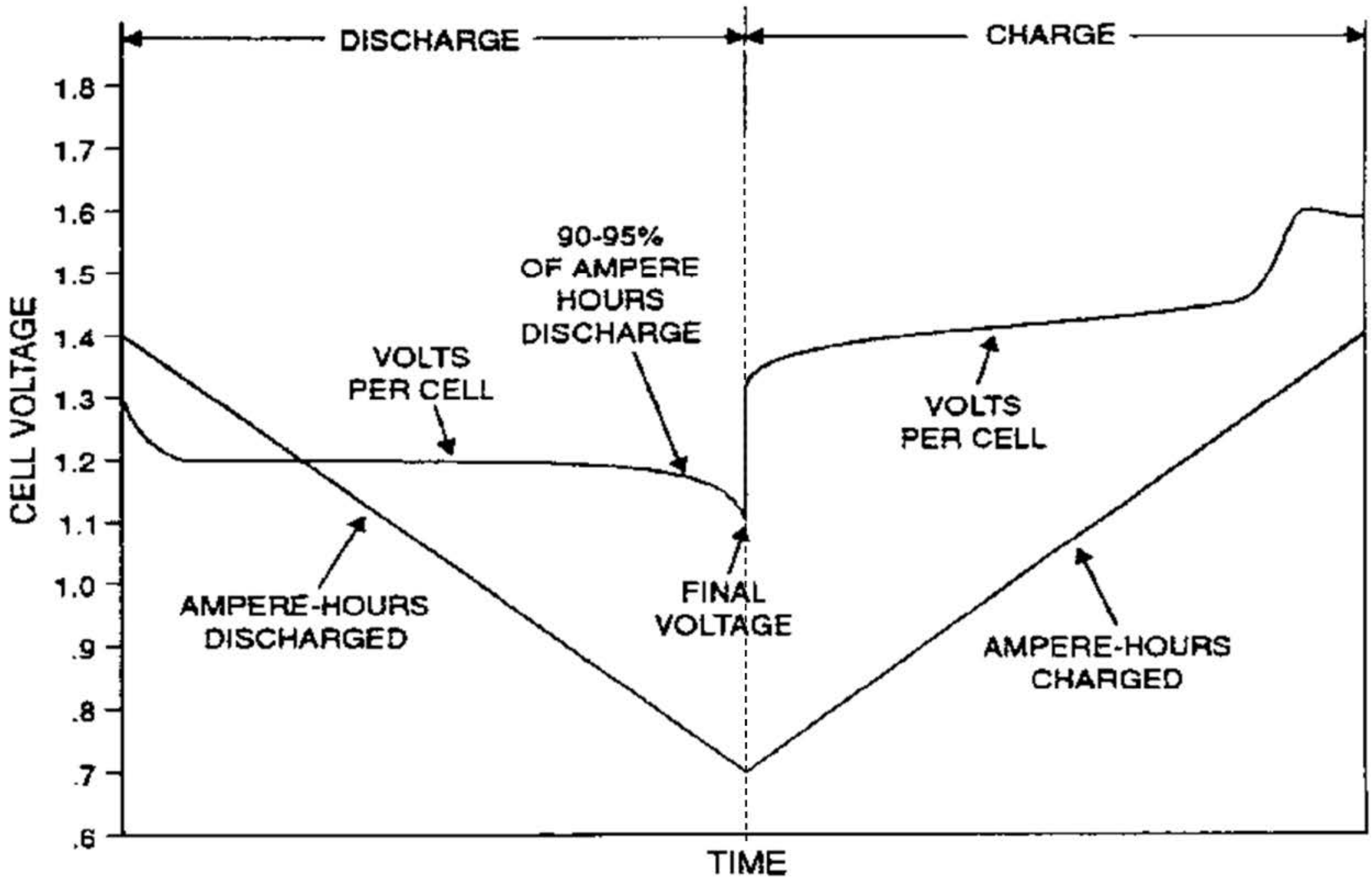
Figure 8
Typical Hydrometer

Cell Voltages

- **Float voltage:** Charging the cell at low voltage barely higher than the battery terminal voltage to keep the cell fully charged and to compensate for self-discharge losses.
- **Equalize voltage:** Charging the cell at elevated voltage to correct inequalities among battery cells.
- **End of discharge voltage (final voltage):** The cell voltage at which the discharge is terminated. Normally, 1.75 V/cell for lead acid and 1.10 V/cell for Ni-Cad.



Lead-Acid Battery Charge/Discharge Characteristic Curves



Nickel-Cadmium Battery Charge/Discharge Characteristic

UPS SYSTEMS

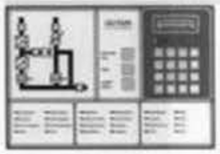
UPS Components

What is a UPS Systems ?

UPS is a device which provides quality and continuity of an AC power source. All UPS shall maintain some specified degree of continuity of load power for a specified stored energy time upon AC input failure

NEMA Standard Publication No. PE 1

UPS System Layout



UPS Components

1. Battery Charger/Rectifier
2. Storage Battery
3. Inverter
4. Static Transfer Switch
5. Maintenance Bypass Switch
6. Bypass Transformer

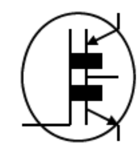
Major Components of UPS

- **Rectifier/Charger**
  A device that converts AC to DC. It maintains battery charged and provides input to inverter when utility power is available
- **Battery**
  A rechargeable electromechanical storage device that, when discharged, produces DC electrical energy. It provides continuous source of electrical power.
- **Inverter**
  A device that converts DC to AC. It provides power to load during normal operation.
- **Static Switch**
  A device that can start or interrupt current flow by the use of gated semiconductors. It transfers load automatically and without disturbance between inverter and utility power.
- **Maintenance Bypass Switch**
  It bypasses the static switch for maintenance.
- **Input and Output Isolation Transformers and Filters**
  They provide appropriate isolation and disturbance attenuation.

Power Electronics Basic Components

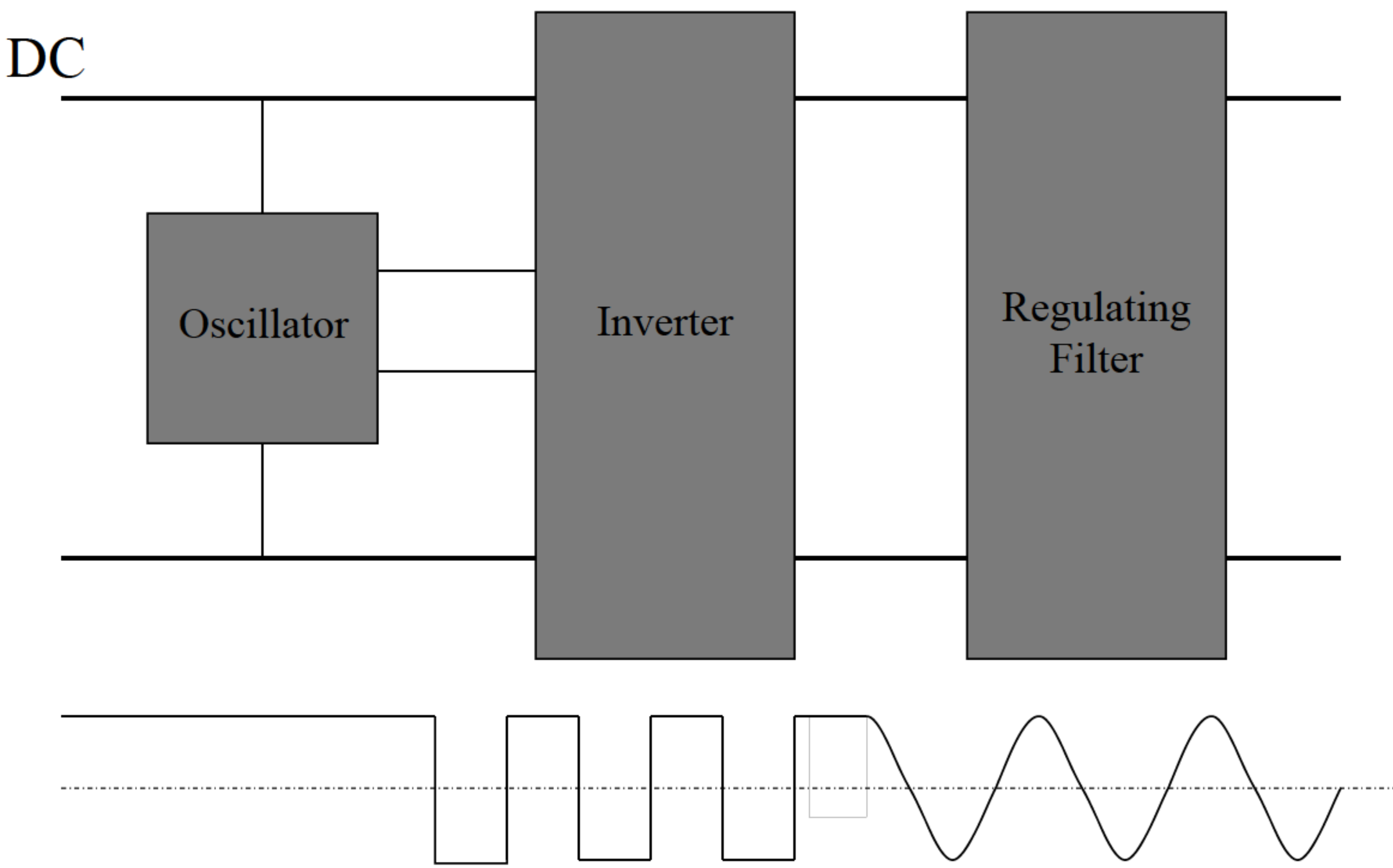
- Diode: *Semiconductor Device that conducts current in one direction*

- Thyristor or SCR (Silicon Controlled Rectifier): *Semiconductor Device that switches ON to conduct current when gate signal is applied*

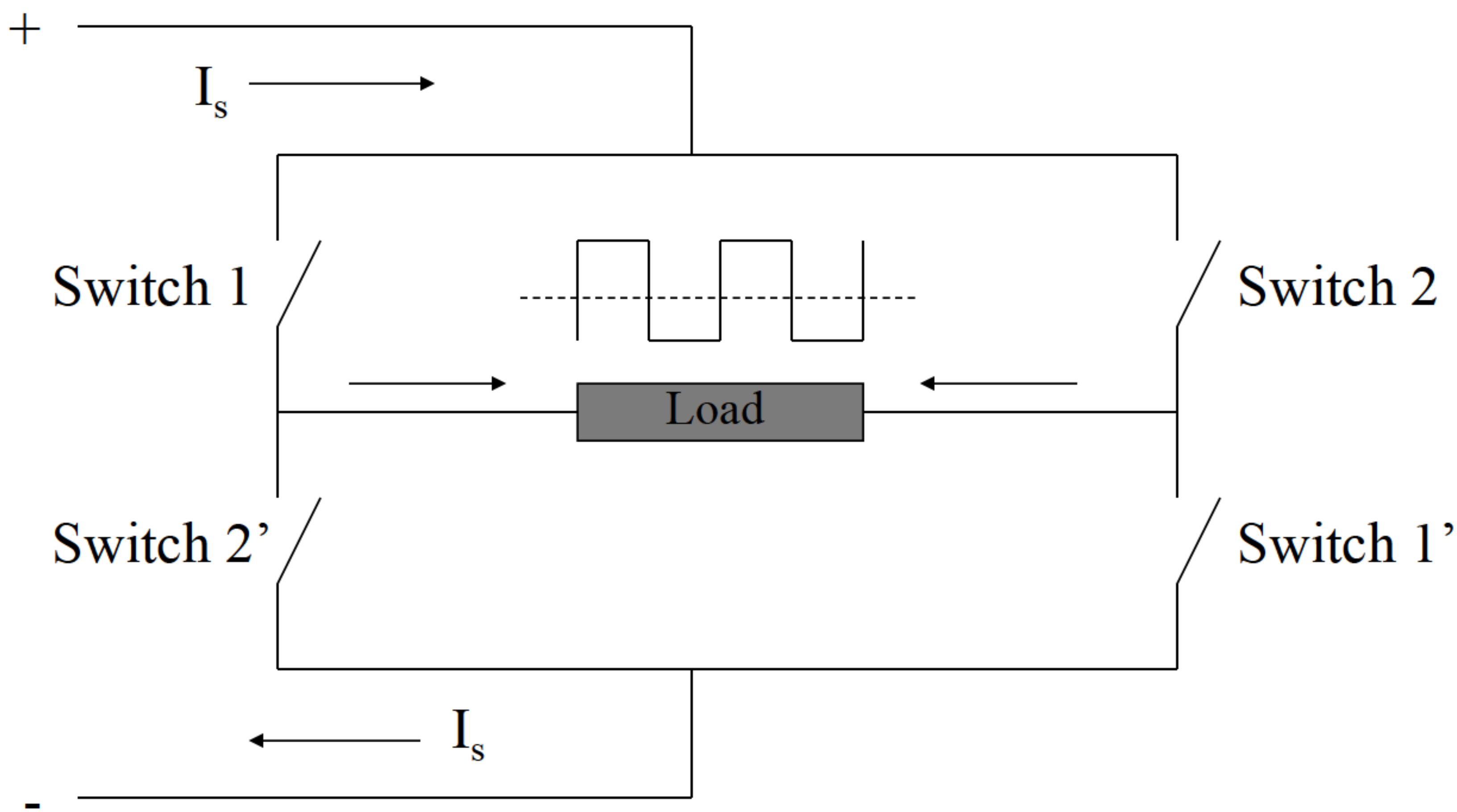


- IGBT (Insulated Gate Bipolar Transistor) : *Semiconductor Device that switches current ON and OFF by a control gate signal*

Inverter Block Diagram



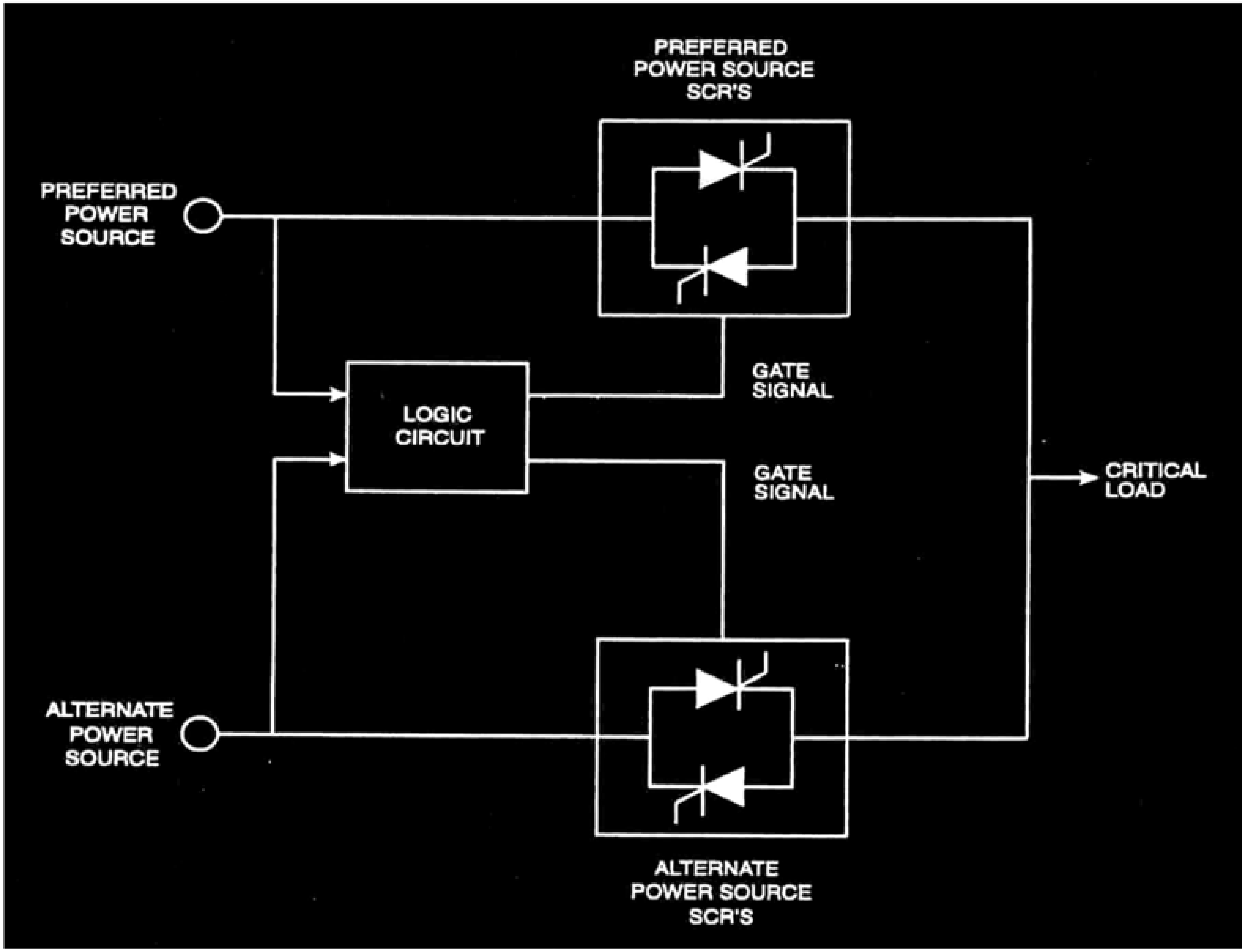
Inverter Switch Bridge Circuit



Static Transfer Switch

- To quickly transfer the critical load to the proper source of power (¼ cycle)
- Static=No moving parts=solid-states$\Rightarrow$SCR
- Make-before-break
- 125% of UPS output current

Static Transfer Switches



Maintenance Bypass Switch

- To completely isolate the UPS to be serviced
- Make-before-break
- 3-position
  - Normal –Inverter and alternate line connected to load through static switch
  - Bypass Test -Load connected to alternate line with inverter and alternate line still connected to static switch input
  - Full Bypass -Load connected to alternate line with static switch totally disconnected from the alternate line

Bypass (Isolation) Transformer

- To provide ground isolation from utility
- To provide voltage matching
- To shield noise from utility

DC/UPS SYSTEMS

UPS Configurations

Major Components of UPS

- Rectifier/Charger

  A device that converts AC to DC

- Batteries

  A rechargeable electromechanical storage device that, when discharged, produces DC electrical energy.

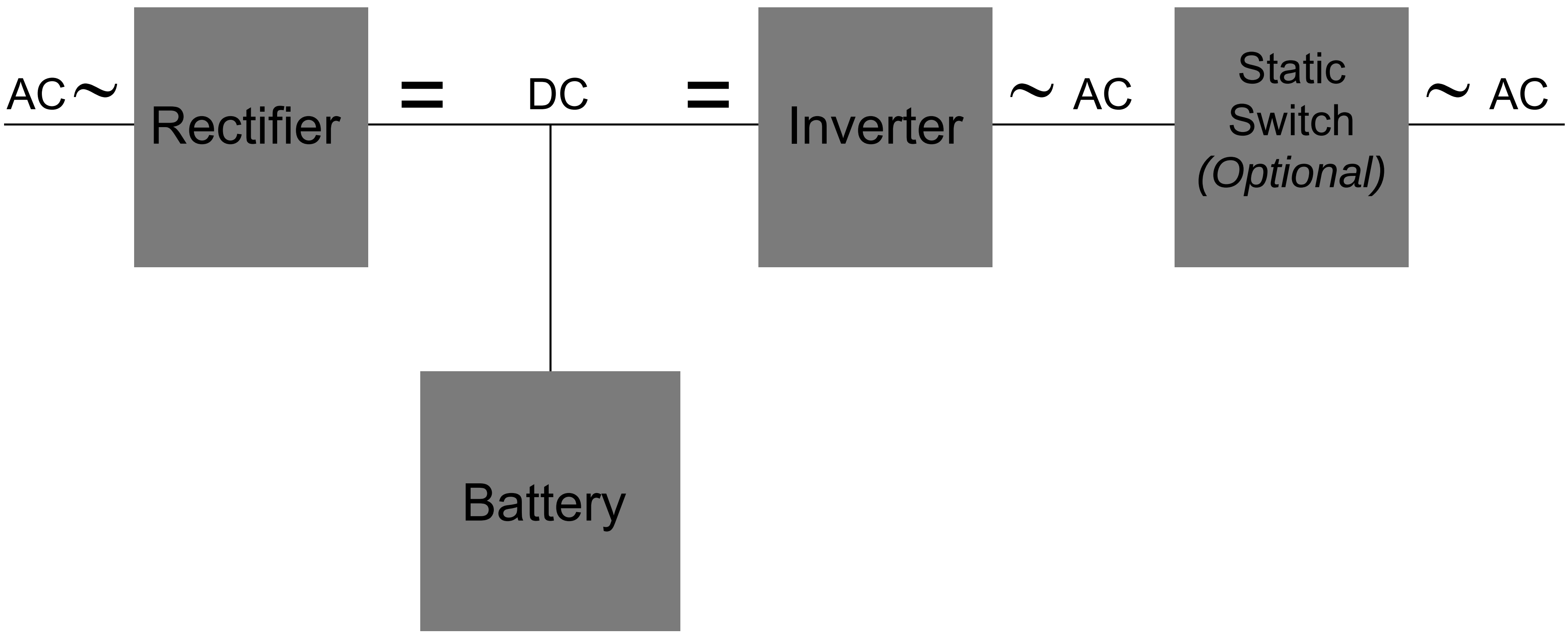
- Inverter

  A device that converts DC to AC

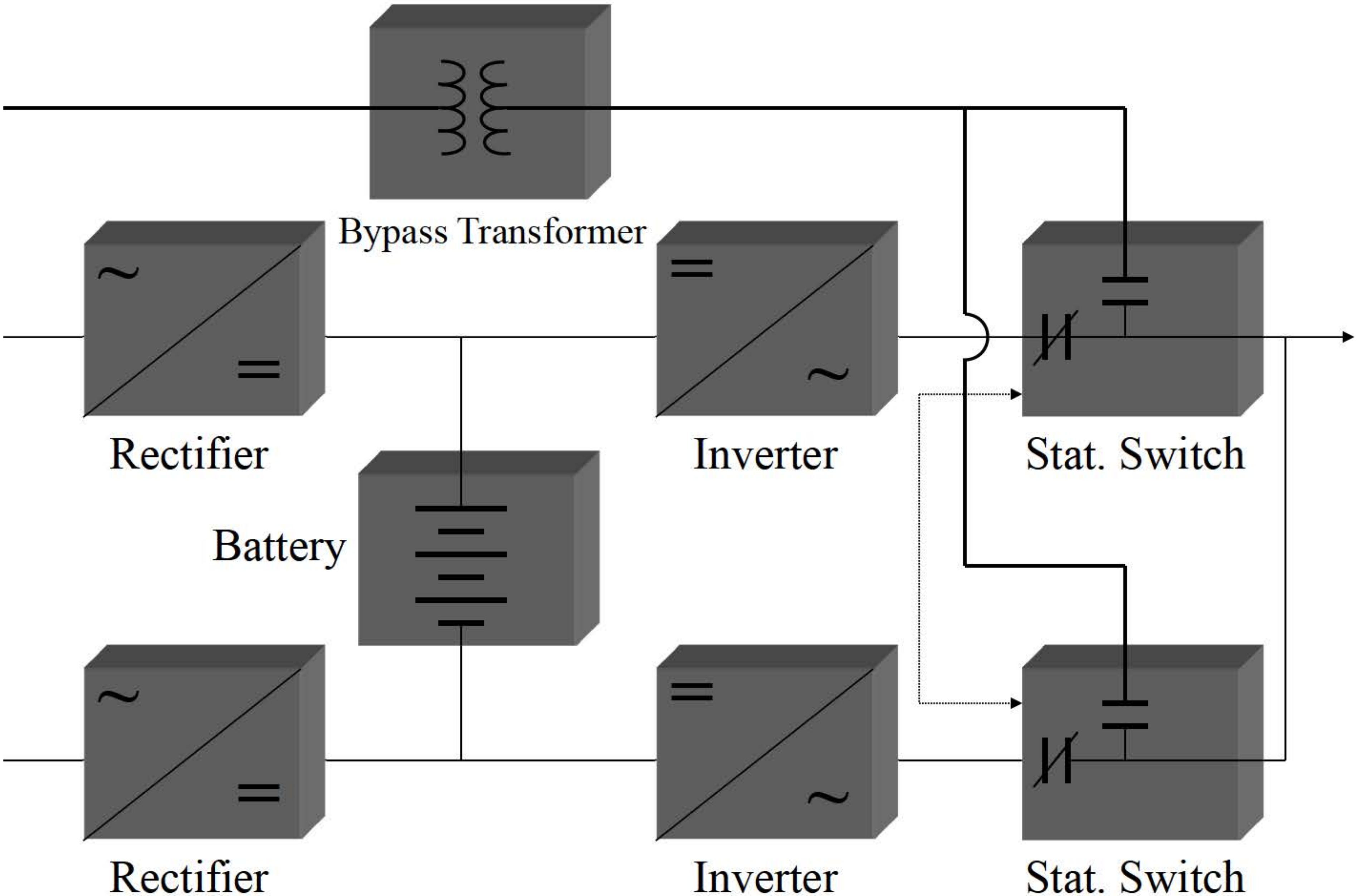
- Static Switch (Optional)

  A device that can start or interrupt current flow by the use of gated semiconductors

Basic UPS System



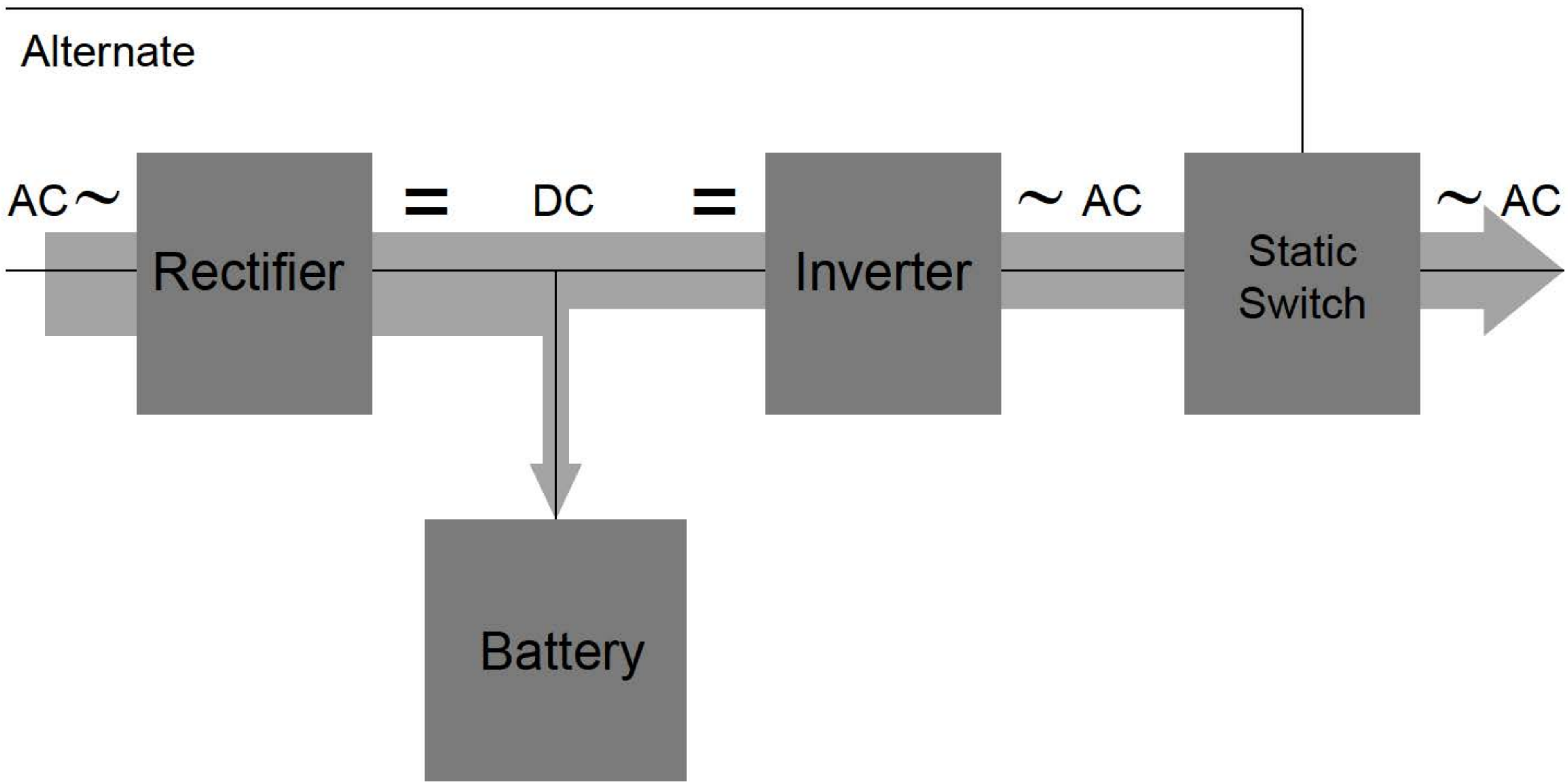
Parallel UPS



Modes of Operations

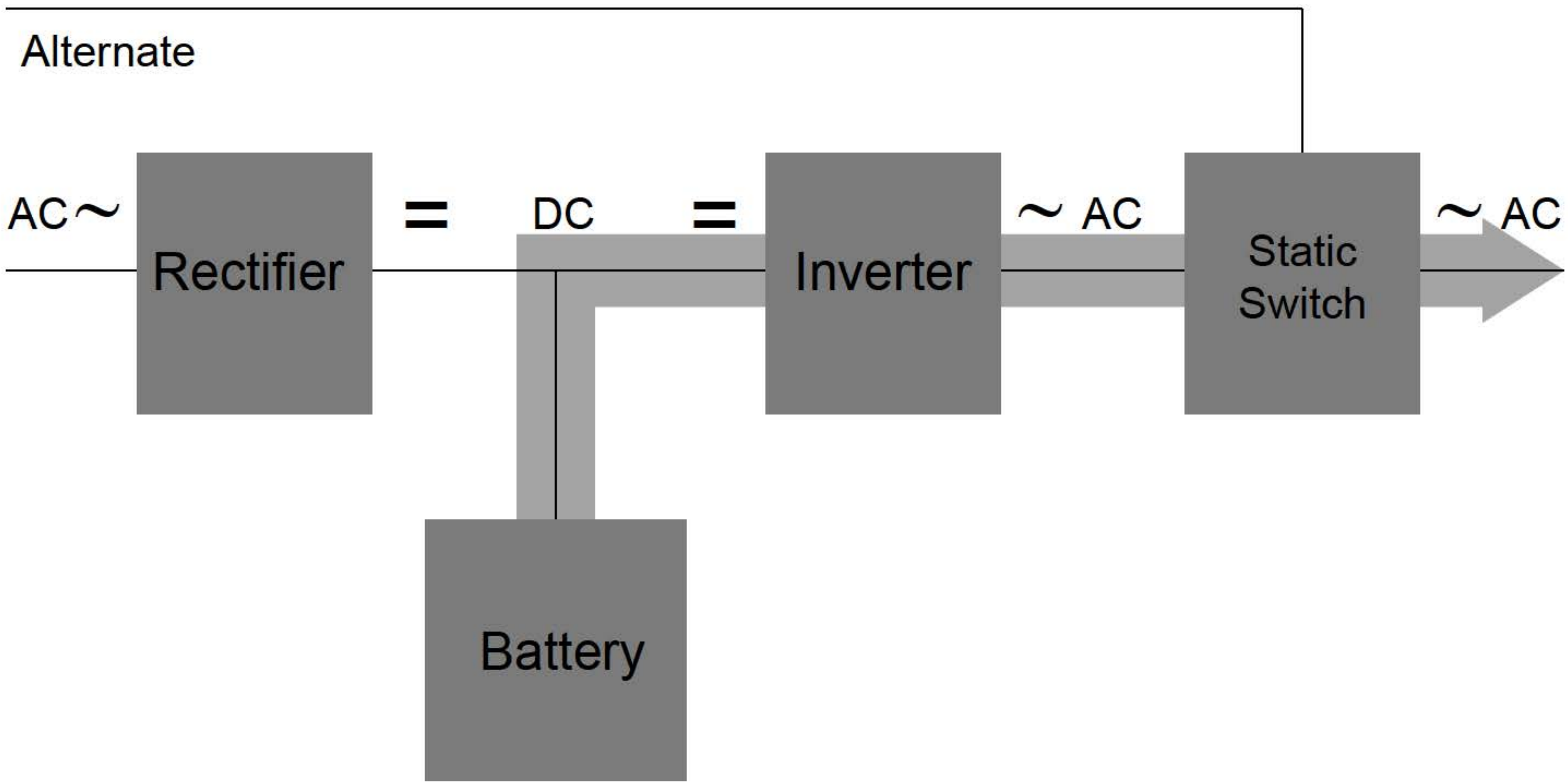
- **Normal Mode** -Load connected to inverter while rectifier supplying the inverter and floating the battery
- **Emergency Mode** -Load connected to inverter in the event of rectifier failure. Battery is supplying the inverter.
- **Recharge/Recovery Mode** -Load connected to inverter while rectifier supplying the inverter and charging the depleted battery
- **Bypass Mode** -Load connected to alternate line in the event of inverter failure
- **Disconnected Battery Mode** -Load connected to inverter while the battery is taken out of service
- **Maintenance Bypass Mode** -Load connected to alternate line and the UPS is completely isolated

Normal Mode

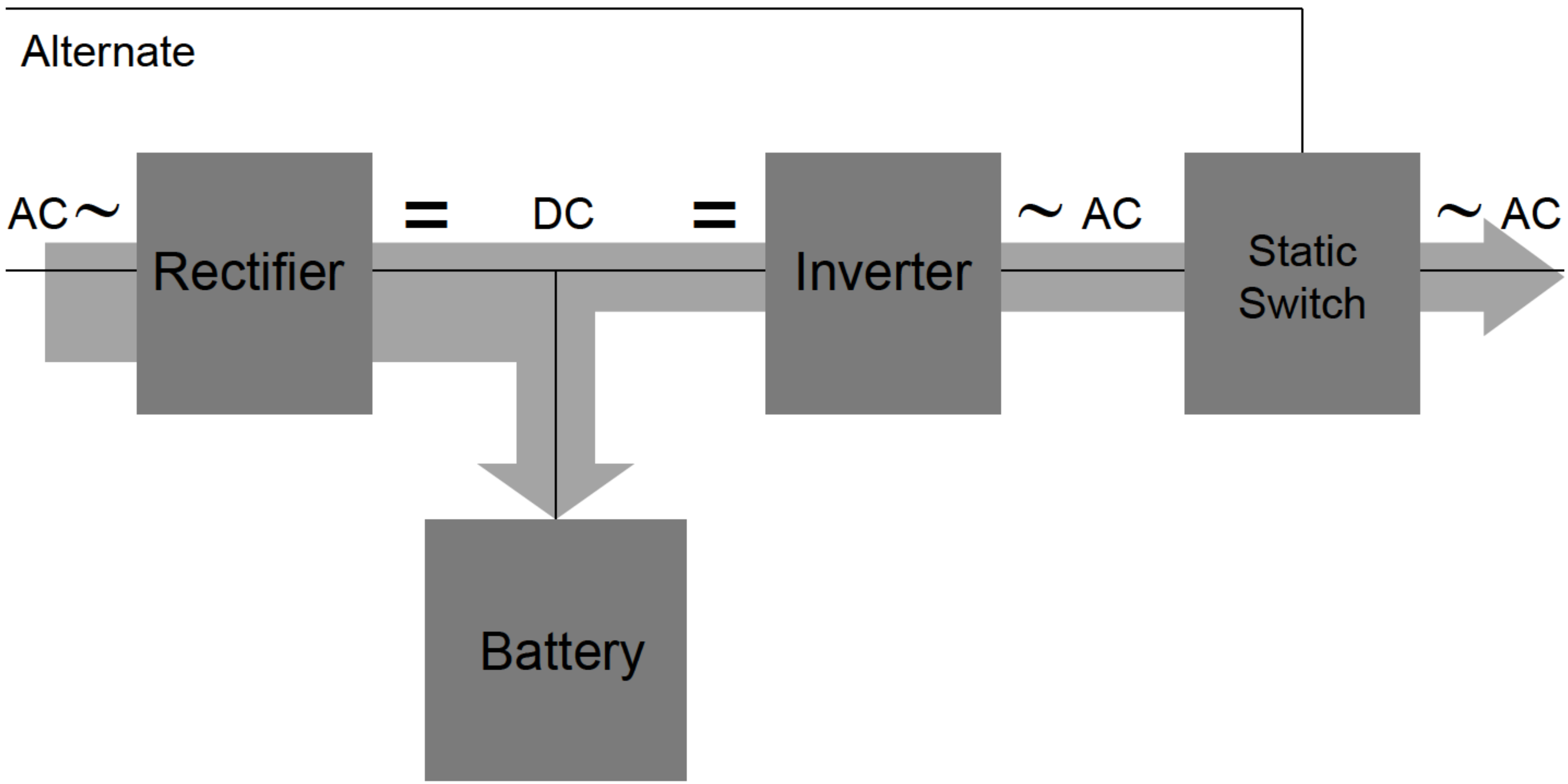


Alternate
AC ~
=
DC
=
~ AC
~ AC
Rectifier
Inverter
Static
Switch
Battery

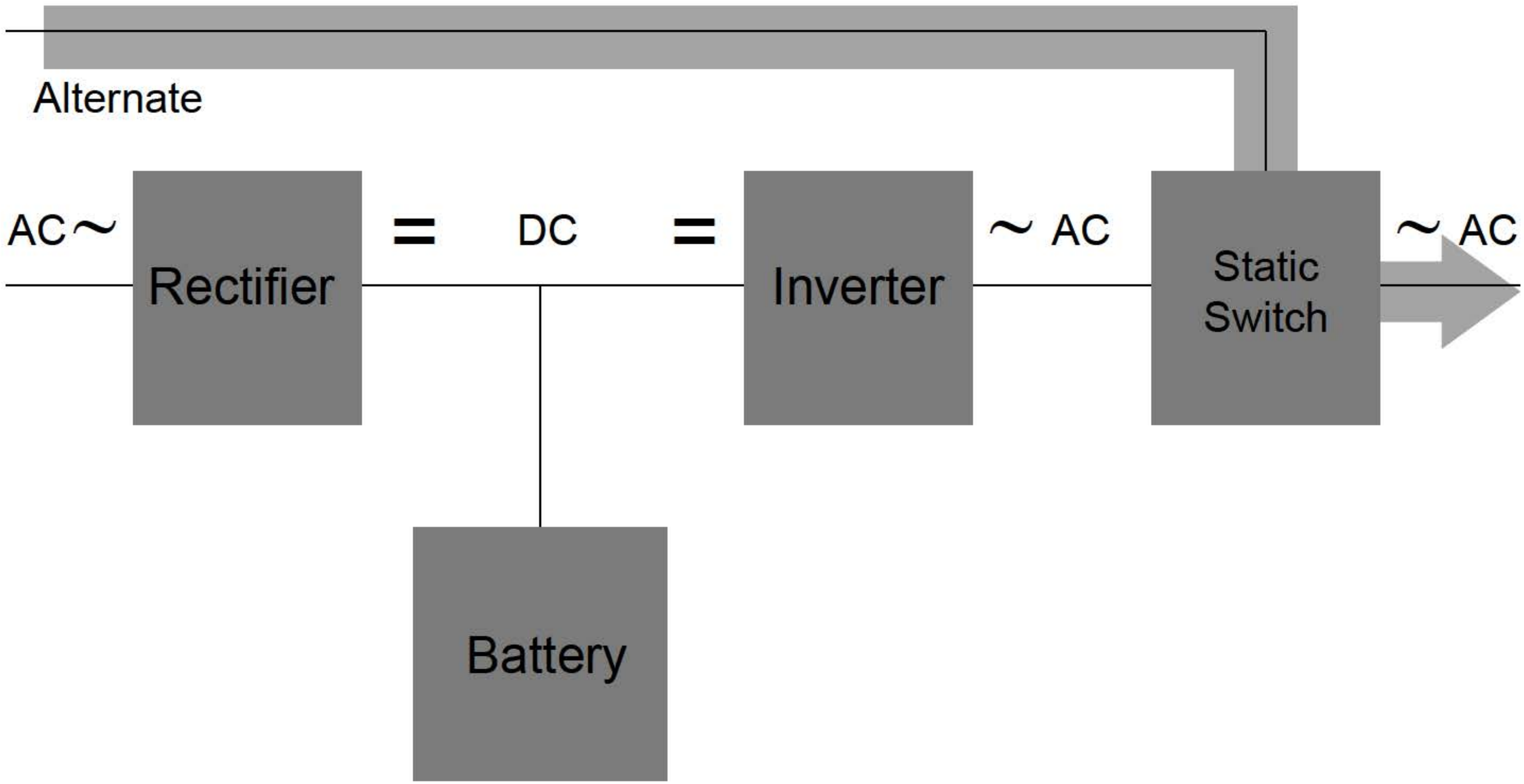
Emergency Mode



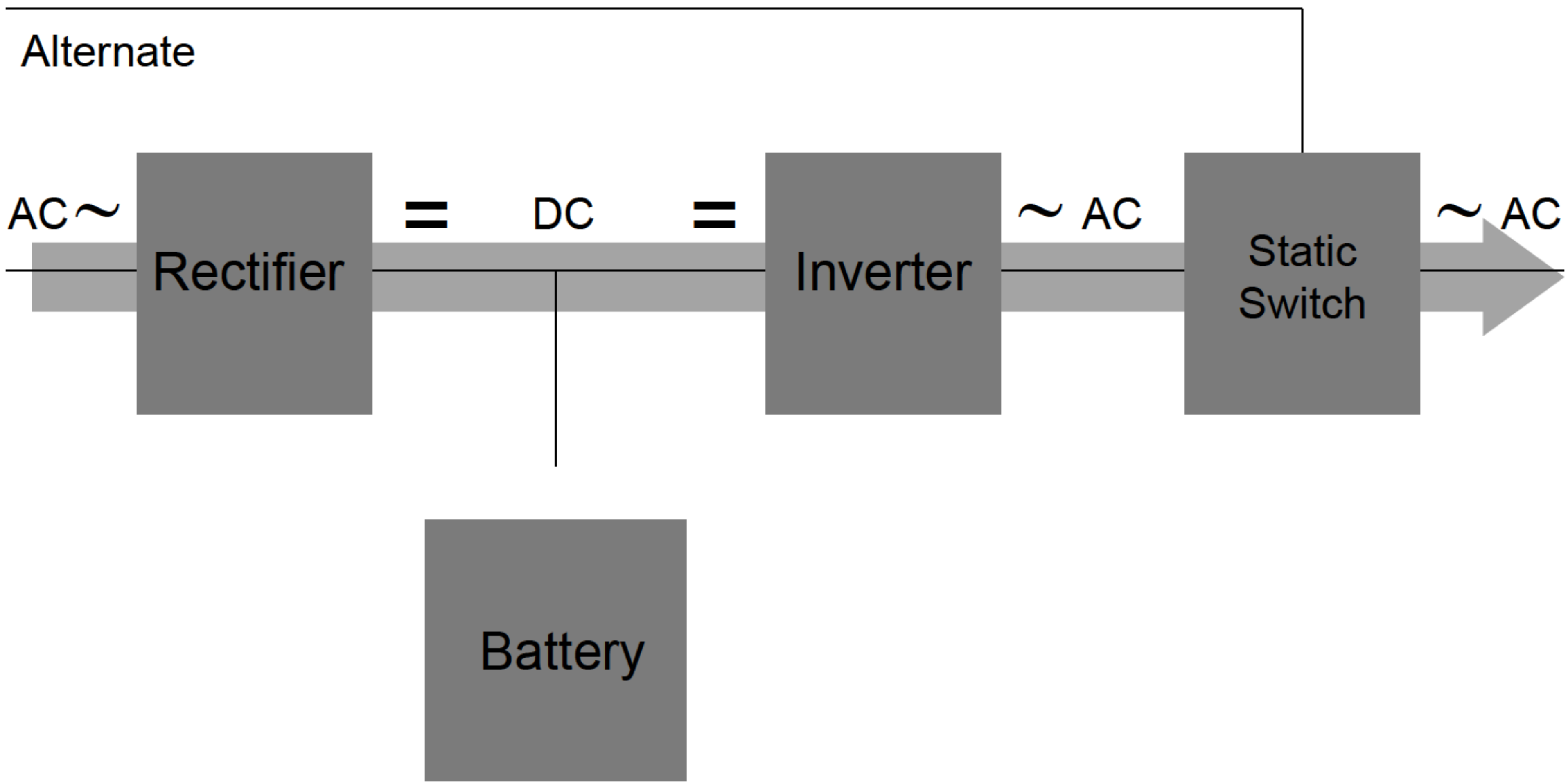
Recharge/Recovery Mode



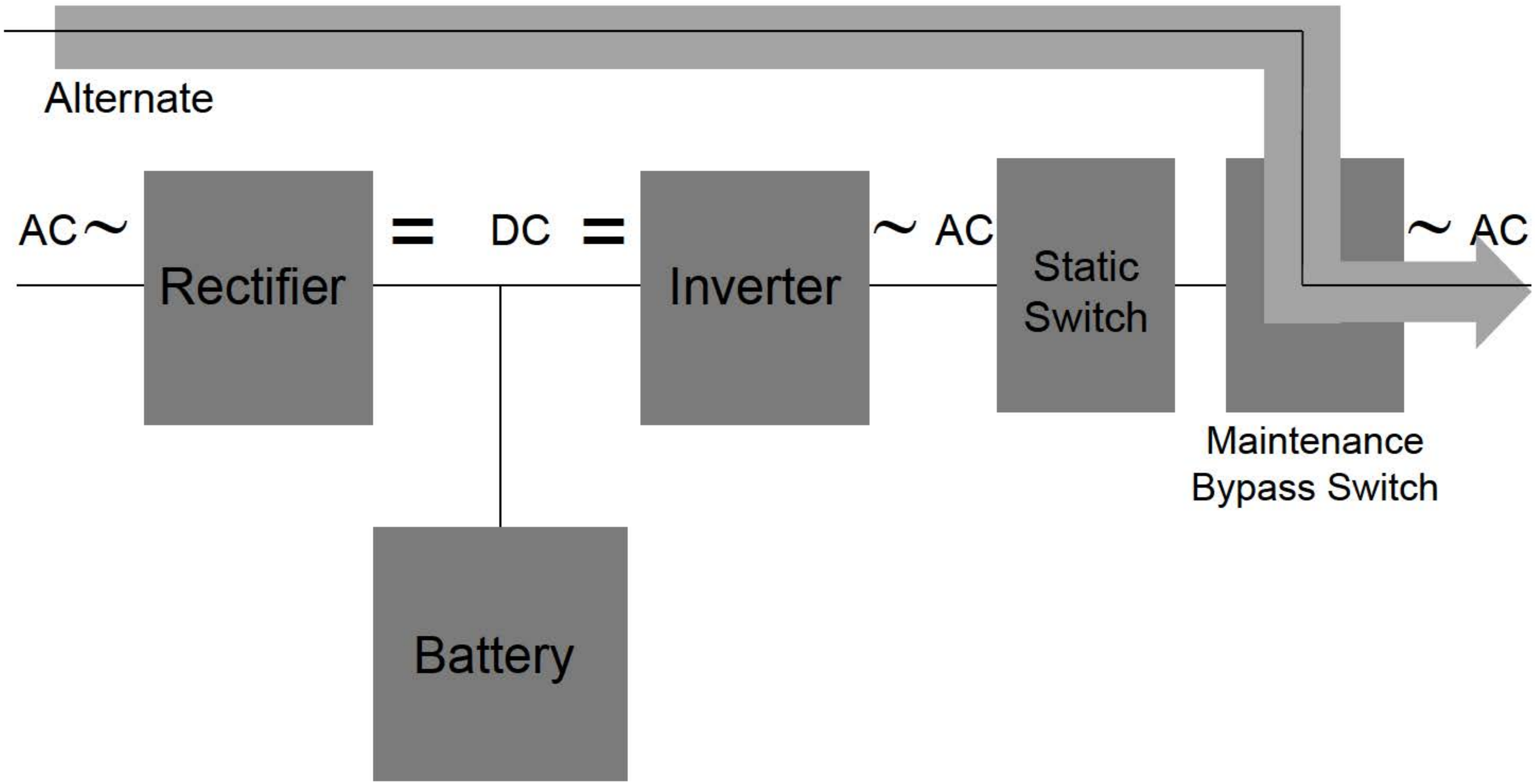
Bypass Mode


Alternate
AC~
Rectifier
=
DC
=
Inverter
~ AC
Static
Switch
~ AC
Battery

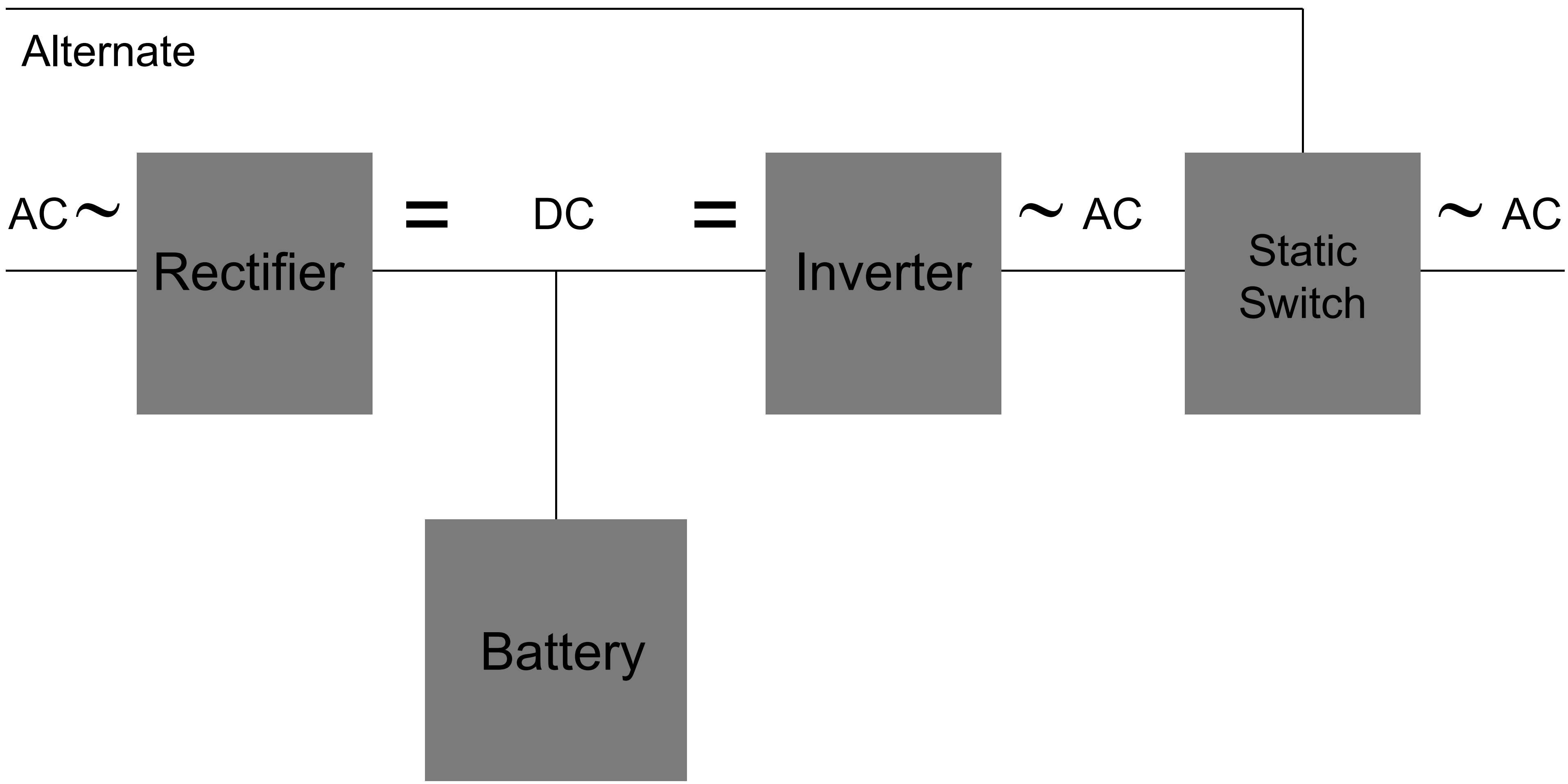
Disconnected Battery Mode



Maintenance Bypass Mode



Non-Redundant UPS



Parallel Redundant Type

Operating Principles:

The parallel redundant UPS is 2 UPS units that operate in parallel and share the load equally. If one unit fails, or is taken out of service, then the other on-line unit automatically picks up the entire load, without causing any disturbance to the load. They are interconnected through a static switch to provide increased reliability.

Parallel Redundant Type

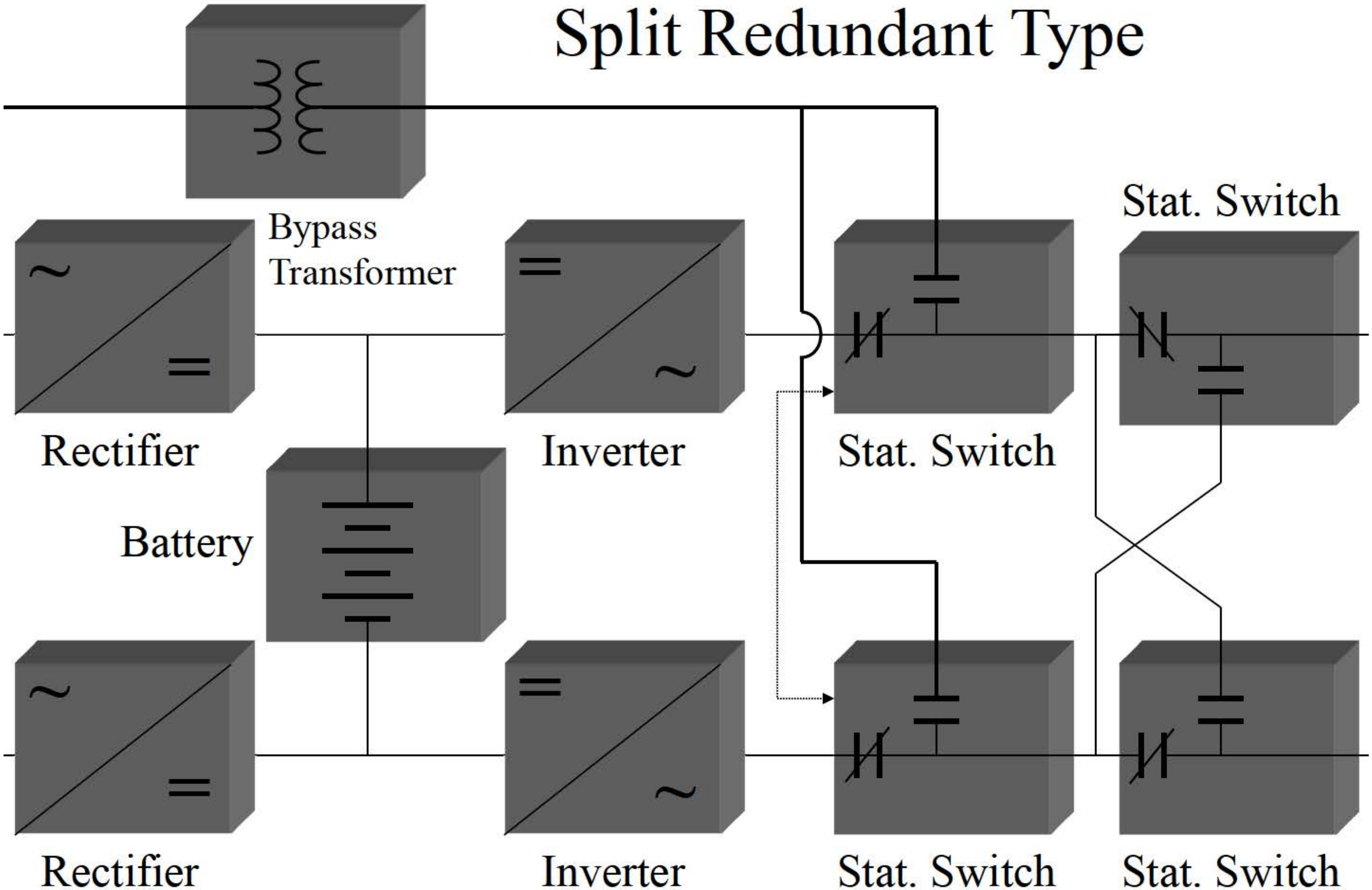
Advantages:

1. Very reliable
2. Less likely to fail during transfer because two units are online concurrently

Disadvantages:

1. Very expensive
2. Single point of failure at the common output bus

Split Redundant Type



Split Redundant Type

Operating Principles:

In the split redundant, 2 UPS units operating independently with two separate output buses. Each unit is normally 50% loaded while designed to carry the entire load.

Split Redundant Type

Advantages:

1. More reliable than cascaded redundant (no single point of failure)

Disadvantages:

1. More expensive (2 output buses, 3/4 static switches)
2. Complicated

Understanding Power Concepts

Part 4 (has not been released, will be released in 2014 REV 1)

- Protective Relaying
  - Bus
  - Feeders
  - Motors
  - Generators
  - Transformers

QUESTIONS?