NEPSI

Northeast Power Systems, Inc.

Fast Switching Capacitor Banks For Starting Large Medium-Voltage Motors

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actiVAR
FAST VAR SWITCHING

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

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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

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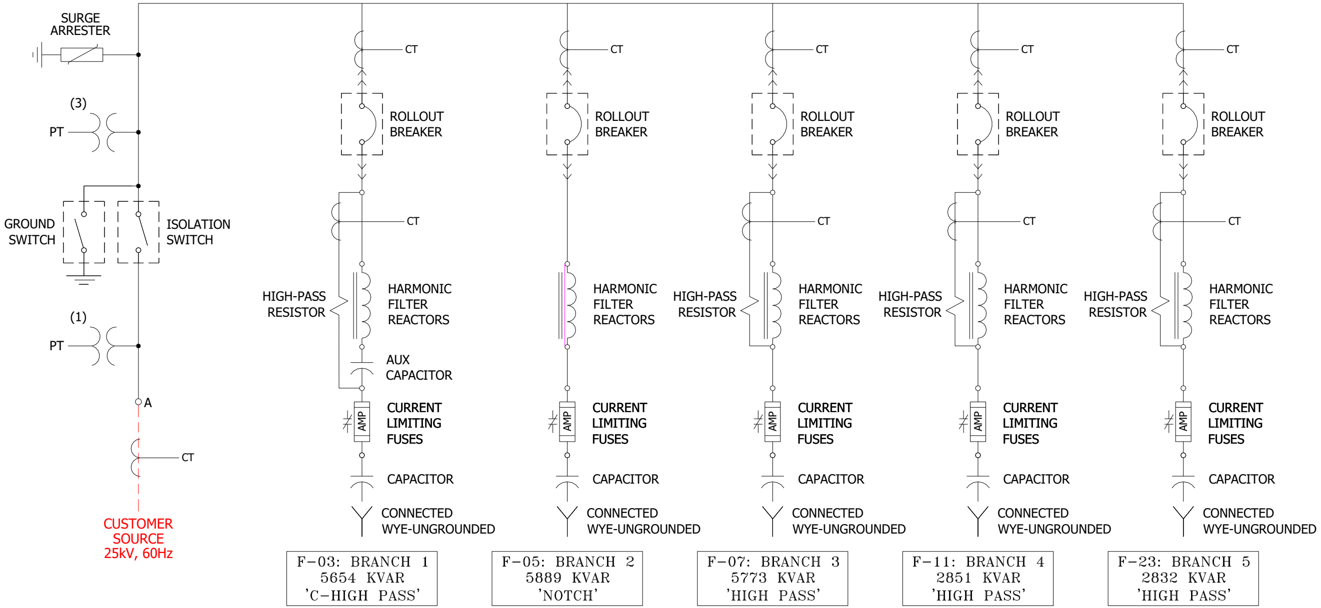
LARGE HARMONIC FILTER ONE-LINE DIAGRAM



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

Solar Wind Petro Chemical Utility Mining

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

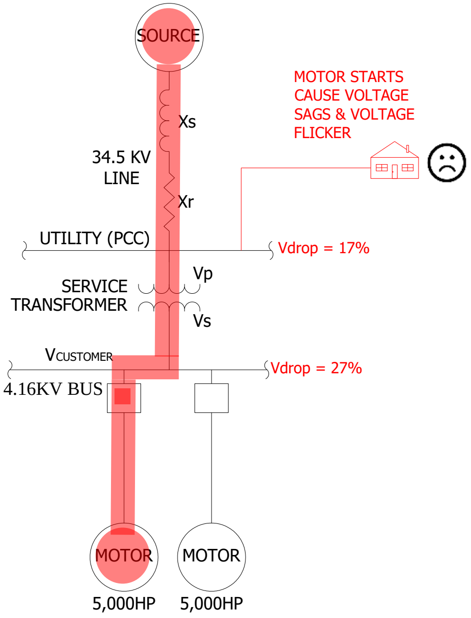
Starting Power Flow
@ XFMR Secondary
Real: 2.5 MW
Reactive: 14 MVAR

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

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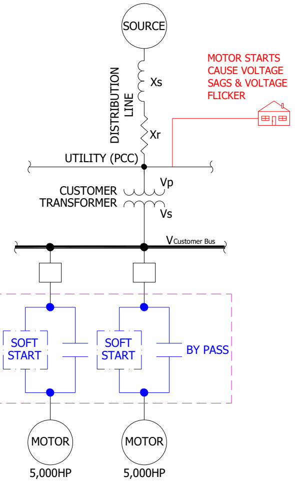
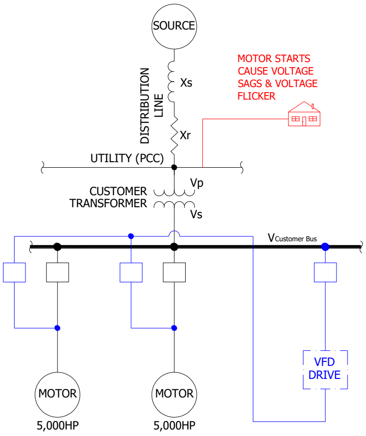
VOLTAGE SAG MITIGATION OPTIONS FOR LARGE MOTOR STARTS

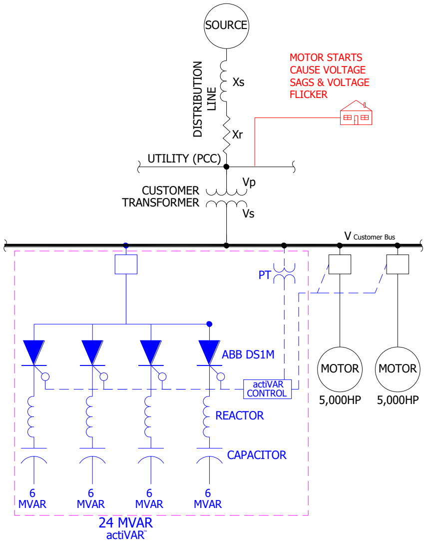
RVSS Start



VFD Start



actiVAR™ Start



COMPARISION OF VOLTAGE SAG MITIGATION OPTIONS

RVSS Start

Advantages
- A potentially low cost option
- Soft mechanical start

Disadvantages
- May not be able to meet starting torque requirements
- May not meet interconnect requirements
- Requires E-House Space
- Produce Harmonics

VFD Start

Advantages
- Provides near rated torque at starting
- Soft mechanical start
- Meets utility voltage sag/inrush limits

Disadvantages
- **Requires E-house space**
- Requires M_n+1 additional motor starters
- Synch Transfer Controls
- **High installed cost $$$$$**
- Produce harmonics
- Long delivery time
- **Complexity of equipment**
- May require cooling equipment

actiVAR™ Start

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)

actiVAR™ ASSISTED MOTOR START

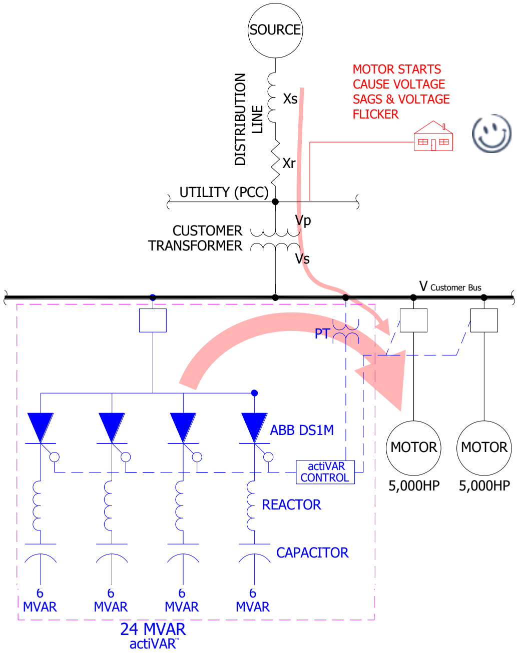
<u>Starting Power Flow @ XFRM Secondary</u>
Real: 4.6 MW
Reactive: 2.5 MVAR

<u>Starting Current</u>
92A @ 34.5kV
770A @ 4.16kV

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

<u>Starting Torque</u>
0.63 PU (of rated torque)

<u>Starting Time</u>
3.7 Seconds



BENEFITS OF USING THE actiVAR

- The actiVAR™ is a fast <u>transient free</u> 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

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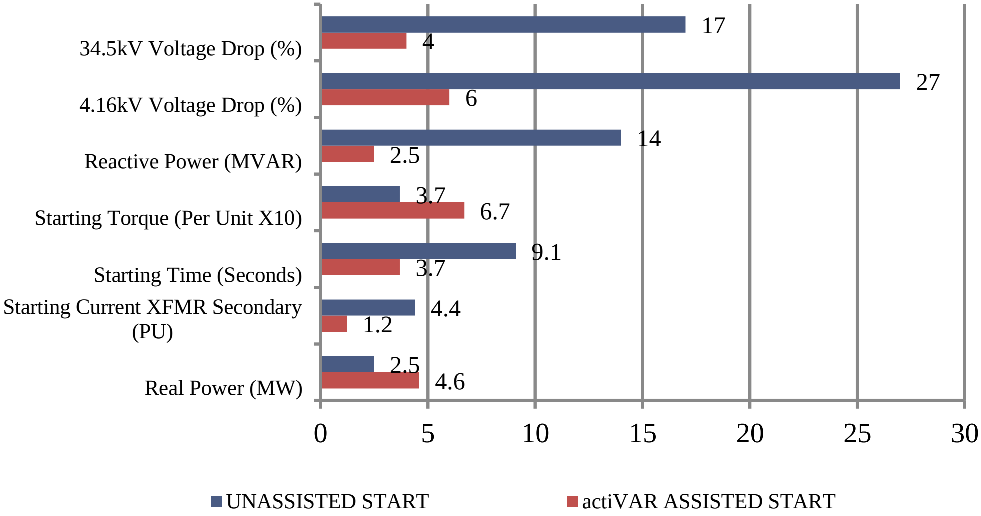
actiVAR™ PERFORMANCE

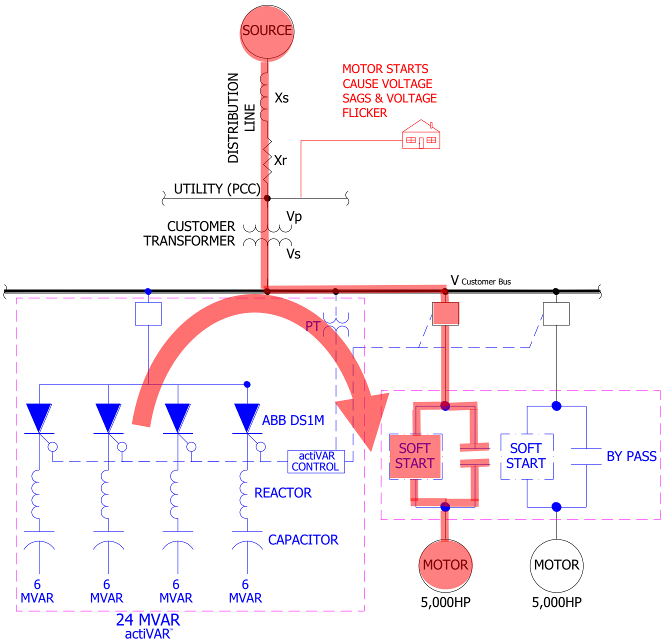


KEY TAKE AWAY

- 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*

actiVAR ASSIST WITH RVSS



RVSS + actiVAR™ Start

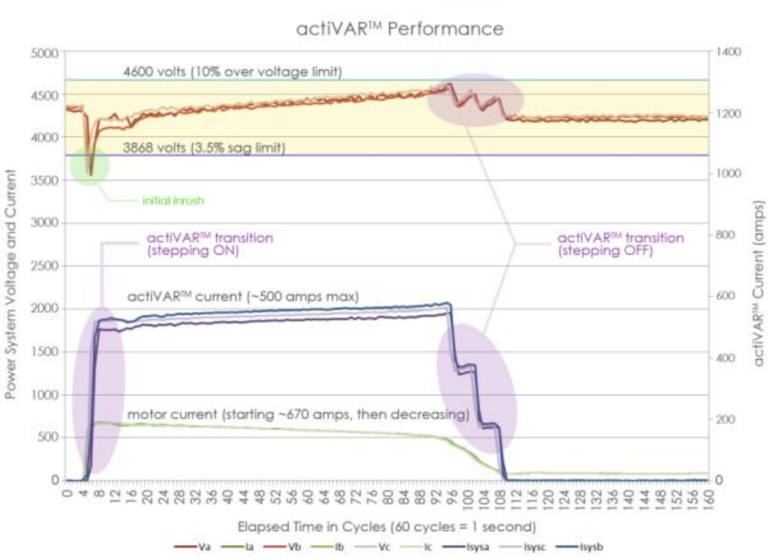
Advantages

- 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

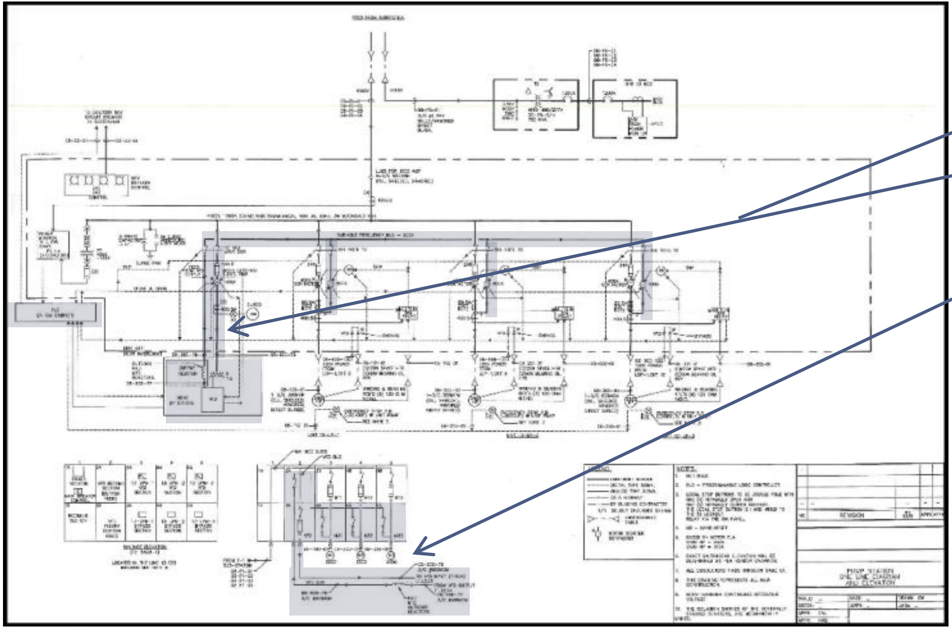
actiVAR™ – BASIC OPERATING SEQUENCE



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.

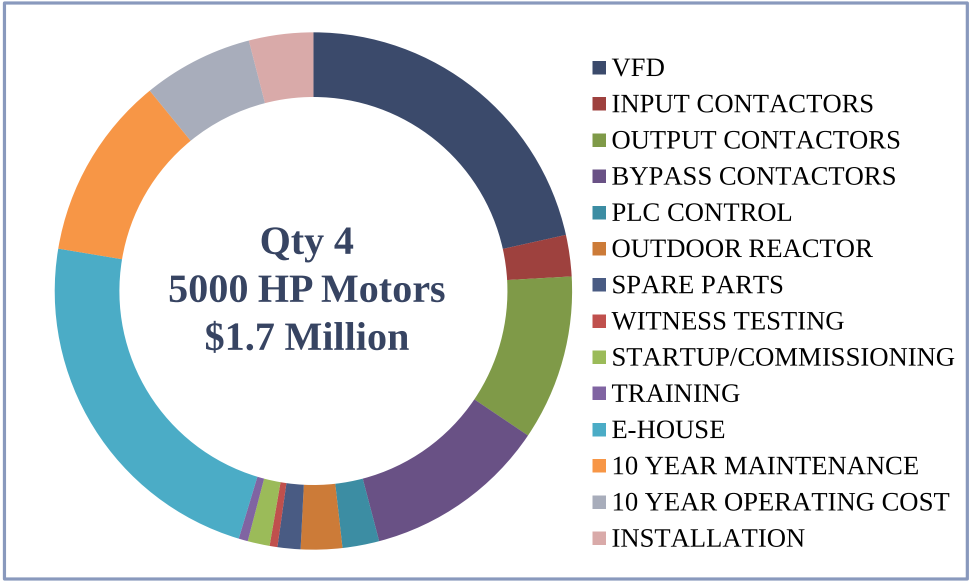
PUMP STATION – 3-MOTOR VFD START WITH SYNCHRONOUS TRANSFER



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

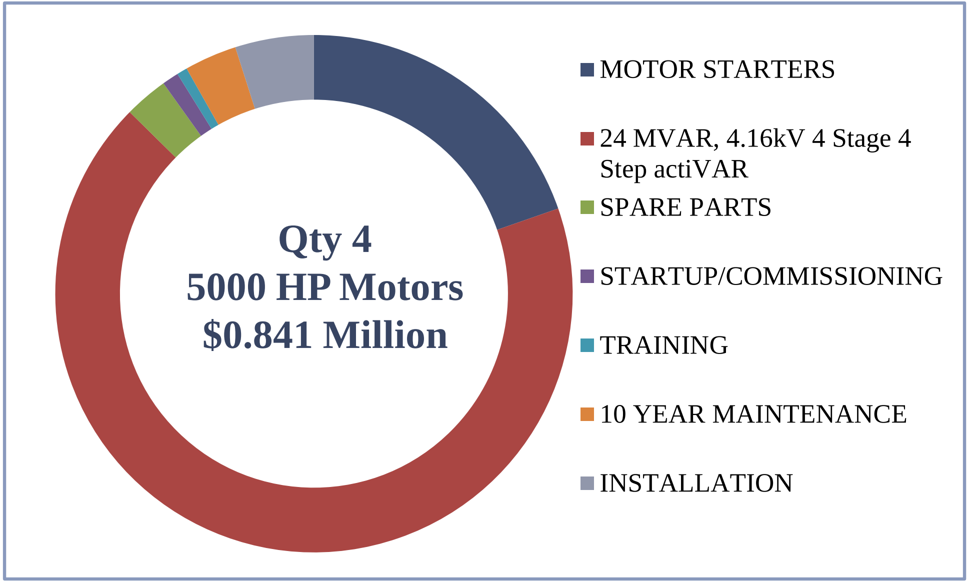


Key Cost Factors

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

** Basis of costs available on request*

actiVAR™ START – COST COMPONENTS



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

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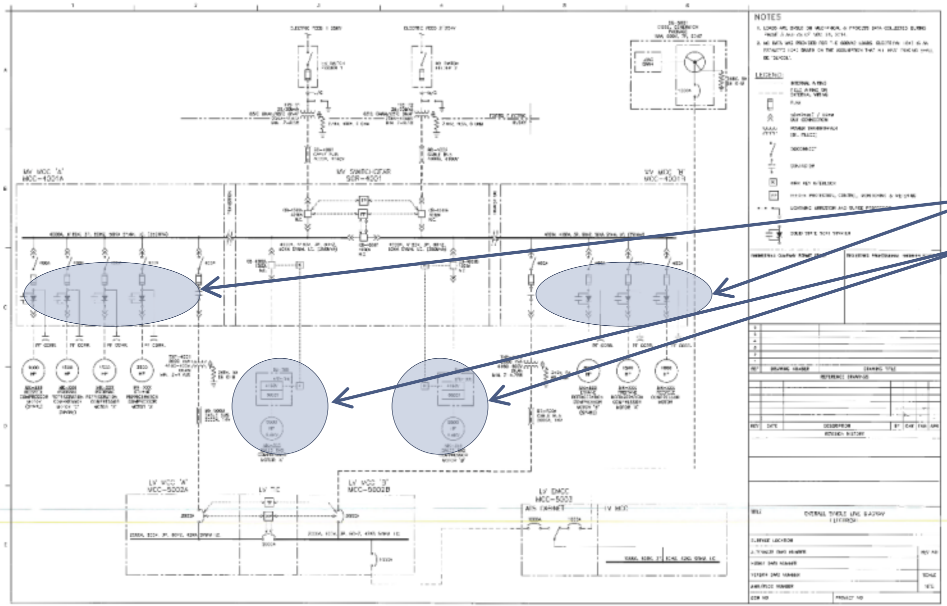
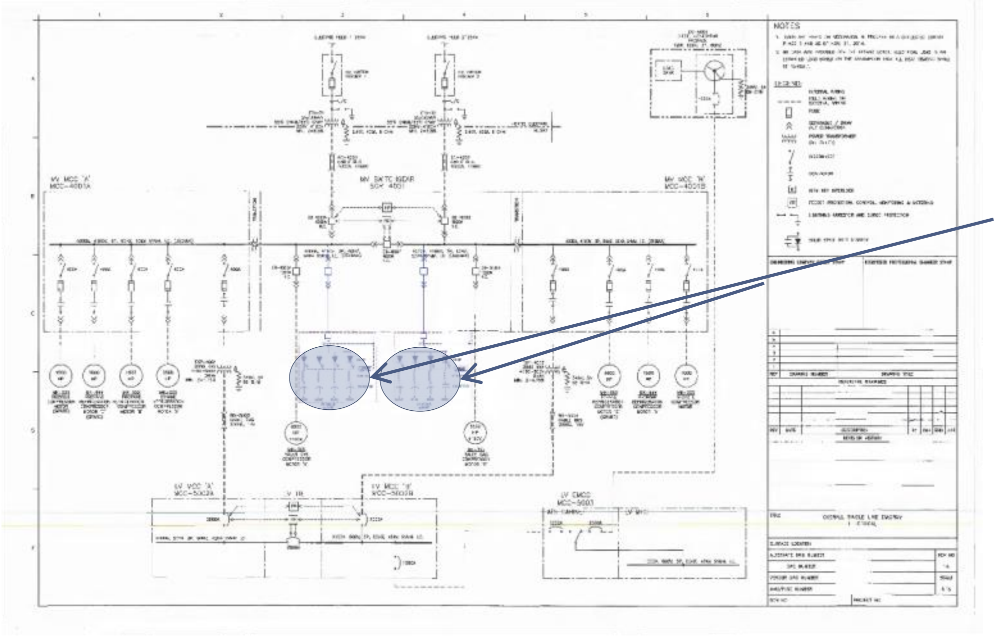
DEEP CUT GAS PLANT APPLICATION - USING RVSS AND VFD'S



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™

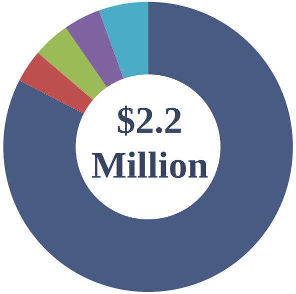


Required Equipment For Starting Motors with actiVAR™

- 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



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actiVAR™

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SAVINGS

$900,000

■ VFD COST, 9500HP
■ RVSS COST, 1000 HP
■ RVSS COST, 1500 HP
■ RVSS COSET, 1500 HP
■ RVSS COST, 3500, HP

■ 42 MVAR, 7 step actiVAR™, all motors

Savings for total plant implementation: $1,750,000

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The actiVAR™ Uses ABB DS1-M Technology

Key Ratings

Rated frequency [Hz]	60	50
Rated Voltage [kV]	**15.0**	**17.5**
Rated Current [A]	**600**	**630**
Mechanical Life [CO]	**50.000**	
STC [kA – s]	20 - 0.5	
Working Temp [°C] [°F]	-15…+55 / +5…+131	

Benifits of Technology

No Power Quality → Transient Free Switching

Concerns

No inrush reactors → Lower Cost/Lower Losses

Re-strike-free → Diode-technology

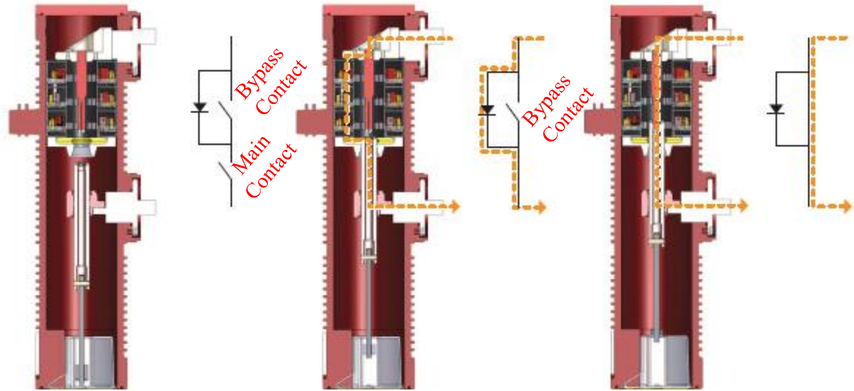
Pre-strike-free → Diode-technology

Maintenance Free → Servomotors

Long Life → Rated for 50,000 Close/Open Operations

ABB DS1-M SWITCHING TECHNOLOGY (cont.)

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.

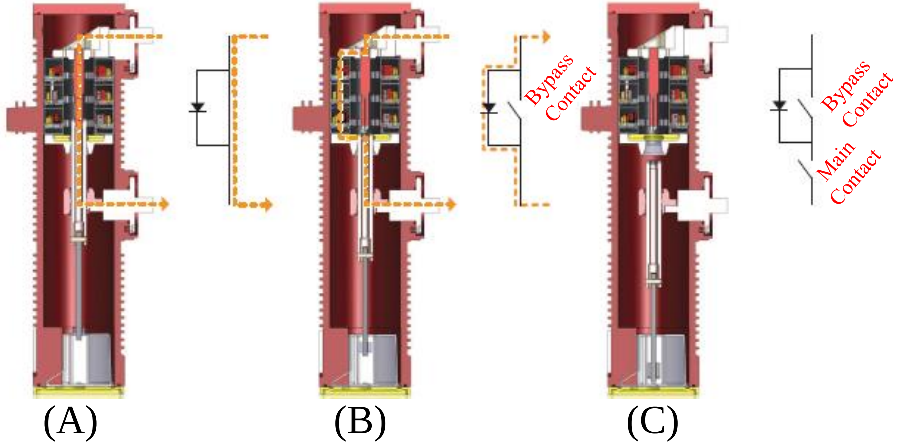


(A) (B) (C)

Closing Sequence

ABB DS1-M SWITCHING TECHNOLOGY (cont.)

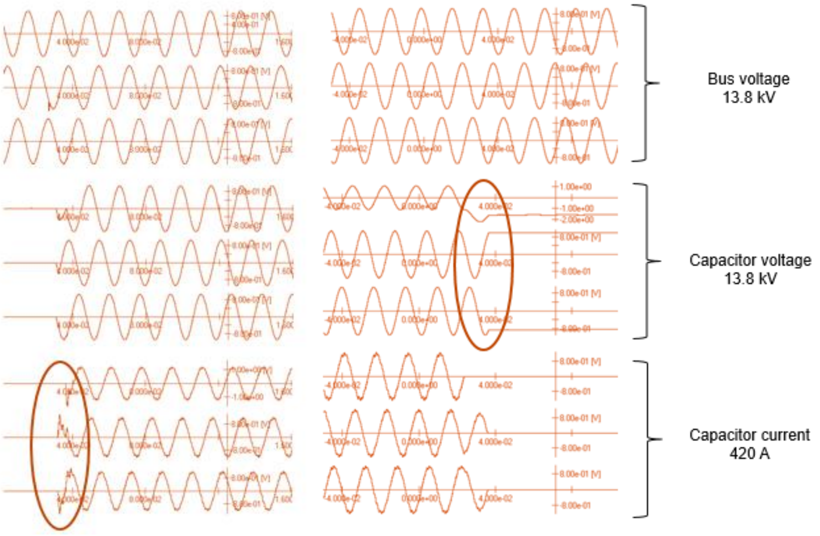
The DS1-M is able to carry out opening operations on capacitor banks without any overvoltage or the possibility of restrike.



Opening Sequence

ABB DS1-M SWITCHING TECHNOLOGY (cont.)

Closing Operation | Opening Operation



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

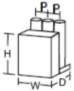
Electrical characteristics		DS1 50	DS1 60
Rated frequency	Hz	50	60
Rated voltage	kV	17.5	15
Rated current	A	630	600
Withstand voltage			
– phase to phase and phase to earth	kV	38 [1]	38 [1]
– across the insulating distance	kV	45	45
Impulse withstand (BIL)			
– phase to phase and phase to earth	kV	95	95
– across the insulating distance	kV	110	110
Short-time current (time)	kA (s)	20 (0.5)	20 (0.5)
Short-time peak current	kAp	52	52
Other characteristics			
Mechanical operations	CO	50.000	
Maximum overall dimensions 	H [mm]	655	
	W [mm]	618	
	D [mm]	561	
	P [mm]	210	
Weight	kg	130	
Working temperature range	°C	-15 … +55	
Maximum installation altitude	mslm	1.000	
Rated dry air absolute pressure	MPa	0.470	

ABB DS1-M SWITCHING TECHNOLOGY (cont.)

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.

ABB DS1-M - MOTOR STARTING APPLICATION – TIMING ISSUES

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

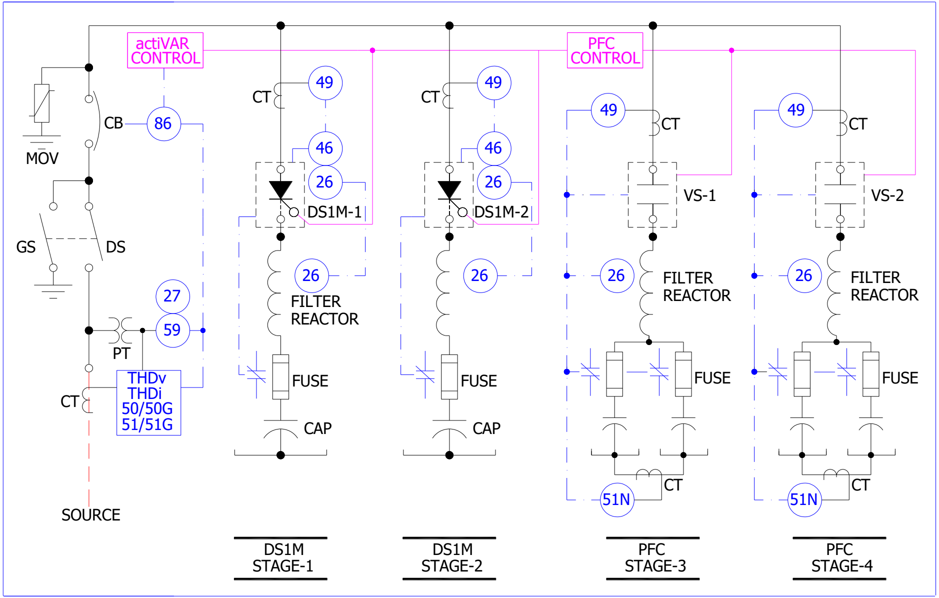
- Communication between actiVAR and motor starters
  - Direct wiring
  - Over network – 61850 protocol

ABB DS1-M - MOTOR STARTING APPLICATION - TIMING

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 trouble shoot, 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

actiVAR™ Gas Plant Project

Compressor Start and PFC Application – 5000 HP Induction Motor
13.8 kV, 24 MVAR 3-Stage actiVAR, 15 MVAR 3-Stage PFC

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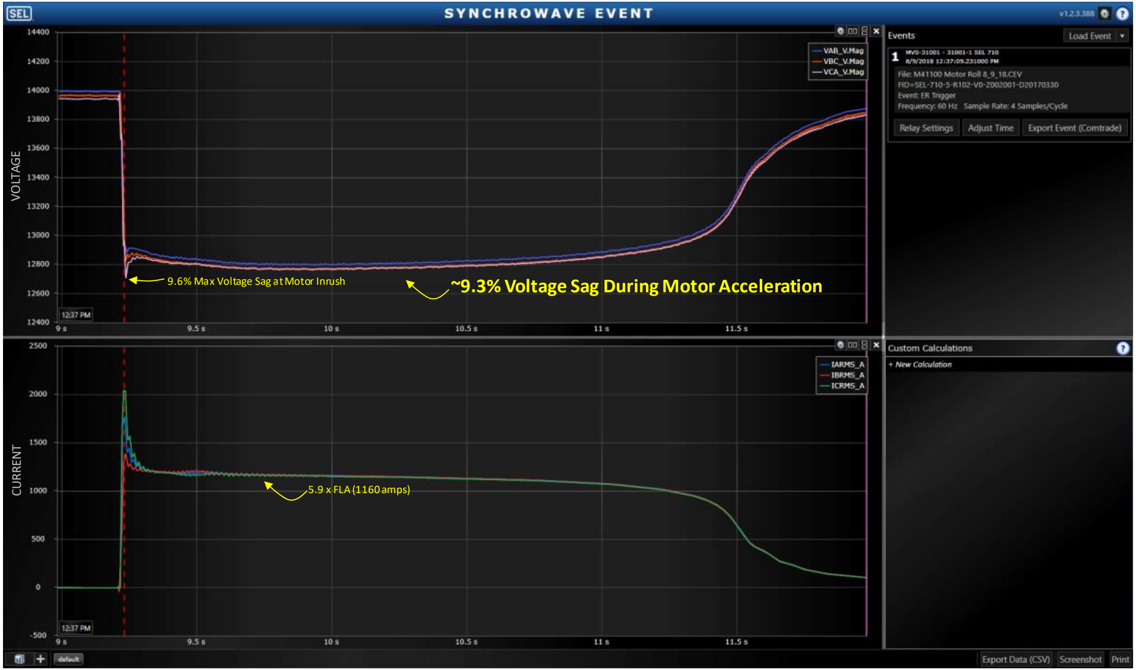
actiVAR™ Gas Plant Project - Mentone 5000 HP Motor Start (Uncoupled) WITHOUT Activar Assist



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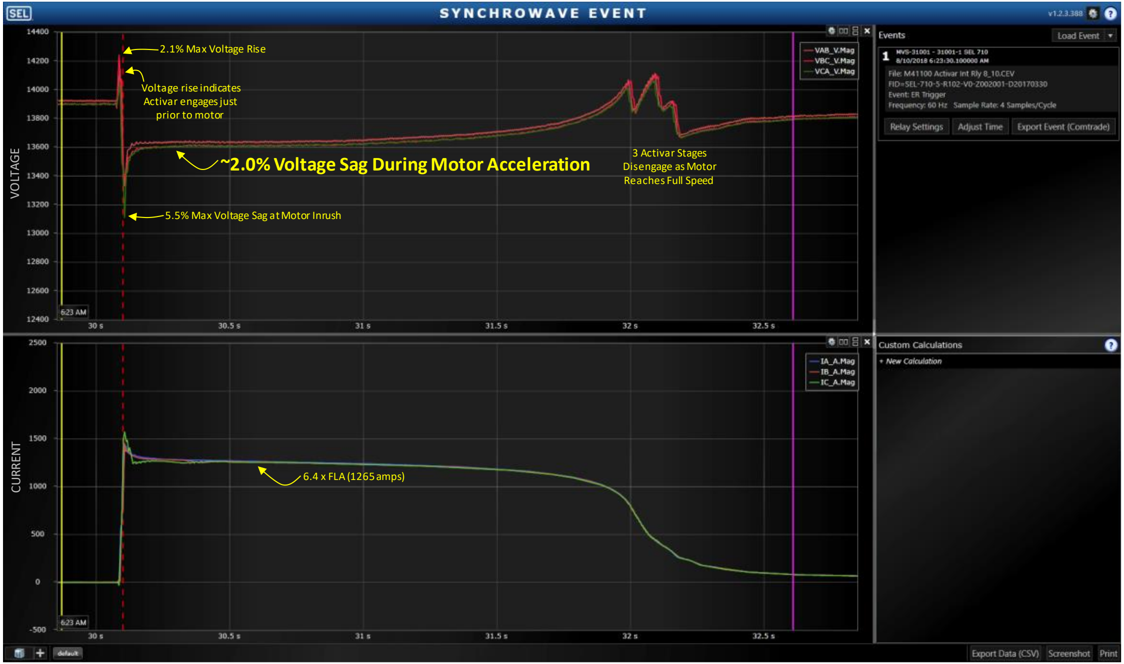
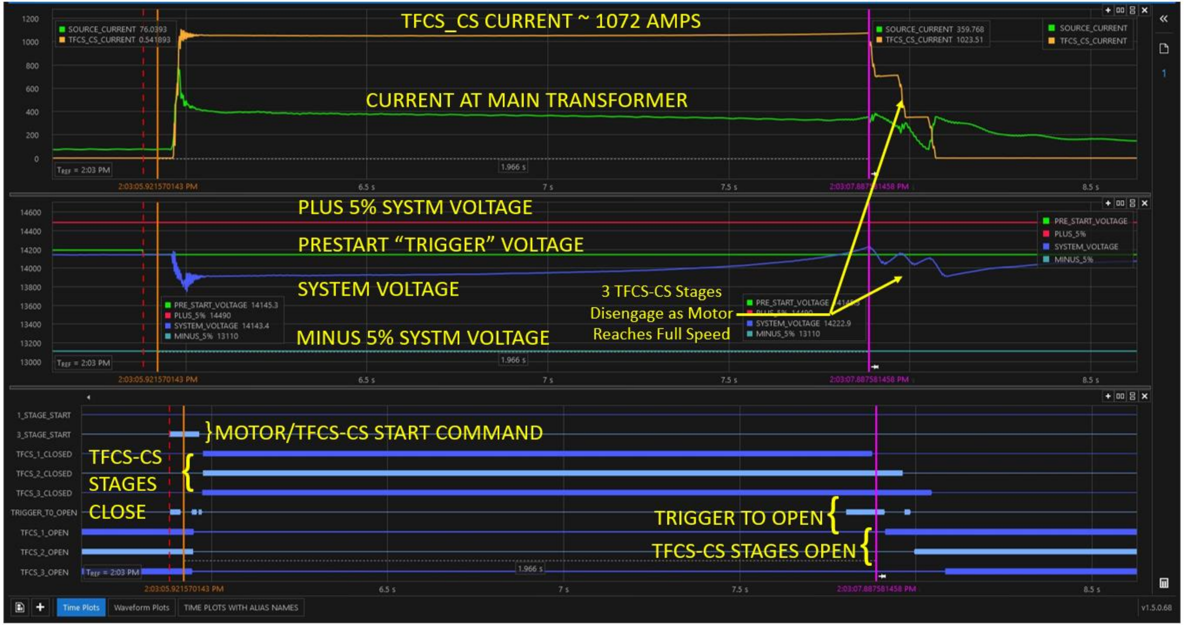
actiVAR™ Gas Plant Project - Mentone 5000 HP Motor Start (Uncoupled) WITH Activar Assist



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



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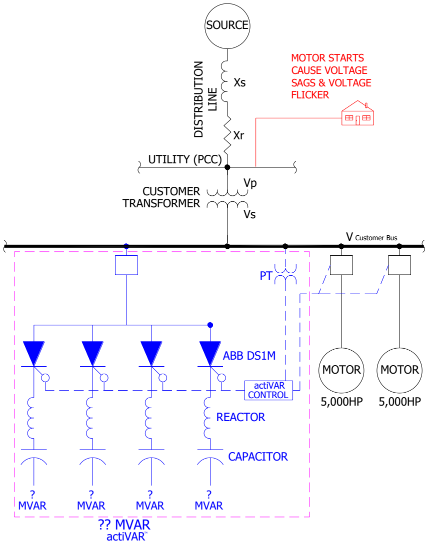
CALCULATION/APPLICATION EXAMPLE – MOTOR START



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?

CALCULATION/APPLICATION EXAMPLE – cont

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/APPLICATION EXAMPLE – cont

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actiVAR™ – MOTOR START CALCULATOR

The following calculator computes the expected performance of NEPSI's actiVAR™ in reducing voltage sags associated with large motor starts. Expected voltage sag and voltage drop are calculated for "across-the-line motor starts" based on system impedance data and motor nameplate ratings.

Calculator-1

Known variables:

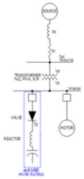
Source Data: Source Voltage, Source Short Circuit Level, and X/R ratio

Supply Side Transformer Data: Transformer Power Rating (MVA), leakage impedance (in % on transformer base), and X/R ratio of leakage impedance

Motor Nameplate Data: Motor Voltage rating, motor full load current (FLA), motor locked rotor current (see code letters following calculator if not known), locked rotor power factor (assume 20% if not known)

Unknown Variables: Voltage drop and voltage sag at motor and supply transformer primary

--------SOURCE DATA--------					
SOURCE VOLTAGE (Kv LINE-TO-LINE):	34.8	CALCULATED			
SOURCE 3-PHASE SHORT CIRCUIT CURRENT (kA):	1.9	Rpu	Xpu		
X/R RATIO:	2	0.016882	0.033764		
--------TRANSFORMER DATA--------					
MVA RATING:	10	CALCULATED			
PERCENT IMPEDANCE (ON TRANSFORMER BASE):	5.55	Rpu	Xpu		
X/R RATIO:	25	0.000959	0.023975		
--------MOTOR DATA--------					
MOTOR VOLTAGE RATING (kV):	4				
FULL LOAD CURRENT RATING (FLA):	624				
LOCK ROTOR CURRENT (%):	550	CALCULATED			
LOCK ROTOR PF (%):	20	Rpu	Xpu		
MOTOR KVA BASE RATING:	4323	0.036364	0.178145		
--------actiVAR™ DATA--------				CAP/MOT EQIV.	
actiVAR™ RATING (kV LINE-TO-LINE):	4.16	Rpu	Xpu	Rpu	Xpu
actiVAR™ RATING (MVAR):	24	0.00	0.194832	0.862294	0.200879



actiVAR™ PERFORMANCE						
	V_{MOTOR}		$V_{PRIMARY}$		TORQUE LOSS FROM VOLTAGE SAG (%)	actiVAR TORQUE ADVANTAGE (%)
	VOLTAGE DROP (%)	VOLTAGE SAG (%)	VOLTAGE DROP (%)	VOLTAGE SAG (%)		
WITHOUT actiVAR™	24.97	75.03	15.60	84.40	43.7	
WITH actiVAR™	3.48	96.52	2.76	97.24	6.8	36.9

Motor Inrush Current				
Inrush Current with actiVAR	680	amps	1.09	Per Unit of FLA
Inrush Current without actiVAR	2575	amps	4.13	Per Unit of FLA

Calculation Procedure

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

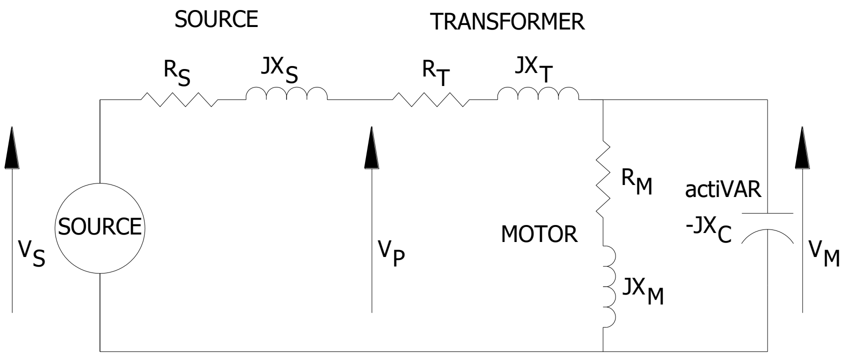
   http://nepsi.com/resources/calculators/actiVAR™-motor-start-calculator.htm

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

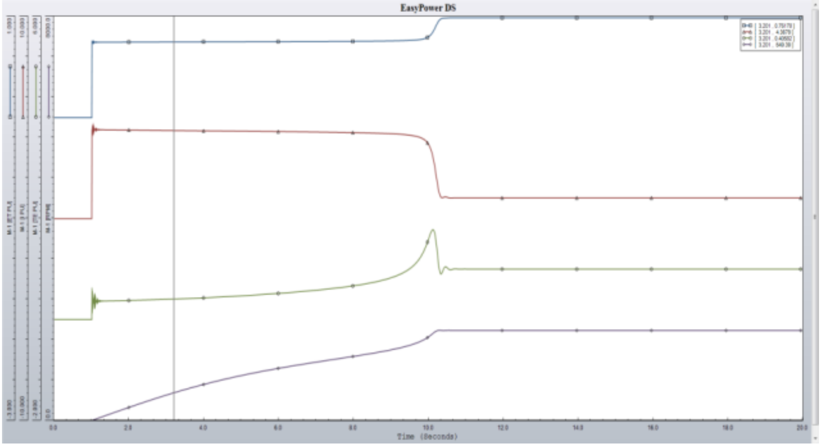
MOTOR START CALCULATION – Steady State Analysis



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



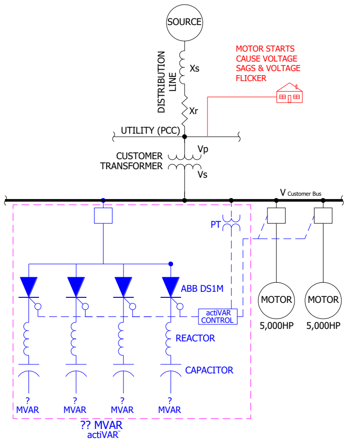
Typical plot output from dynamic analysis software showing motor terminal voltage, motor current, motor speed, and motor torque versus time

DYNAMIC ANALYSIS

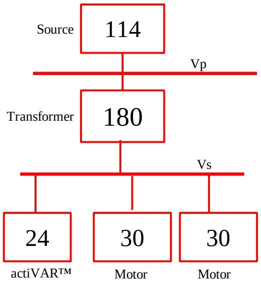
- Performed by NEPSI for all actiVAR™ orders and RFQ's
- Accurately calculates motor starting time, motor current, voltage, torque, power, and speed for the entire starting period
- Determines whether a motor will start or not start
- Accurately predicts actiVAR™ performance
- Requires more Data
  -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

MOTOR START CALCULATION – Back-of-Envelope

One-Line Diagram



MVAsc Diagram



"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.

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

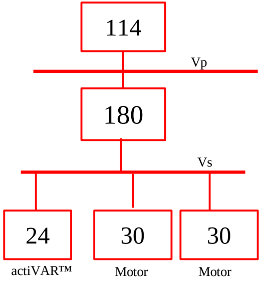
<u>Transformer Data</u>
MVA Rating (OA Rating): 10
Transformer Base Impedance: 5.55%
MVAsc = (10/.0555) = 180

<u>Motor Data</u>
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

<u>actiVAR™</u>
MVA Rating: 24
MVAsc = 24

MOTOR START CALCULATION – Back-of-Envelope cont.

MVAsc Diagram



Primary Side Voltage Drop

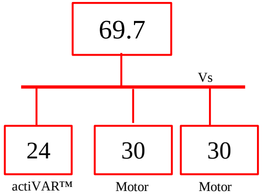
$$25.7 = \left(\frac{1}{30} + \frac{1}{180}\right)^{-1} \text{(without actiVAR)}$$

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

$$V_{p\ Drop\ without} = \frac{25.7}{25.7 + 114} = 0.183\ PU$$

$$V_{P\ Drop\ with\ actiVAR} = \frac{5.8}{5.8 + 180} = 0.031\ PU$$

MVAsc Diagram Reduced



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

$$V_{s\ Drop\ without} = \frac{30}{30 + 69.7} = 0.30\ PU$$

$$V_{s\ Drop\ with\ actiVAR} = \frac{30-24}{30-24+69.7} = 0.079\ PU$$

<u>For more information on MVA Short Circuit Method</u>

http://www.jmpangseah.com/wp-content/uploads/2003/01/chapter-5.pdf