Fast Switching Capacitor Banks For Starting Large Medium-Voltage Motors

The Cost-Effective Alternative to VFD Starters
Who is NEPSI – What We Do

• Based in Queensbury, NY
• Work for/co-own a company named NEPSI that Offers the following key products:
  • Medium-voltage metal-enclosed products (2.4kV – 38kV) 200 kV BIL Max
  • Shunt Power Capacitor Banks (capacitive vars)
  • Harmonic Filter Banks
  • Shunt Reactor Banks (inductive vars)
  • Hybrid Shunt Capacitor and Shunt Reactor Banks
  • actiVAR - Fast Switching Capacitor Banks/Harmonic Filter Banks (2.4kV – 13.8kV) for motor start – an alternate to large VFD drives and RVSS
  • Medium Voltage Surge Protection Products
    • RC-Snubbers
    • Motor Surge Protection
    • Medium-Voltage Transient Voltage Surge Protection
• Services
  • Startup | Commissioning | Maintenance
  • Power System Studies
    • Harmonic Analysis, Power Factor, Motor Start
LARGE HARMONIC FILTER SYSTEMS

Red Chris Mine - British Columbia
C-High Pass, High Pass, and Notch Filter Branches
23 MVAR, 24.9 kV, 5-Stage, All-Inclusive Harmonic Filter System
LARGE HARMONIC FILTER ONE-LINE DIAGRAM
MAJOR MARKETS

- Mining (Copper, Gold, Diamond, Oil Sands, Limestone)
- Renewable Energy (Wind & Solar Power)
- Petro-Chemical
- Utilities (large IOU’s, Coops, Muni’s)
- Steel
- Pulp & Paper
- Institutions (Hospitals, Universities, Military Bases)
- Private Label
- Others
  - semiconductor, scrap recycling, pharma, waste water
WHAT CAN THE actiVAR™ BE USED FOR?

- It is a cost effective alternative to VFD motor starters where speed or process control is not required
- Fast “local” supply of reactive power
- Voltage Support
- Meet utility interconnect requirements
  - Inrush current limits
  - Voltage sag limits
5000 HP ACROSS-THE-LINE MOTOR START

Starting Power Flow @ XFMR Secondary
Real: 2.5 MW
Reactive: 14 MVAR

Starting Current
328A @ 34.5kV
2745A @ 4.16kV

Starting Torque
0.37 PU (of rated torque)

Starting Time
9.1 Seconds

Full Load Current (FLA) ≈626 amps

TYPICAL PROBLEMS ASSOCIATED WITH ACROSS-THE-LINE STARTING OF LARGE MOTORS

- Voltage sags
- Reduced starting torque of motor
  - Increased starting times
  - Increased motor heat
  - May cause motor to not start
- Motor and transformers may need to be larger to overcome motor starting torque requirements
- May not meet utility interconnect requirements
VOLTAGE SAG MITIGATION OPTIONS FOR LARGE MOTOR STARTS

RVSS Start

VFD Start

actiVAR™ Start

MOTOR STARTS CAUSE VOLTAGE SAGS & VOLTAGE FLICKER

MOTOR STARTS CAUSE VOLTAGE SAGS & VOLTAGE FLICKER

MOTOR STARTS CAUSE VOLTAGE SAGS & VOLTAGE FLICKER

NEPSI
Northeast Power Systems, Inc.
<table>
<thead>
<tr>
<th>RVSS Start</th>
<th>VFD Start</th>
<th>actiVAR™ Start</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>• A potentially</td>
<td>• Provides near</td>
<td>• Provides near</td>
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<tr>
<td>low cost option</td>
<td>rated torque at</td>
<td>rated torque at</td>
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<tr>
<td>• Soft mechanical start</td>
<td>starting</td>
<td>starting</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td><strong>Disadvantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>• May not be</td>
<td>• Soft mechanical</td>
<td>• Provides a soft</td>
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<tr>
<td>able to meet</td>
<td>start</td>
<td>start function</td>
</tr>
<tr>
<td>starting torque</td>
<td>• Meets utility</td>
<td>for mechanical</td>
</tr>
<tr>
<td>requirements</td>
<td>voltage sag/inrush</td>
<td>loads that</td>
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<tr>
<td>• May not meet</td>
<td>limits</td>
<td>require it</td>
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<tr>
<td>interconnect</td>
<td></td>
<td>• Requires</td>
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<tr>
<td>requirements</td>
<td></td>
<td>communication</td>
</tr>
<tr>
<td>• Requires E-House Space</td>
<td></td>
<td>with motor</td>
</tr>
<tr>
<td>• Produce</td>
<td></td>
<td>starters (IEC 61850 or</td>
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<tr>
<td>Harmonics</td>
<td></td>
<td>direct wiring)</td>
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<td>• Requires</td>
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<td>E-house space</td>
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<td>• Outdoor rated</td>
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<tr>
<td></td>
<td><strong>Disadvantages</strong></td>
<td></td>
</tr>
<tr>
<td>• Requires E-house space</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Requires Mₙ₊₁ additional motor starters</td>
<td></td>
<td></td>
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<tr>
<td>• Synch Transfer Controls</td>
<td></td>
<td></td>
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<tr>
<td>• High installed cost $$$$</td>
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<td></td>
</tr>
<tr>
<td>• Produce harmonics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Long delivery time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Complexity of equipment</td>
<td></td>
<td></td>
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<tr>
<td>• May require cooling equipment</td>
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</tbody>
</table>

**Advantages**:
- Provides near rated torque at starting
- Meets interconnect requirements
- Lower cost
- Simplest to install and maintain
- E-House not required – Outdoor rated

**Disadvantages**:
- Does not provide a soft start function for mechanical loads that require it
- Requires communication with motor starters (IEC 61850 or direct wiring)
Starting Power Flow @ XFRM Secondary
Real: 4.6 MW
Reactive: 2.5 MVAR

Starting Current
92A @ 34.5kV
770A @ 4.16kV

actiVAR™ Power Flow
(VAR Supply to Motor)
Real: ≈ 0 MW
Reactive: 21.3 MVAR

Starting Torque
0.63 PU (of rated torque)

Starting Time
3.7 Seconds

BENEFITS OF USING THE actiVAR

- The actiVAR™ is a fast transient free local supply of VARs
- The reduction in var flow through the source impedance reduces voltage sag at transformer primary and secondary
- Utility voltage sag, flicker, and inrush limits are met
- Power quality is improved throughout the system
- The motor starts faster due to higher starting torque
- Less heating in the motor during motor start
actiVAR™ PERFORMANCE

KEY TAKE AWAY

- Voltage drop is significantly reduced to within utility voltage drop limits.
- Starting Torque Proportional to $V^2$, translating to quicker motor starts
- Current through service transformer allows customers to meet utility maximum inrush current limits
- Higher voltage to motor results in higher available real power to motor

* Per Unit Starting Current Based on FLA = 624 Amps
RVSS + actiVAR™ Start

Advantages
- Lower cost than VFD start
- Extends the functional range of soft start option to higher HP ratings
- Provides “automatic redundancy” in functional HP range of soft start
- Soft mechanical start
- Starting impact < running impact
- Soft start harmonics are reduced while actiVAR is active

Disadvantages
- More complicated than either alone
- Produce some harmonics – but at a lower level than standalone RVSS
actiVAR™ – BASIC OPERATING SEQUENCE

STEP-BY-STEP OPERATING SEQUENCE OF actiVAR™

1. actiVAR™ sits ready for action waiting for motor start control signal (IEC61850 or direct communication)
2. actiVAR™ receives control signal to close DS1-M’s, transitions on near 5-cycles later (at near the time the motor starter contacts make) and supplies the necessary reactive power for the motor being started.
3. As motor comes up to speed, the actiVAR™ (voltage sensing relay) senses the rise in system voltage, based on anticipated delay of DS1-M in opening, will issue command to open stage 1 DS1-M at or near 0.97 per unit voltage.
4. Additional stages (if present) switch off based on time (near 5 to 10 cycle spread between stages to maintain system voltage as motor pulls into synchronism.
5. After motor start, the actiVAR™ capacitors stages are quickly discharged (less than 3 seconds) allowing for another motor start.
6. A permissive signal is sent after 10 seconds to allow other plant motors to start.
PUMP STATION – 3-MOTOR VFD START WITH SYNCHRONOUS TRANSFER

Required Equipment For VFD Start – Multiple Motors

- VFD
- Drive transformer
- VFD starter/breaker
  - Output isolation switch
- Drive output reactor for synchronous transfer
- VFD bus
- VFD output contactors (1 per motor)
- PLC & associated controls
- E-house
VFD START – COST COMPONENTS

Qty 4
5000 HP Motors
$1.7 Million

Key Cost Factors

• VFD and E-House costs are significant
• Input and output contactors, VFD Bus, PLC contribute additional cost

* Basis of costs available on request
Qty 4
5000 HP Motors
$0.841 Million

Key Cost Factors
• actiVAR™ dominates the initial cost

• Without the costs associated with the E-House or the synch switchgear, the actiVAR™ saves significantly on equipment cost

actiVAR™ - a lower cost alternative

Basis of costs available on request
DEEP CUT GAS PLANT APPLICATION - USING RVSS AND VFD’S

Required Equipment For Starting Motors

- 7 RVSS starters
- Two 9,500 HP VFD starters
  - E-house space
  - Complexity
  - Possible need for cooling equipment
  - Lead-time
DEEP CUT GAS PLANT APPLICATION USING actiVAR™

Required Equipment For Starting Motors with actiVAR™

- Qty (2) 42 MVAR actiVARs™
  - No E-house space
  - Comes fully assembled
  - Can be set up with a tie breaker to allow for redundancy
  - Simplicity
- Feeder breaker for each actiVAR™
DEEP CUT GAS PLANT - SAVINGS WITH actiVAR™

RVSS/VFD

$2.2 Million

- actiVAR™

$1.3 Million

= $900,000

Savings for total plant implementation: $1,750,000
The actiVAR™ Uses ABB DS1-M Technology

Key Ratings

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>60</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated frequency [Hz]</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Rated Voltage [kV]</td>
<td>15.0</td>
<td>17.5</td>
</tr>
<tr>
<td>Rated Current [A]</td>
<td>600</td>
<td>630</td>
</tr>
<tr>
<td>Mechanical Life [CO]</td>
<td>50,000</td>
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</tr>
<tr>
<td>STC [kA – s]</td>
<td>20 - 0.5</td>
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</tr>
<tr>
<td>Working Temp [°C] [°F]</td>
<td>-15…+55 / +5…+131</td>
<td></td>
</tr>
</tbody>
</table>

Benefits of Technology

- No Power Quality → Transient Free Switching
- Concerns
  - No inrush reactors → Lower Cost/Lower Losses
- Re-strike-free → Diode-technology
- Pre-strike-free → Diode-technology
- Maintenance Free → Servomotors
- Long Life → Rated for 50,000 Close/Open Operations

The actiVAR™ Uses ABB DS1-M Technology
The DS1-M is able to carry out closing operations on capacitor banks without any transient of current, voltage, frequency or the possibility of prestrike.

**Closing Sequence**

(A) Bypass Contact

(B) Bypass Contact

(C)
The DS1-M is able to carry out opening operations on capacitor banks without any overvoltage or the possibility of restrike.

Opening Sequence
ABB DS1-M SWITCHING TECHNOLOGY (cont.)

**Waveforms**

13.8kV, 10 MVAR Capacitor Bank Switching against a 10 MVAR energized Bank (back-to-back switching)

**On Closing**
- Low Transient Current (near 0 inrush current)
- Low Transient Voltage (from 2PU to near 0)

**On Opening**
- No events, no signs of current chopping
## ABB DS1-M SWITCHING TECHNOLOGY (cont.)

### Detailed Ratings

<table>
<thead>
<tr>
<th>Electrical characteristics</th>
<th>DS1 50</th>
<th>DS1 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated frequency</td>
<td>Hz</td>
<td>50</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>kV</td>
<td>17.5</td>
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<tr>
<td>Rated current</td>
<td>A</td>
<td>630</td>
</tr>
<tr>
<td>Withstand voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- phase to phase and phase to earth</td>
<td>kV</td>
<td>38(1)</td>
</tr>
<tr>
<td>- across the insulating distance</td>
<td>kV</td>
<td>45</td>
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<tr>
<td>Impulse withstand (BIL)</td>
<td></td>
<td></td>
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<tr>
<td>- phase to phase and phase to earth</td>
<td>kV</td>
<td>95</td>
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<tr>
<td>- across the insulating distance</td>
<td>kV</td>
<td>110</td>
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<td>Short-time current (time)</td>
<td>kA (s)</td>
<td>20 (0.5)</td>
</tr>
<tr>
<td>Short-time peak current</td>
<td>kAp</td>
<td>52</td>
</tr>
</tbody>
</table>

### Other characteristics

| Mechanical operations             |        | 60,000 |
| Maximum overall dimensions       |        |        |
|                                  | H [mm] | 655    |
|                                  | W [mm] | 618    |
|                                  | D [mm] | 561    |
|                                  | P [mm] | 210    |
| Weight                           | kg     | 130    |
| Working temperature range        | °C     | -15 ... +65 |
| Maximum installation altitude    | mslm   | 1,000  |
| Rated dry air absolute pressure  | MPa    | 0.470  |
Application Requirements

1. **Phase rotation** must be A-B-C as labeled on the incoming bus. Improper phase rotation can cause failure to the DS1.
2. **Wye-ungrounded capacitor connection**
3. **Completion of “homing” procedure**
4. **Direct connection** of DS1-M Switch and sensor to capacitor bank (no impedance between DS1-M and Capacitor Bank)

Retrofit Application:
Harmonic filter reactors and transient inrush reactors must be removed if located on the load side of the DS1-M. Transient inrush reactors are no longer required. Harmonic filter reactors can be located on the source side of the DS1-M and DS1-M Voltage Sensor.
Timing Differences
- DS1 is a 4 to 5 cycle device on opening and closing
- Motor starters are typically 4 to 5 cycle devices

Impact of Timing Differences (using current/voltage sensing technology)
- Voltage sag at start (about 2.5 cycles)
- Voltage swell at synchronization

Mitigation Techniques
- Communication between actiVAR and motor starters
- Direct wiring
- Over network – 61850 protocol
SEL Relay Operating Times (487V)
Voltage/Current Element: 1.5 cycles (worst case)
Hide-speed contacts: <50 micro-sec 0.003 cycles
Total Relay Time 1.503 cycles

DS1 Closing Time:
Binary Input filter: 1 cycle
Synchronization: 0-1 cycle
Preparation for closing: 0.5 cycle
Actual mechanical closing: 2.25 cycles
Diode Energizing: 0.25 cycles
Total DS1 closing time: 4-5 cycles

Total Time: 5.503-6.503 cycles

Typical Motor Starting Time: 4 to 5 cycles

Without taking other measures, a voltage sag for as much as 2.5 cycles may occur between motor start and application of reactive power (vars).
actiVAR™ - Hybrid Design (PFC Stages and DS1-M Stages)

- Hybrid Designed actiVAR’s are equipped with both DS1-M’s for motor starting (fast vars) and vacuum switches/contactors for power factor correction (slow vars).
- DS1-M’s respond to motor starts and provide reactive power to support motor inrush current.
- Vacuum switches/contactors respond to system power factor and automatically correct system to a preset value (PF = 1.0).
- DS1-M – Fast VARS
- PFC – Slow Vars
actiVAR™ - HYBRID DESIGN (PFC STAGES AND DS1-M STAGES)

Hybrid Designs Meets All Power Quality Concerns

actiVAR Stages -
• Voltage Sag Limits
• Voltage Flicker Limits
• Inrush Current Limits

PFC Stages –
• Power factor
• IEEE 519 Harmonic Distortion Limits
### actiVAR™ - Typical I/O and System Requirements

#### Power
- Phase Conductors
  - Cable for Top/Bottom/Side Entry
  - Transient Rated for Application
- Ground Conductors
  - Per National/Local Code

#### CT/PT Signals
- PT Signals for Over/Under Voltage Protection
- 3-Phased CT Signals for Phase and Ground Fault Protection

#### Control Power
- Prefer 125 or 48 VDC for control (but not necessary)
- 120 VAC Control Power For Environmental Control (fans, heaters, air conditioners, etc)

#### Digital I/O
- Communication with motor starters
- Several alarm output for various operating conditions
- Permissive inputs to enable controls (not required, but available)
- Ethernet for remote connection to control to troubleshoot, set, and retrieve data logs
NEPSI RESOURCES TO ASSIST IN APPLICATION OF actiVAR™

• Contact NEPSI about your application
  • NEPSI will provide motor start and actiVAR™ performance study, quote, and drawings to allow for comparison against alternate technologies

• Web – nepsi.com/actiVAR™
  • Product literature
  • Guide form specifications
  • Case studies
  • actiVAR™ calculator for motor starting applications
  • actiVAR™ RFQ form to fill out and submit
Compressor Start and PFC Application – 5000 HP Induction Motor
13.8 kV, 24 MVAR 3-Stage actiVAR, 15 MVAR 3-Stage PFC
actiVAR™ Gas Plant Project - Mentone 5000 HP Motor Start (Uncoupled) WITHOUT Activar Assist

- 9.6% Max Voltage Sag at Motor Inrush
- ~9.3% Voltage Sag During Motor Acceleration
- 5.9 x FLA (1160 amps)
actiVAR™ Gas Plant Project - Mentone 5000 HP Motor Start (Uncoupled) WITH Activar Assist

Voltage rise indicates Activar engages just prior to motor

- 2.1% Max Voltage Rise
- 5.5% Max Voltage Sag at Motor Inrush
- ~2.0% Voltage Sag During Motor Acceleration

3 Activar Stages Disengage as Motor Reaches Full Speed

6.4 x FLA (1265 amps)
actiVAR™ Gas Plant Project - Mentone 5000 HP Motor Start (Uncoupled) WITH Activar Assist
Plots of What is Happening at the actiVAR and the Main Transformer
KEY INFORMATION

- Company XXX has to start a 4000 Volt, 5000 HP Induction Motor with an FLA rating of 626 Amps and a Locked-Rotor Code letter of F

- The serving utility limits voltage sags to 97% (3% voltage drop) at PCC during motor starts

- For power quality reasons, company XXX wants to maintain their line voltage to 96% during motor starting

- What size actiVAR™ is required to meet this performance?
  - How many stages/steps?
REQUIRED DATA FOR ANALYSIS

Performance Requirements:
Primary voltage sag limit: 97%
Secondary voltage sag limits: 96%
Maximum inrush current: sometimes specified

Source Data
Primary voltage: 34.8kV
Source 3-phase short circuit current level: 1.9kA
Short circuit X/R ratio: 2.0

Transformer Data
MVA rating (OA Rating): 10
Transformer base impedance: 5.55%
Transformer X/R ratio: 25

Motor Data
Motor voltage: 4000 Volt
Motor HP: 5000 HP
FLA rating: 626 Amps
Locked-rotor code letter: F
Locked-rotor power factor: 20%
Calculation Procedure

1. Use actiVAR™ calculator at nepsi.com or request spreadsheet analysis tool from NEPSI

   http://nepsi.com/resources/calculators/actiVAR™-motor-start-calculator.htm

2. Enter motor, source, and transformer impedance data

3. Through trial and error determine MVAR rating of actiVAR™ to meet performance requirements

4. Consider voltage resolution and valve ampere rating in determining number of stages and steps
MOTOR START CALCULATION – Steady State Analysis

STEADY STATE ANALYSIS
• Good for estimating initial voltage drop and torque at motor start
• A relatively easy calculation when done with per unit system
• Does not provide motor acceleration time and whether motor will start.
  • Dynamic simulation techniques required for this analysis.
• Dynamic Analysis Software Programs
  • ETAP
  • ESA- Easypower
  • CYME
  • Many others
MOTOR START CALCULATION – Dynamic Analysis

**DYNAMIC ANALYSIS**
- Performed by NEPSI for all actiVAR™ orders and RFQ’s
- Accurately calculates motor starting time, motor current, voltage, torque, power, and speed for the entire starting period
- Determines whether a motor will start or not start
- Accurately predicts actiVAR™ performance
- Requires more Data
  - System impedance data
  - Motor impedance data; torque speed curves and inertia data
  - Load torque and inertia data

Typical plot output from dynamic analysis software showing motor terminal voltage, motor current, motor speed, and motor torque versus time.
**MOTOR START CALCULATION – Back-of-Envlope**

### “MVA METHOD”
- Calculate MVAsc of all devices
- Convert single-line diagram to equivalent MVAsc diagram
- Reduce MVAsc diagram to a single MVAsc value at the motor
- Calculate approximate voltage drop without actiVAR™
- To calculate voltage drop with actiVAR™, subtract actiVAR™ MVAR rating from Motor MVAsc – then calculate voltage drop.

### Transformer Data
- MVA Rating (OA Rating): 10
- Transformer Base Impedance: 5.55%

### Motor Data
- Motor HP: 5000 HP
- Locked-rotor code letter: G
  - G = 5.6 – 6.3 kVA/HP Use 6 kVA/HP
  - MVAsc = 6 kVA /HP * 5000HP/1000 = 30

### One-Line Diagram

**Source Data**
- Primary voltage: 34.8kV
- Source 3-phase short circuit current level: 1.9kA
- MVAsc = 1.73*1.9kA*34.8kV = 114

**Transformer Data**
- MVAsc = (10/0.0555) = 180

**Motor Data**
- Motor HP: 5000 HP
- Locked-rotor code letter: G
  - G = 5.6 – 6.3 kVA/HP Use 6 kVA/HP
  - MVAsc = 6 kVA /HP * 5000HP/1000 = 30
MOTOR START CALCULATION – Back-of-Envelope cont.

MVAsc Diagram

<table>
<thead>
<tr>
<th>114</th>
<th>180</th>
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</thead>
<tbody>
<tr>
<td>24</td>
<td>30</td>
</tr>
</tbody>
</table>

actiVAR™ Motor Motor

Primary Side Voltage Drop

\[
25.7 = \left( \frac{1}{30} + \frac{1}{180} \right)^{-1} \text{ (without actiVAR)}
\]

\[
5.8 = \left( \frac{1}{30-24} + \frac{1}{180} \right)^{-1} \text{ (with actiVAR)}
\]

\[
V_{\text{p drop without actiVAR}} = \frac{25.7}{25.7 + 114} = 0.183 \text{ PU}
\]

\[
V_{\text{p drop with actiVAR}} = \frac{5.8}{5.8 + 180} = 0.031 \text{ PU}
\]

MVAsc Diagram Reduced

<table>
<thead>
<tr>
<th>69.7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>24</th>
<th>30</th>
<th>30</th>
</tr>
</thead>
</table>

actiVAR™ Motor Motor

\[
69.7 = \left( \frac{1}{114} + \frac{1}{180} \right)^{-1}
\]

\[
V_{\text{s drop without actiVAR}} = \frac{30}{30 + 69.7} = 0.30 \text{ PU}
\]

\[
V_{\text{s drop with actiVAR}} = \frac{30 - 24}{30 - 24 + 69.7} = 0.079 \text{ PU}
\]

For more information on MVA Short Circuit Method