Generator Advanced Concepts

Common Topics, The Practical Side

- Machine Output Voltage Equation
- Pitch
- Harmonics
- Circulating Currents when Paralleling
- Reactances and Time Constants
- Three Generator Curves Used for System Coordination
  - Thermal Damage Curve
  - Decrement Curve
  - Reactive Capability
- Efficiency
- Parallel Operation

What Determines Voltage Output?

- $E = 4 \times f \times fb \times kd \times kp \times N \times F$, where

f = Frequency of operation which correlates to the difference in relative speeds of the field and conductors

fb = Shape of the magnetic flux wave arising from rotor lamination design

kd = Winding distribution factor related to winding details

kp = Winding pitch

N = Number of turns per phase in winding

F = Total magnetic flux per pole, which includes machine stack length and operating magnetic flux density

Application of V Output Equation

- $E = 4 \times f \times fb \times kd \times kp \times N \times F$
- What if we want a 60 Hz machine to run at 50 Hz too?
  - f decreases by a ratio of 50/60
  - E will also decrease by a ratio of 50/60 unless another factor changes:
    - Increase magnetic flux densities (F)?
      - May not be possible due to material characteristics.
      - Can cause excess heating.
    - Increase stack length (F) – Increases cost.
    - Change other aspect of the design, including different laminations and different winding configuration or turns.

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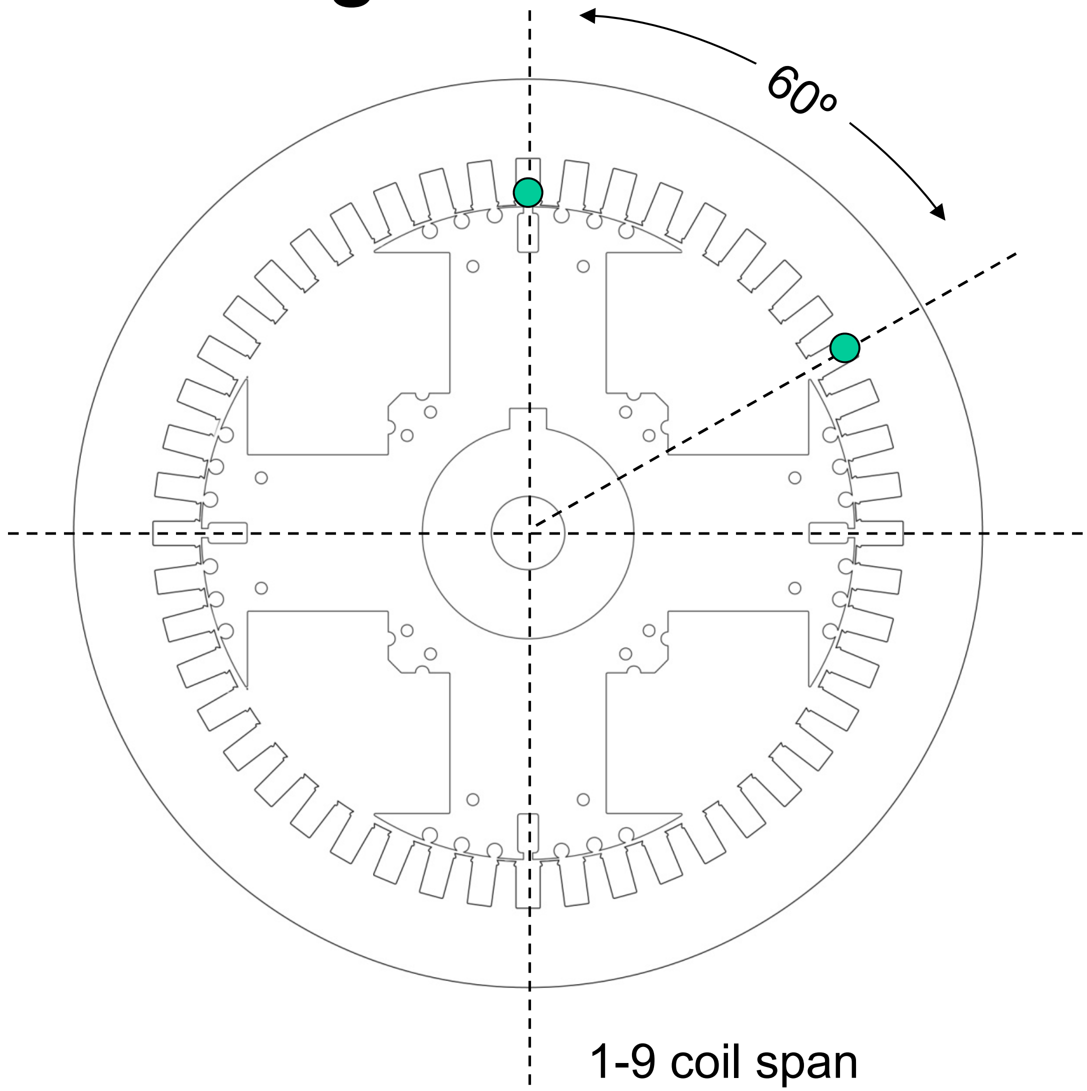
Pitch: Pole and Winding

- Pole pitch is the mechanical angle between adjacent poles, e.g. 4 pole = 90º.
- Winding pitch is the coil span divided by the pole pitch, e.g. 60º / 90º = 2/3.
- Key design factors include number of poles, number of slots, and number of slots spanned by coils.



Pitch: Common Values Specified

- Optimum pitch allows the designer flexibility used to balance generator performance to effectively utilize the generator's active materials.
- 2/3 pitch is often specified because it reduces 3rd harmonic content. However this may require a larger machine to meet the power ratings.
- Lower pitches
  - $E = 4 \times f \times fb \times kd \times kp \times N \times F$
  - kp decreases with lower pitch. If the voltage is to remain the same, something else has to increase.
    - Increase magnetic flux densities
    - Increase stack length
    - Increase turns
    - Use a different lamination set

Pitch: Effects When Reduced

- Coils spanning anything less than the full distance from pole to pole are called short-pitched.
- Reactances are reduced as pitch decreases (keeping all other design factors).
- Harmonics are generally reduced more than the fundamental, and specific harmonics can be cancelled entirely.
  - 2/3 pitch reduces 3rd harmonic L-N at the expense of increasing 5th and 7th harmonics.
  - There is never a 3rd harmonic L-L on a balanced system.
- Generator may need to be oversized to meet its rated power output and temperature.

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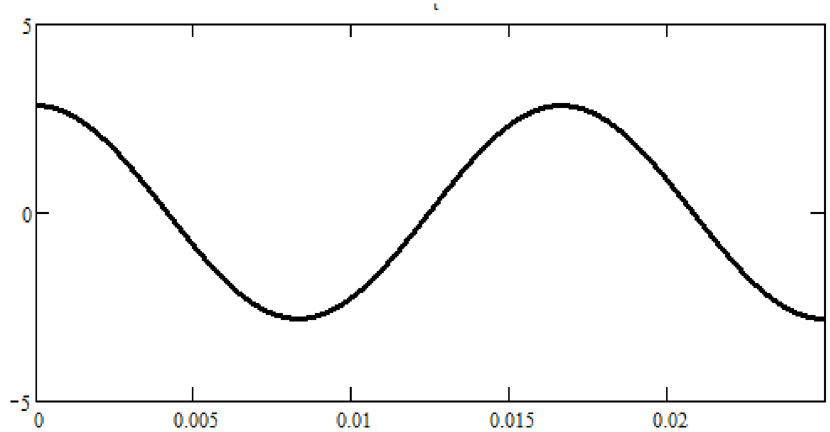
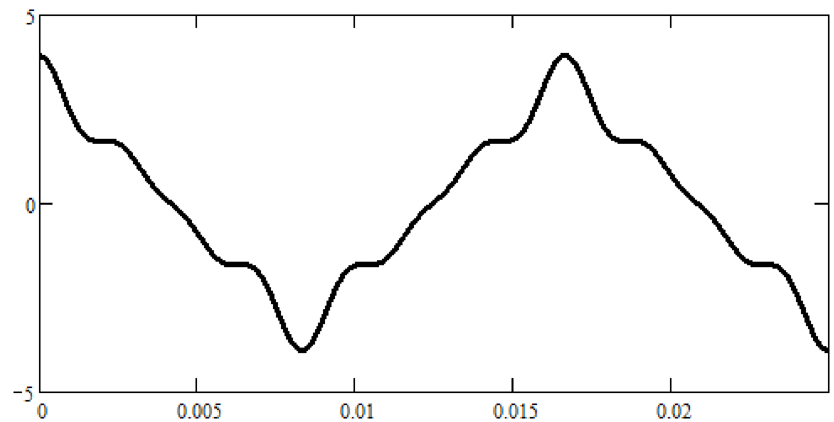
Harmonics

- Purely sinusoidal (clean and smooth) waveforms are desirable.
- Clean and smooth waveforms minimizes sudden changes in voltages, currents and power.
- Power system waveforms typically are NOT clean and smooth.

Note: Example is for demonstration purpose only and is not typical of generator waveforms. It shows exaggerated harmonics without phase shift.



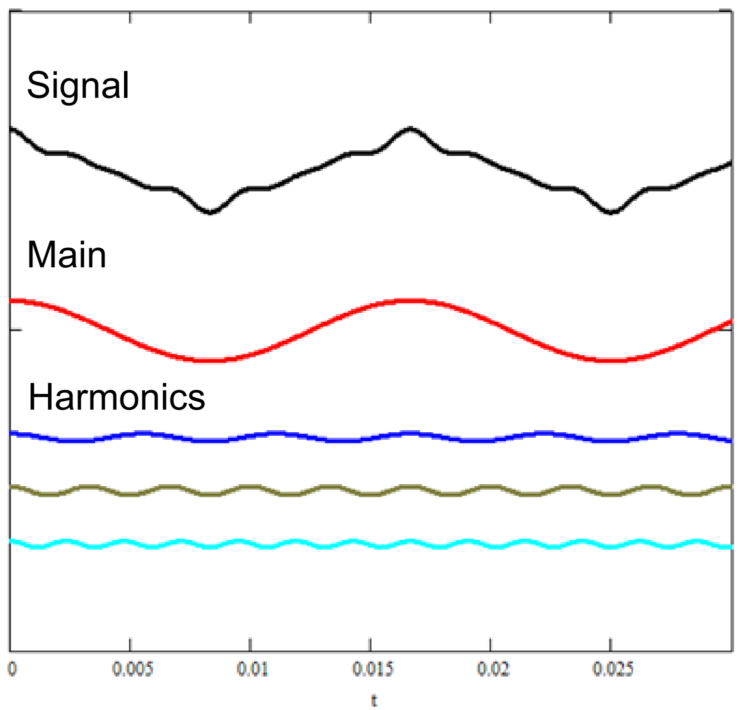
Pure sinusoidal waveform



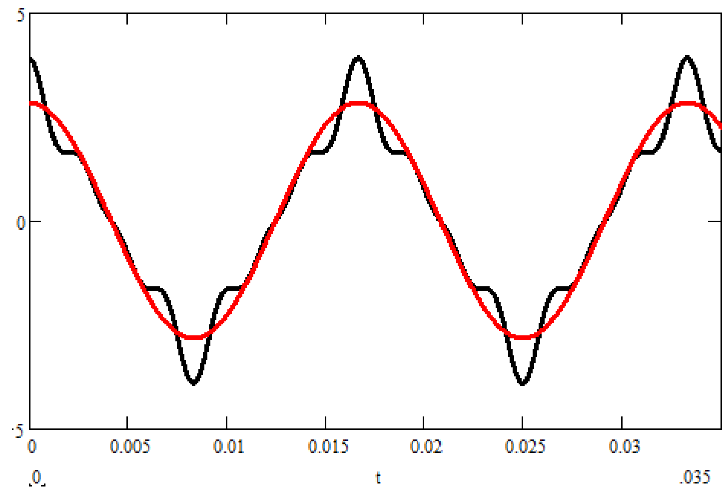
Waveform with harmonics

Harmonics (cont.)

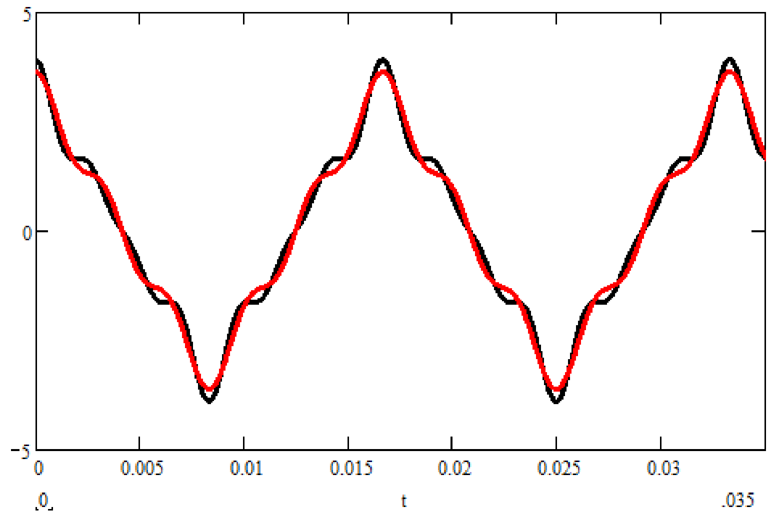
- Signals can be broken into a main (fundamental) sinusoidal (smooth) waveform and a series other smooth waveforms at frequencies that are multiples of the fundamental waveform frequency.
  - Harmonics are the extra signals other than the fundamental waveform.
  - Lowest harmonic usually has highest amplitude.
  - Specifications call out individual harmonic limits as well as total harmonic distortion (THD).



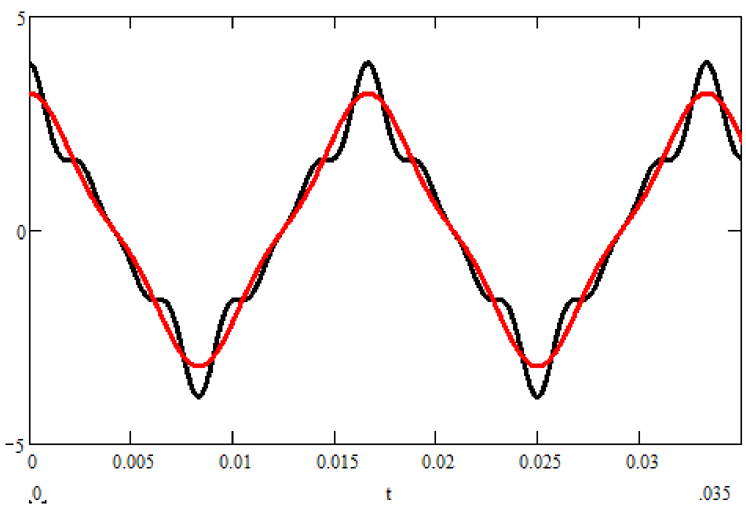
Harmonics (cont.): Signal Breakdown



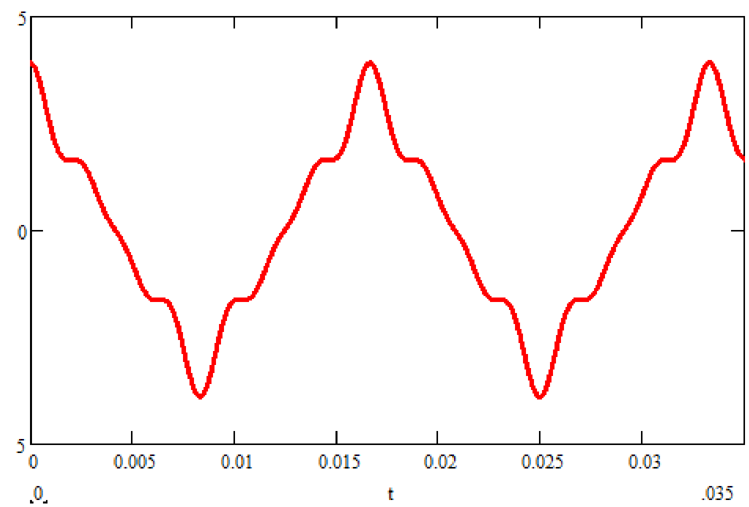
Signal --- fundamental ---



Signal --- fund+3rd+5th ---



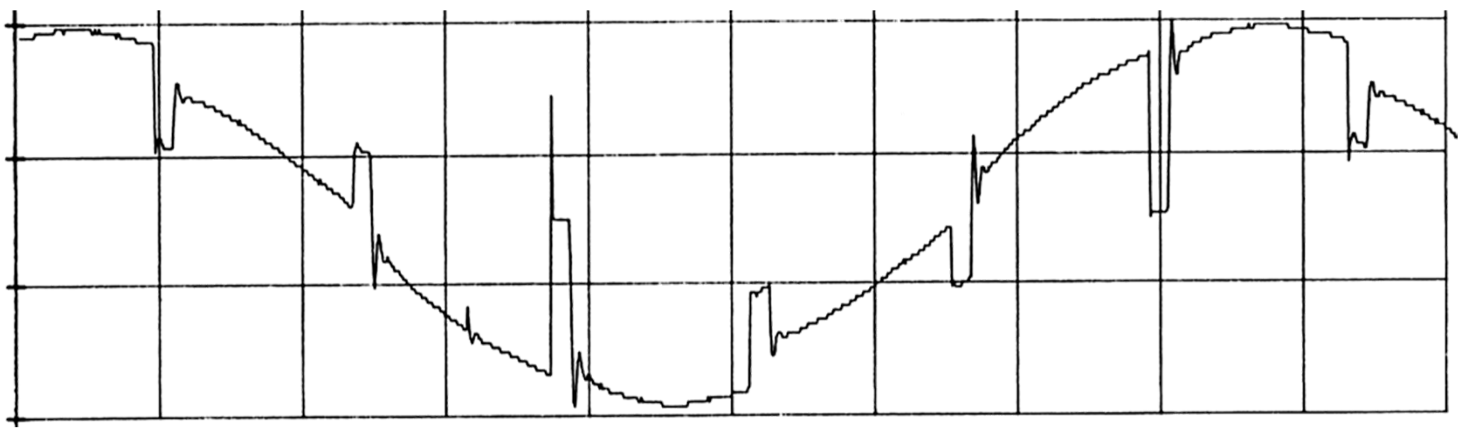
Signal --- fund+3rd ---



Signal --- fund+3rd+5th+7th ---

Load-Induced Distortion Example

- Pictured below is a real waveform that has notching caused by SCR loads
- This increased harmonic content and the issues associated with higher harmonics.



Harmonics (cont.): Resultant Problems

- Insulation systems may stress and get damaged.
- Generator components may overheat, requiring derating of the generator.
- Motors on the system may experience overheating, high audible noise or increased torque ripple.
- Transformers may overheat due to harmonic flux core losses.
- Power factor correction capacitors and other electronic equipment may receive excess currents and/or voltages.
- Telephone systems may get interfered with by higher order harmonics - telephone-influence factor (TIF).

Harmonics (cont.): Sources

- Arc furnaces
- Transformers
- Fluorescent lamps
- Rotating machines
- SCR (thyristor)-controlled devices
- Pulse width modulated devices
- Switch-mode power supplies
- Battery chargers
- Adjustable-speed drives

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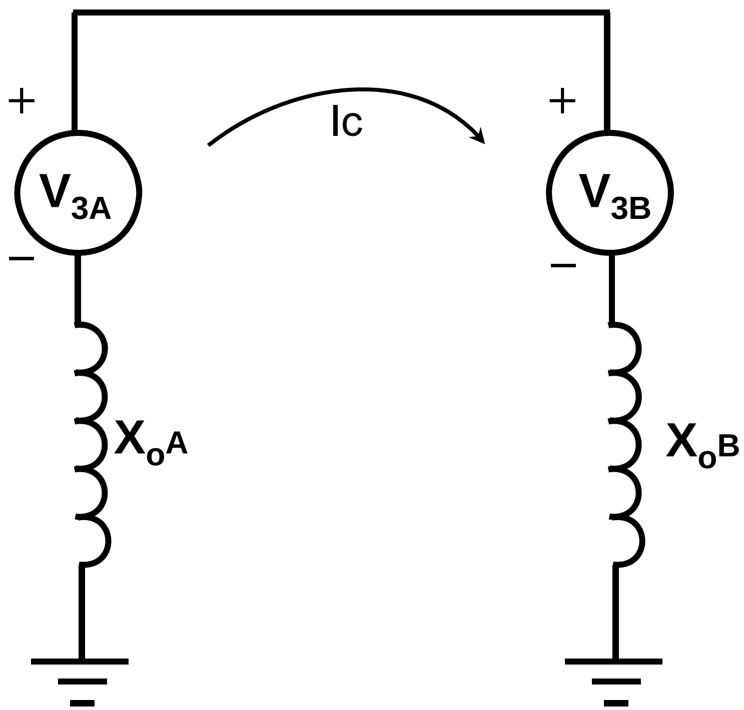
Circulating Currents When Paralleling

- Circuit diagram is of two generators in parallel.
- When there are differences in specific harmonics (3rd harmonic in this diagram) then circulating currents will flow through the generators



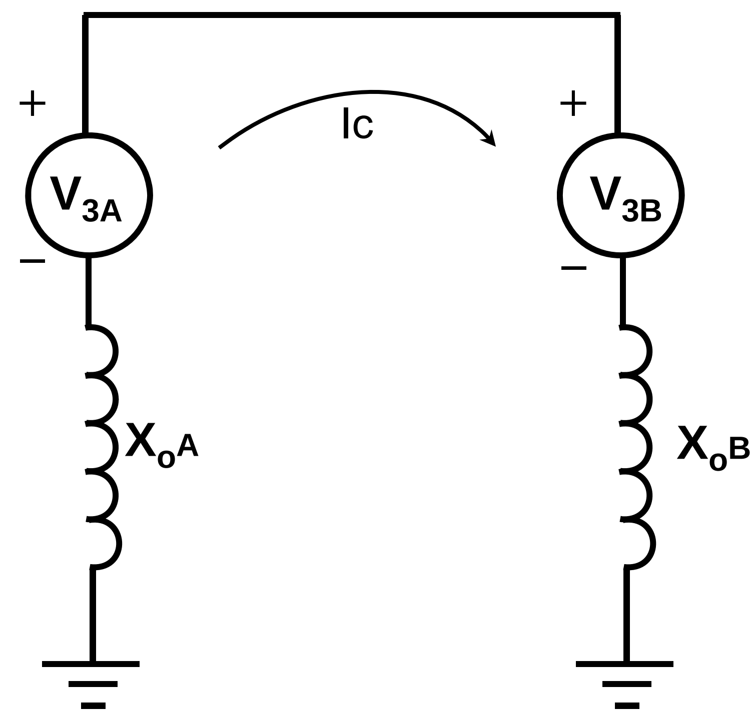
$$I_C = \frac{V_{3A} - V_{3B}}{3 \times (X_{0A} + X_{0B})}$$

V_3 is L-N third harmonic voltage.

X_0 is zero-sequence reactance of each source (including external grounding reactance).

Circulating Currents When Paralleling

- For non-2/3 pitch generators, the key harmonic is the third
  - The difference in third harmonic voltage is the driving force behind circulating currents.
  - It flows in neutral and can cause false tripping of the differential protection relay and other problems.
  - The grounding method used can greatly decrease current magnitudes.
  - Identical generator pitch does NOT guarantee successful parallel operation.



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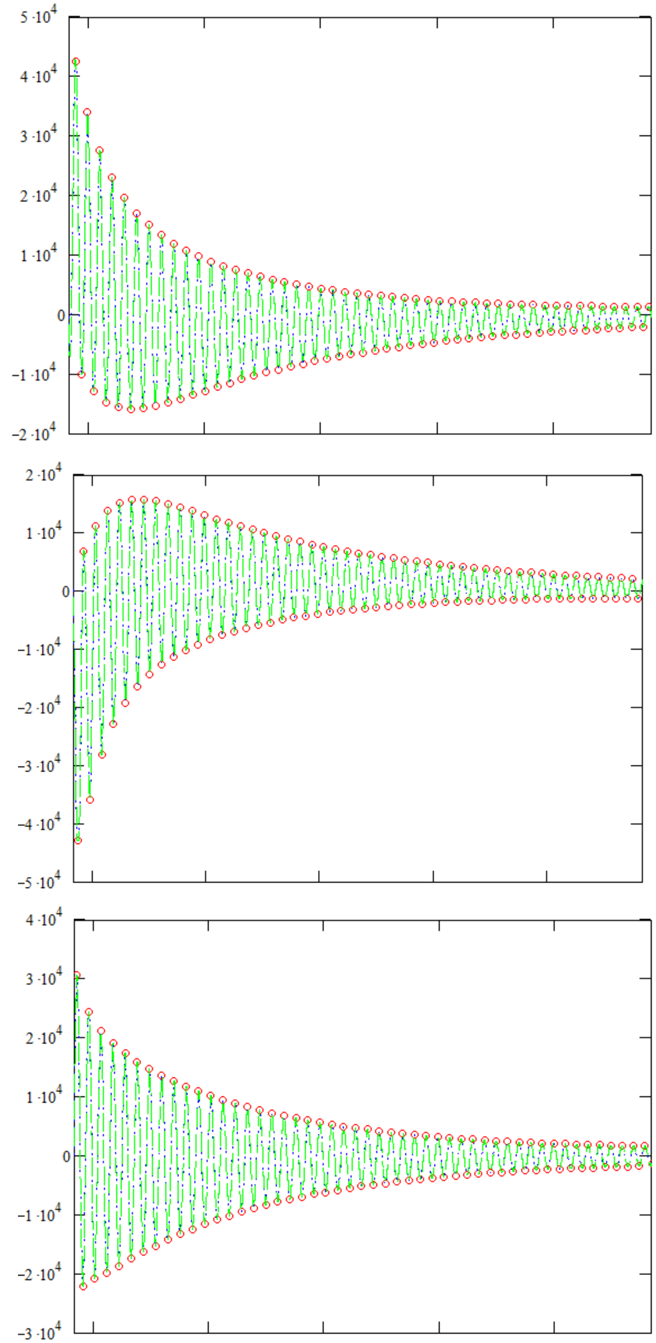
Reactances

- Reactance is the opposition to AC current flow (like resistance, but recall that there are more than just simple toasters in power systems).
- Reactances are used to describe the behavior of a generator during certain operating conditions.
- X'd is used in motor starting calculations.
  - lower X'd results in better motor starting (i.e. lower voltage dip).
- X"d is used in short-circuit current and arc flash calculations.
  - lower X"d results in higher short circuit currents.
- There are other reactances for different situations.
  - e.g. direct and quadrature axis, zero and negative sequence, saturated and unsaturated.

Reactances (Cont.)

- Test method to obtain X'd, X"d:
  - Machine operating at rated voltage, no-load, manual excitation
  - Short circuit is applied across all three phases simultaneously
  - Current envelope in each phase is captured over time as it decays

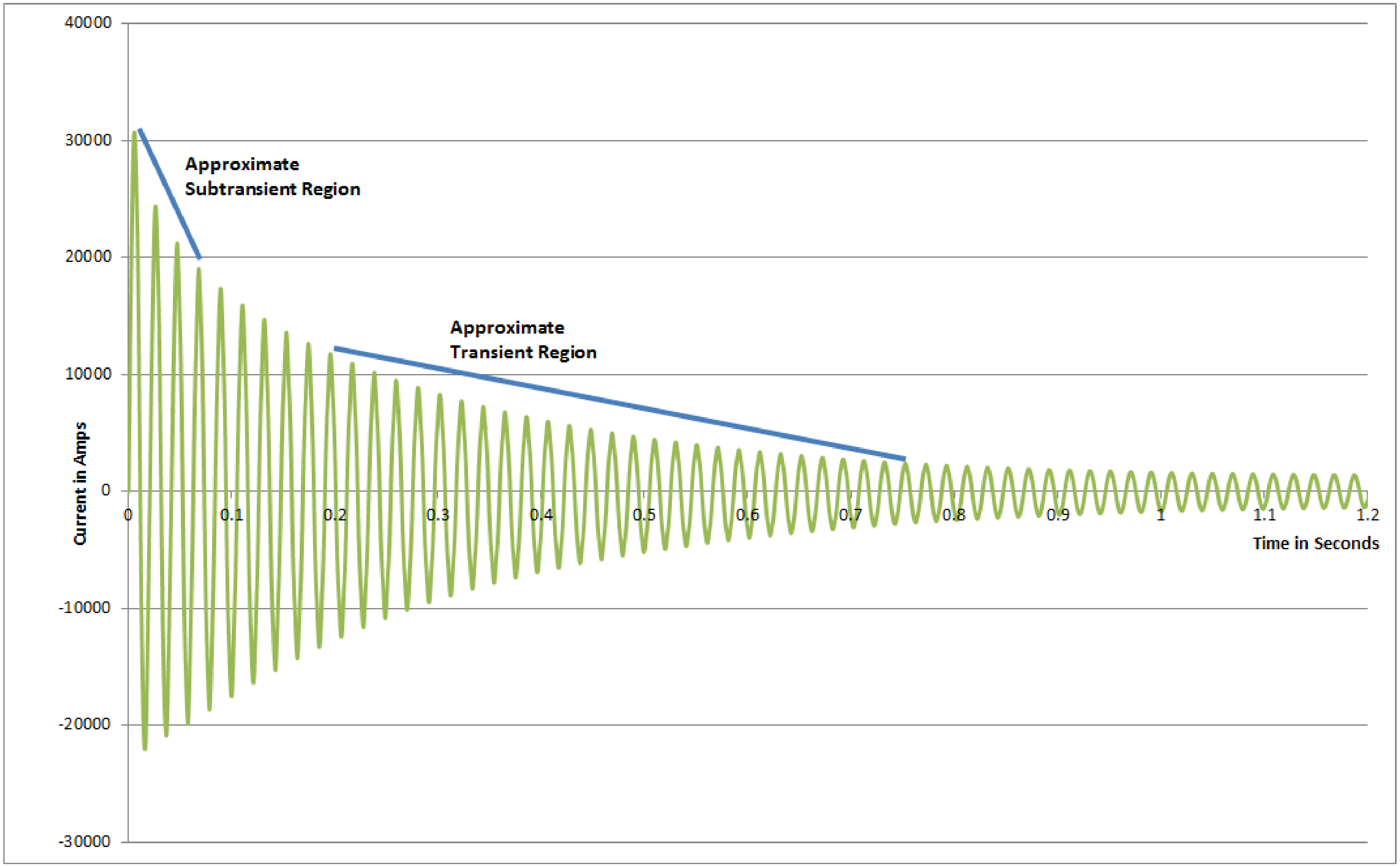


Sample data

Time Constants

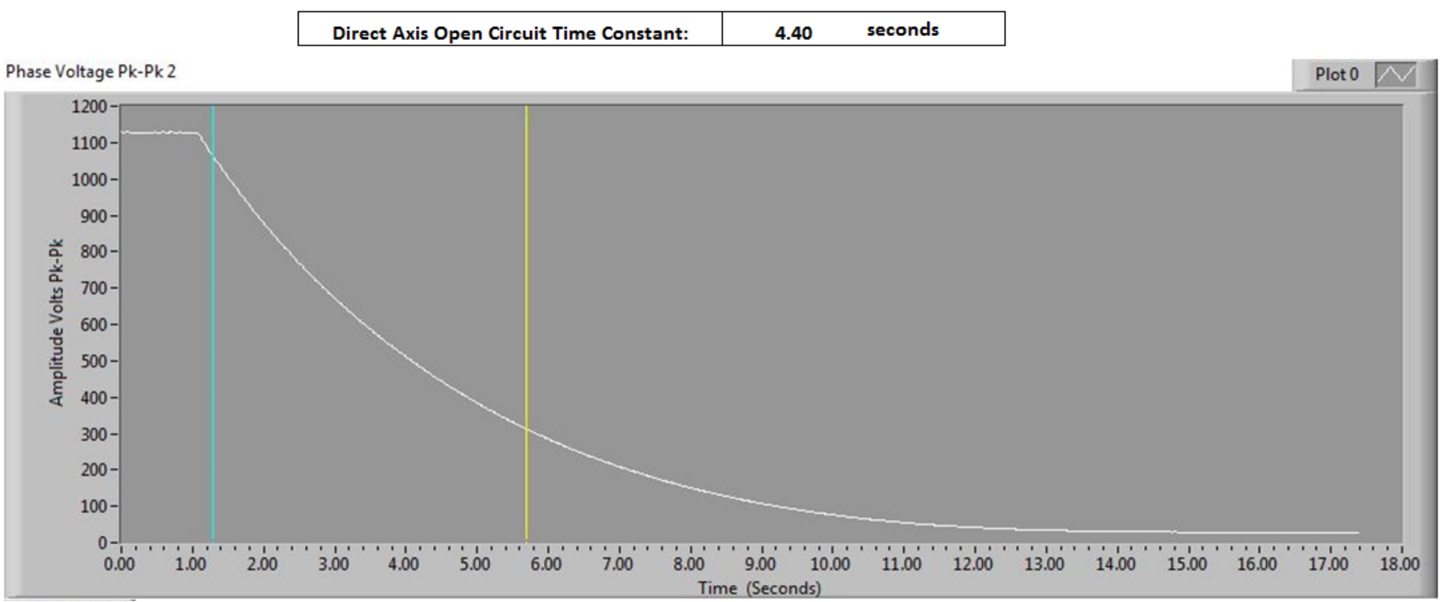
- Time constants characterize the length of time that currents flow during a specific instant in time of a given configuration.
- The two most common are the subtransient time constant T”d and the transient time constant T’.
  - Sub-transient time constant T”d determines length of time sub-transient (damper) current flows.
  - Transient time constant T’d determines length of time transient current flows.

Time Constants



Time Constants (cont.)

- Another time constant example: Open circuit transient T’d0.
  - This represents the decay in armature output voltage when main field excitation is lost
  - This requires a different test setup than previously mentioned time constants: slip rings to manually control the main field.



Reactances, Time Constants: Why are they Important?

- Very useful to predict performance in large system simulations because they simplify and speed up calculations.
- Now, for many users, the reactances and time constants are plugged into simulators used for system modeling and coordination studies.
- Generator manufacturers use this information to produce three curves commonly used for system coordination:
  - Thermal damage curve
  - Short-circuit decrement curve
  - Reactive Capability

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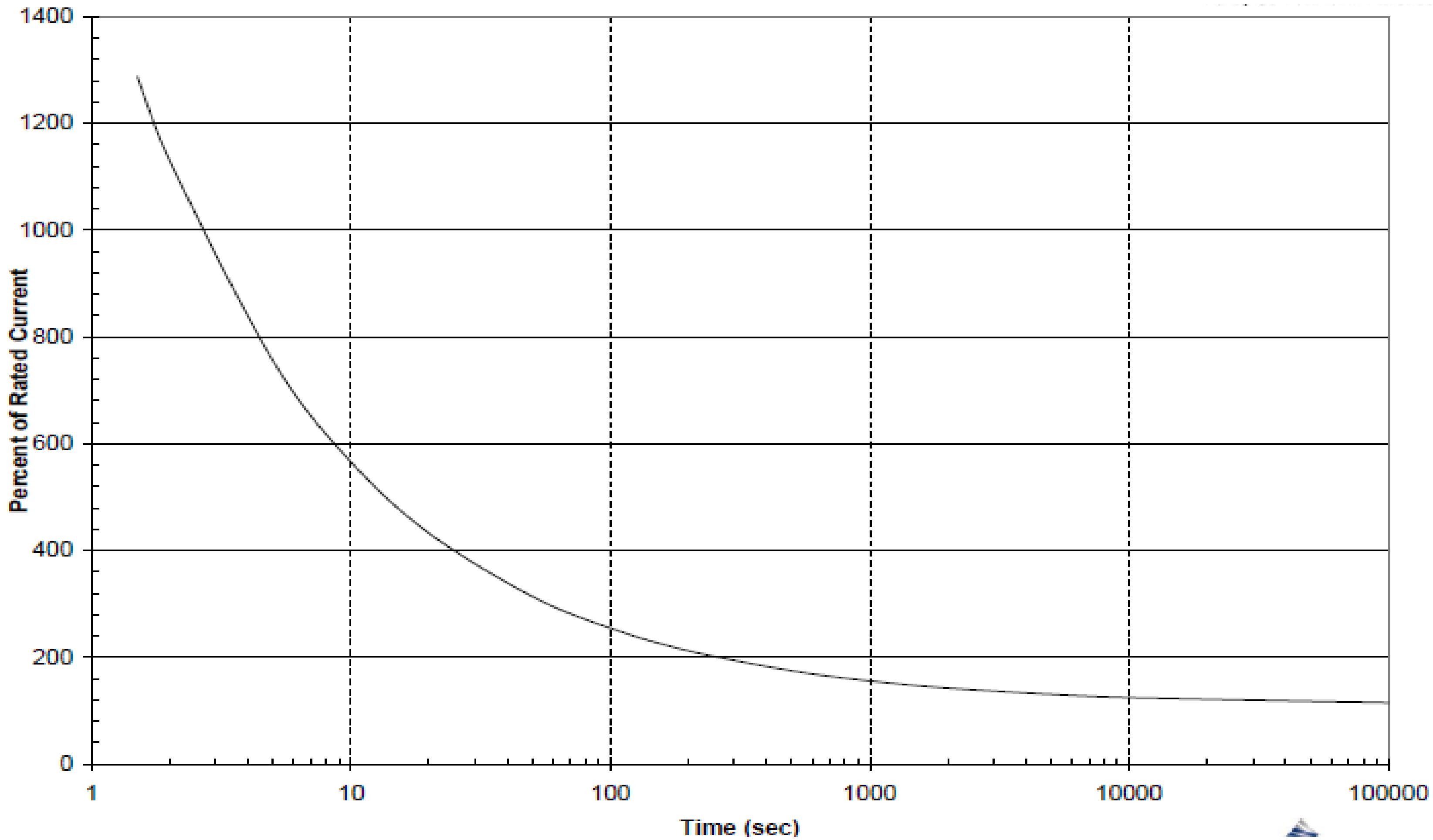
Thermal Damage Curve

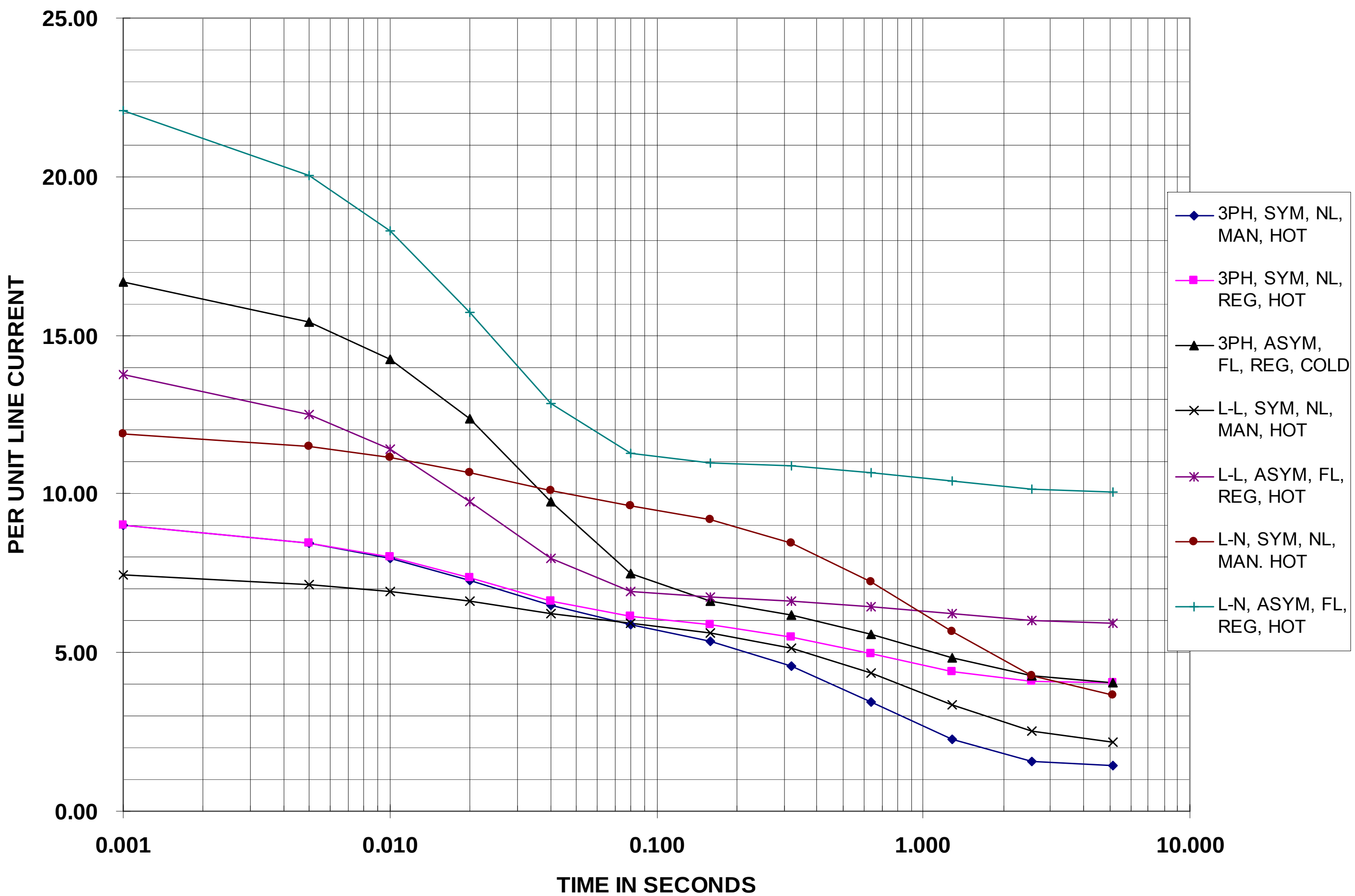
- Plot of armature current vs. time for the class of insulation provided.

Sample damage curve for a Class-H insulated, Class F rise machine.

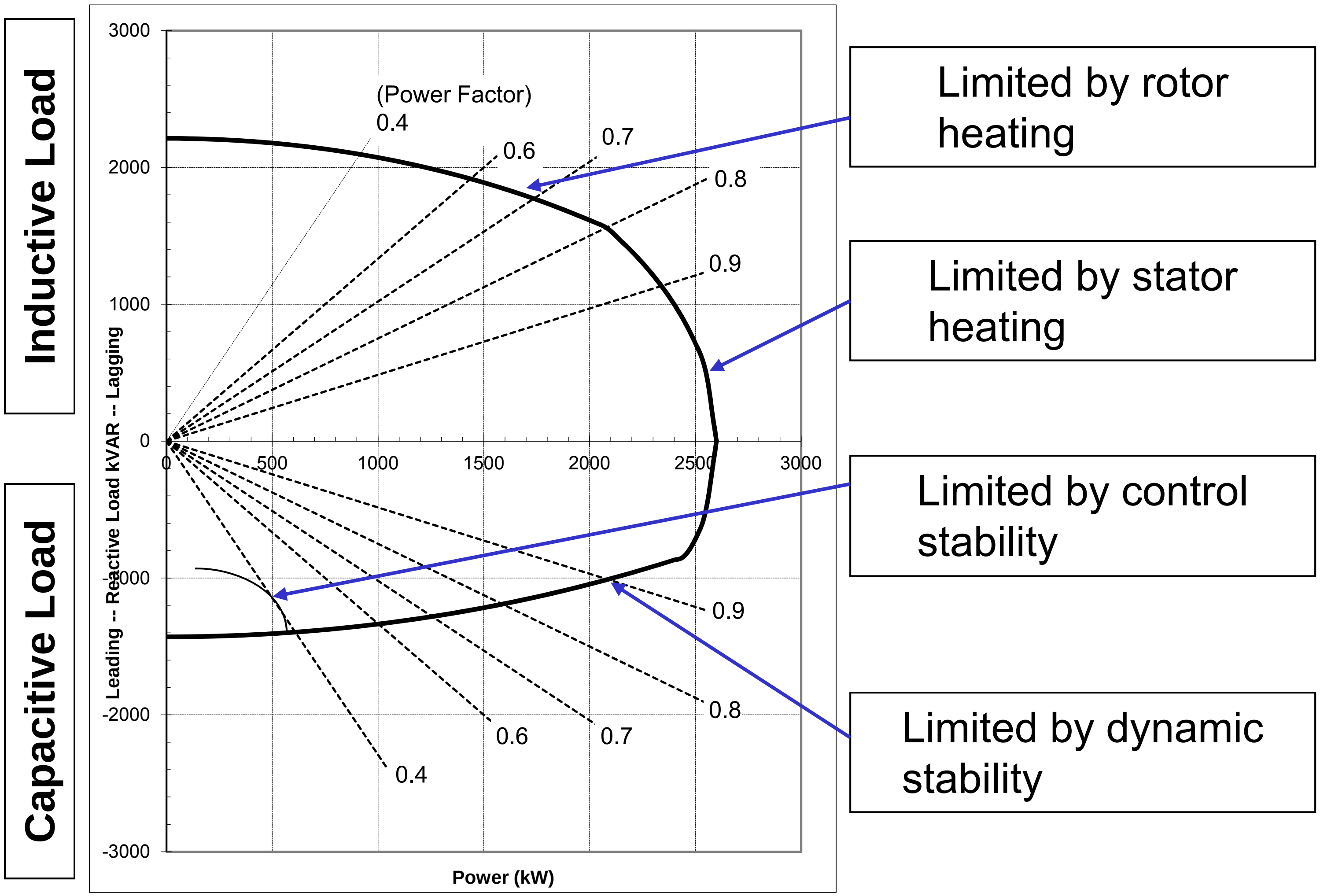


Short-Circuit Decrement Curve

- Plot of fault current vs. time that the generator produces for various fault conditions.



Reactive Capability Curve



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Efficiency

- Ratio of electrical energy output against the required mechanical energy input.
- Usually expressed as a percentage and always less than 100 percent.
- Usually improves with increasing sizes.
  - For a 5 kW output, a typical efficiency is about 80%.
  - For a 500 kW output, efficiency is typically 93% or better.
- Reduced by losses:
  - Fixed losses (independent of load current)
  - Variable losses (directly proportional to load current)

Efficiency: Fixed Losses

- Fixed losses
  - Friction and windage losses:
    - Bearing friction and wind resistance spinning rotor and associated fans
    - Reduce by optimizing fan blade pitch
  - Laminated core losses:
    - Hysteresis
      - Heat losses in the stator core due to change in magnetic flux flow
      - Reduce by using low-loss silicon steel
    - Eddy-current losses
      - Loses due to induced current in the stator core
      - Reduce by using low-loss silicon steel

Efficiency: Variable Losses

- Variable losses
  - I^2R losses in the armature and field coils
    - Losses in the form of heat due to resistance in the windings
    - Main armature I^2R losses can be reduced by using insulation with higher dielectric strength and adding more copper.
    - Main field I^2R losses can be reduced by controlling the load power factor and reducing excitation requirements.
    - Brushless exciter losses are typically negligible.
  - Stray losses
    - Due to changes in the flux distribution, eddy currents, and high-order harmonics.
    - Can be reduced by using higher cost materials for the lamination clamping plates and stranding the armature copper into thinner cross sections.

Efficiency: Example

- Assume a generator is 90 percent efficient; that means if 1000 kW is applied to the generator shaft, only 900 kW can be extracted as electrical energy.
- The prime mover must provide the real power of the alternator. One horsepower is equal to 0.746 kW. So, for a generator to deliver 900 kW of three-phase power at 90% efficiency, a prime mover with the following horsepower is required (no capability for overload is included):

$$\frac{900 \text{ kW}}{0.9 \text{ efficiency} \times 0.746 \text{ kW per HP}} = 1340 \text{ HP}$$

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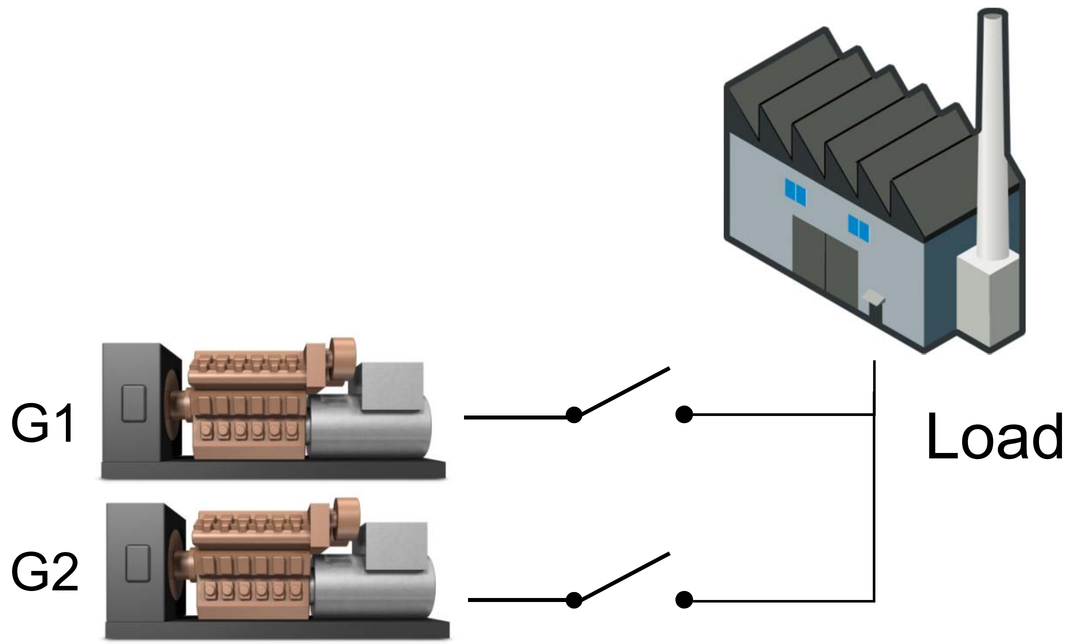
Parallel Operation: Basics

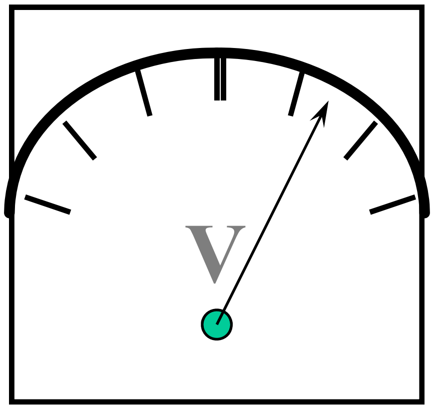
- The generators share the power needed by the load.
- The operating points will depend on the load and set ups
- Why?
  - To increase the power of an installation,
  - To add flexibility, reliability or dependability.



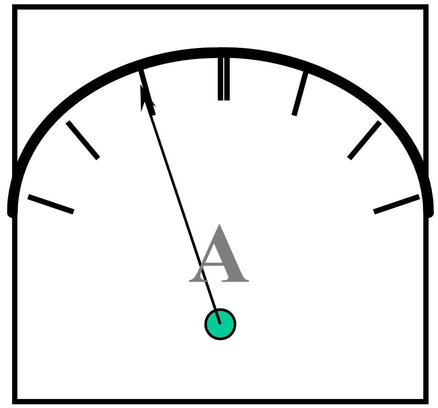
Requirements

- Must have +/- the same
  - Frequency
  - Voltage
  - Phase angle
  - Phase sequence
- The voltage regulator must have parallel operation capability and fitted with a paralleling CT or be controlled by a bias signal coming from the genset controller.
- The active and reactive power sharing must be balanced or prorated if they are of different sizes.

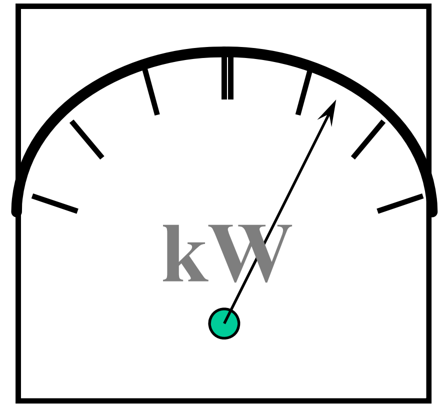
Metering Required



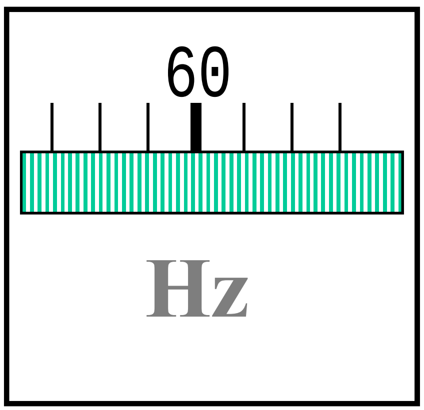
Volts



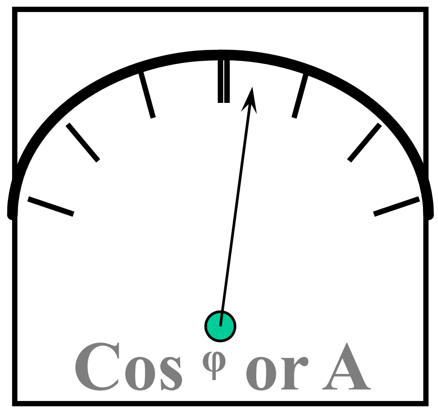
Amperes



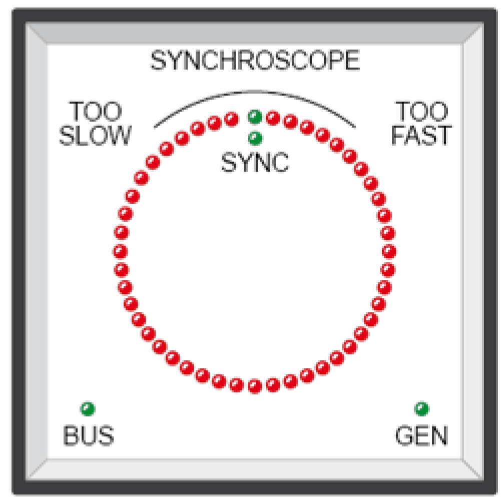
Watts



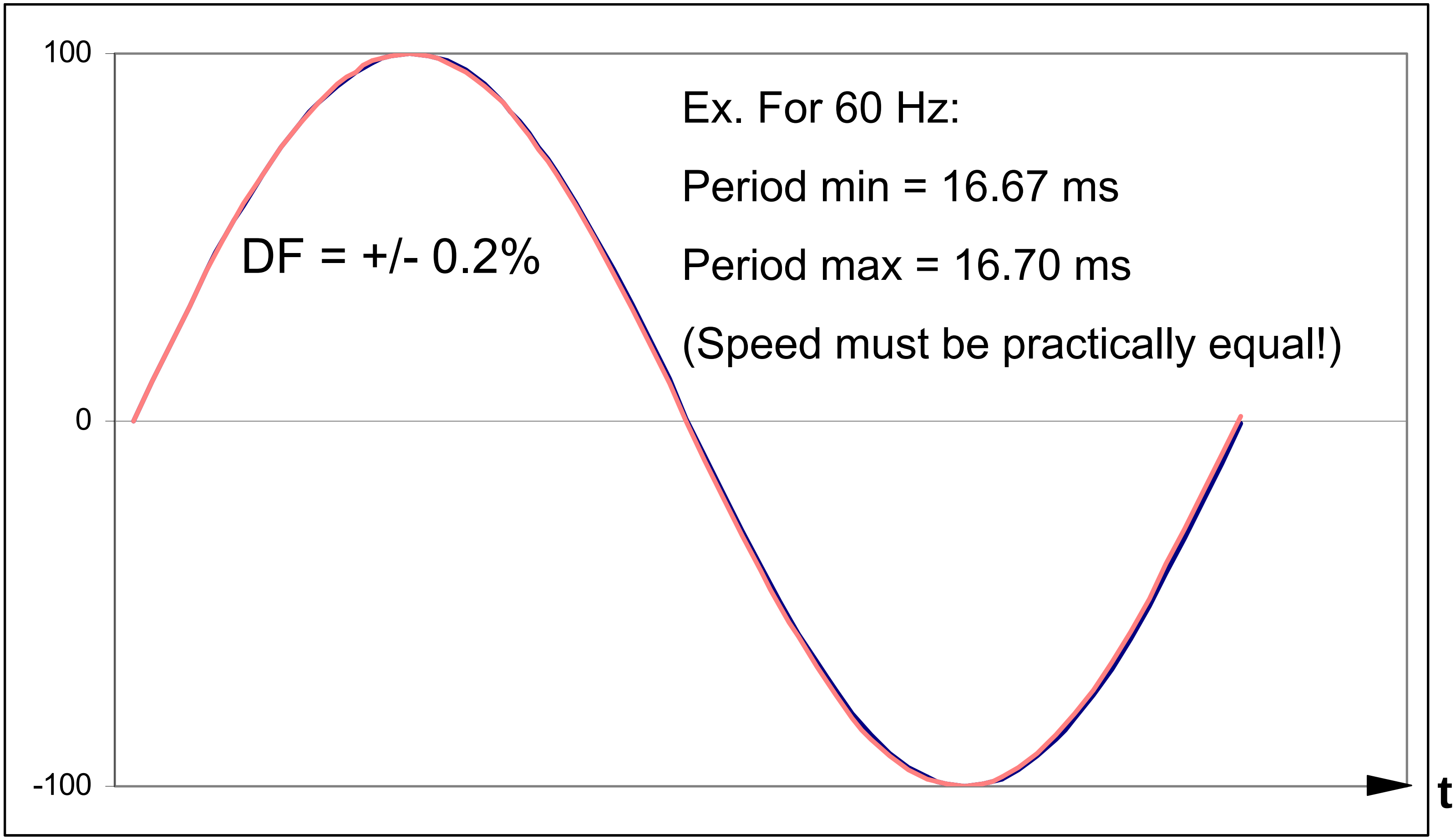
Frequency



PF or exciter field current

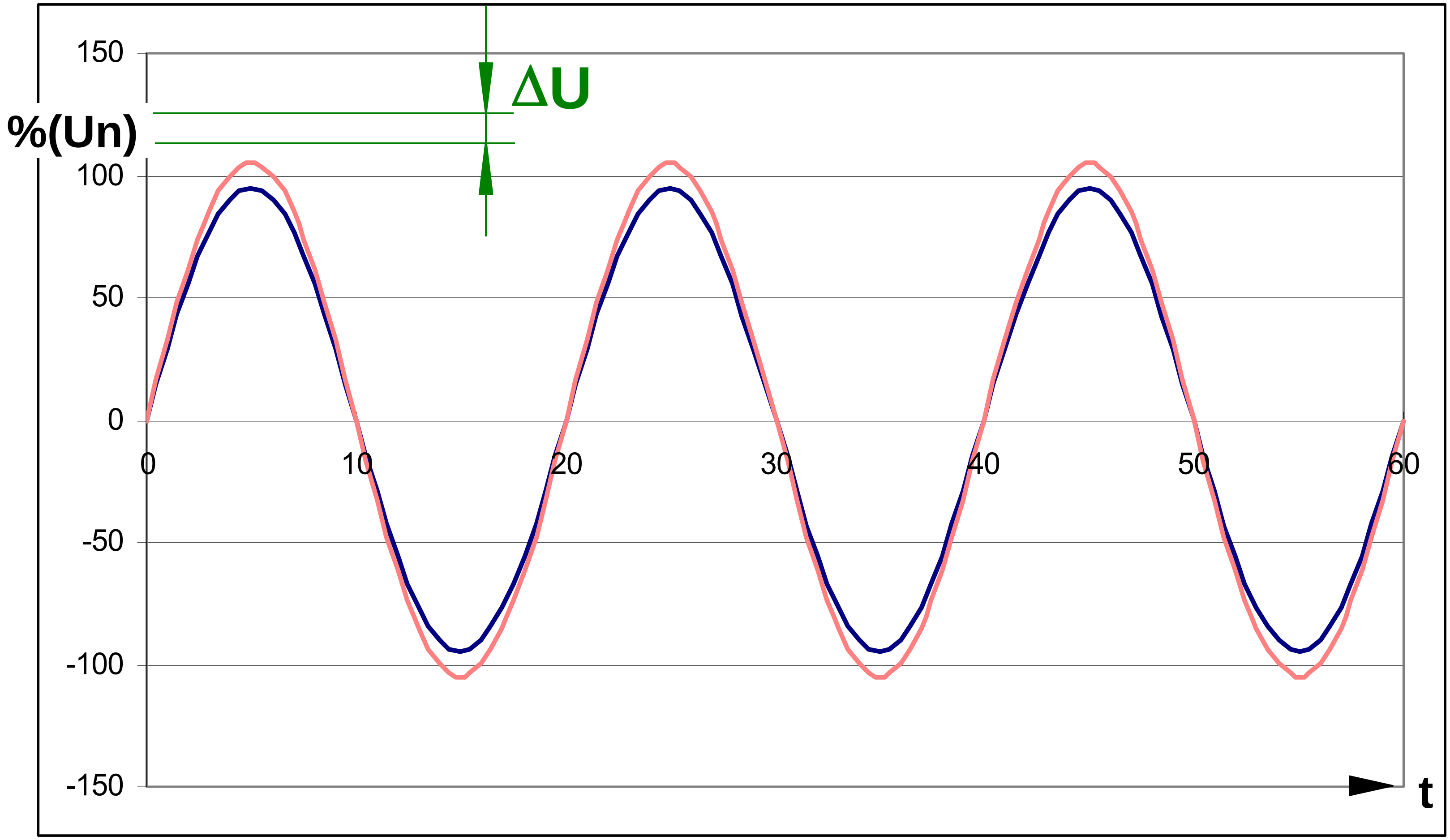


Synchronizing Parameters: Frequency



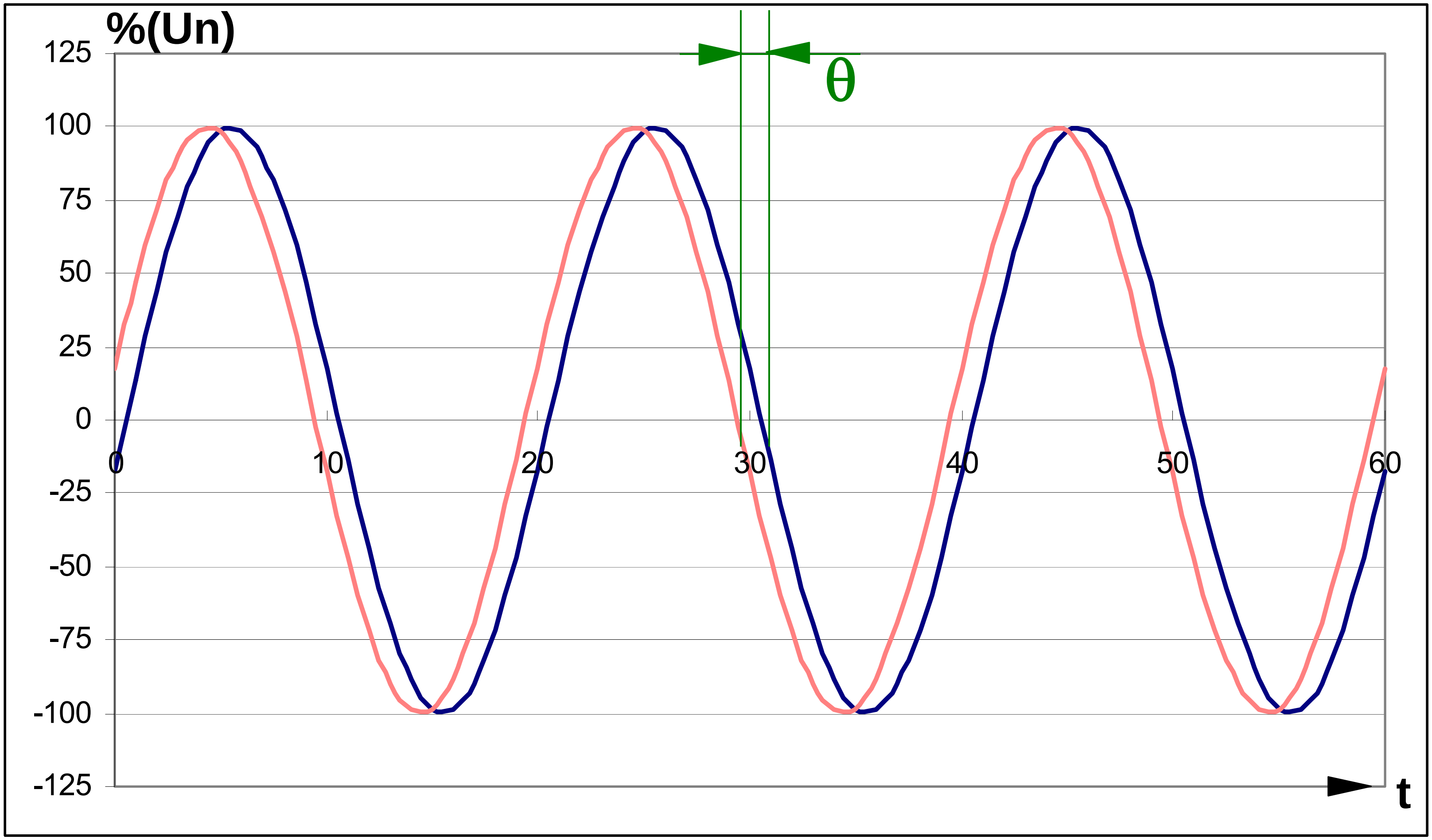
Maximum frequency shift: ± 0.12 Hz

Synchronizing Parameters: Voltage



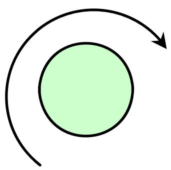
Maximum voltage difference: ±5%

Synchronizing Parameters: Phase



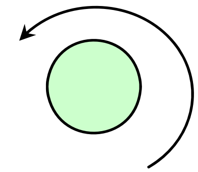
Maximum phase offset: ±10°

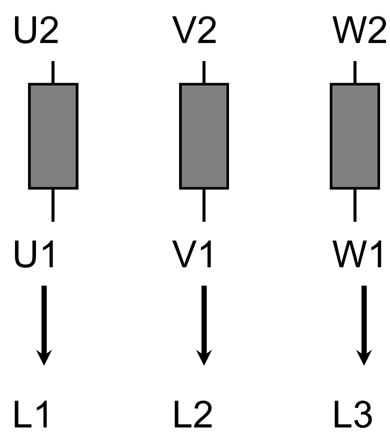
Synchronizing Parameters: Phase Order

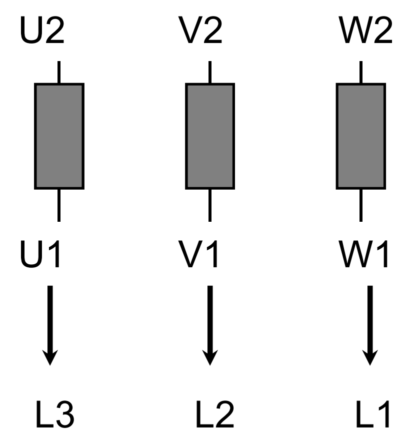


Clockwise rotation
from drive end
Generator terminals
U1 - V1 - W1
T1 - T2 - T3
Network connections
L1 - L2 - L3

CCW rotation
From drive end
Generator terminals
U1 - V1 - W1
T1 - T2 - T3
Network connections
L3 - L2 - L1







Sequence

1. Verify the wiring and polarity of the sensing voltage and paralleling CT.
2. Equalize perfectly the no-load voltage of each generator.
3. Set the same droop for each generator.
4. Run the generators at the same voltage, phase sequence, frequency and phase angle.
5. Monitor the meters as you close the breaker and open it if the Amp meter fluctuates wildly.
6. After closing the breaker, adjust the engine governors per their power.
7. Ensure the reactive power of identical sets is roughly the same without any voltage adjustment.

Summary

- When an generator is running in island mode supplying power to a load or a factory, there is no requirement to synchronize it. The engine will regulate the RPM or the frequency and voltage regulator will regulate the voltage and the load connected will dictate how much power is drawn.
- When more than one generator run together or with the utility, it is necessary to synchronize them together.
- In order to synchronize one generator with another unit or with the mains, both sinusoidal wave forms must match.
- Any greater-than-rated difference could damage the generator to be synchronized.