KPN - ProSmart

Relay Protection in Smart Grid Context

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Advisor:

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Dr. Sumit Paudyal (co-advisor of 2nd PhD student)

Today's Topic - Background

- Frequency domain methods are commonly used to predict the following behaviors:
  - Frequency scan – (small signal phasor-domain model at each frequency)
  - Ferroresonance (old-time methods of Rudenburg)
  - Power line carrier (modal analysis)
  - Voltage collapse (continuous power flow)
- Issues:
  - Nonlinearities: magnetic saturation, in controllers
  - FACTS devices, switching harmonics
  - Frequency dependencies of transmission lines, etc.
  - Small-signal response does not include behavior at rated voltage or overvoltage. We need to obtain the "large-signal" response.
  - Step response of system following faults, switching, etc.

Work done to date

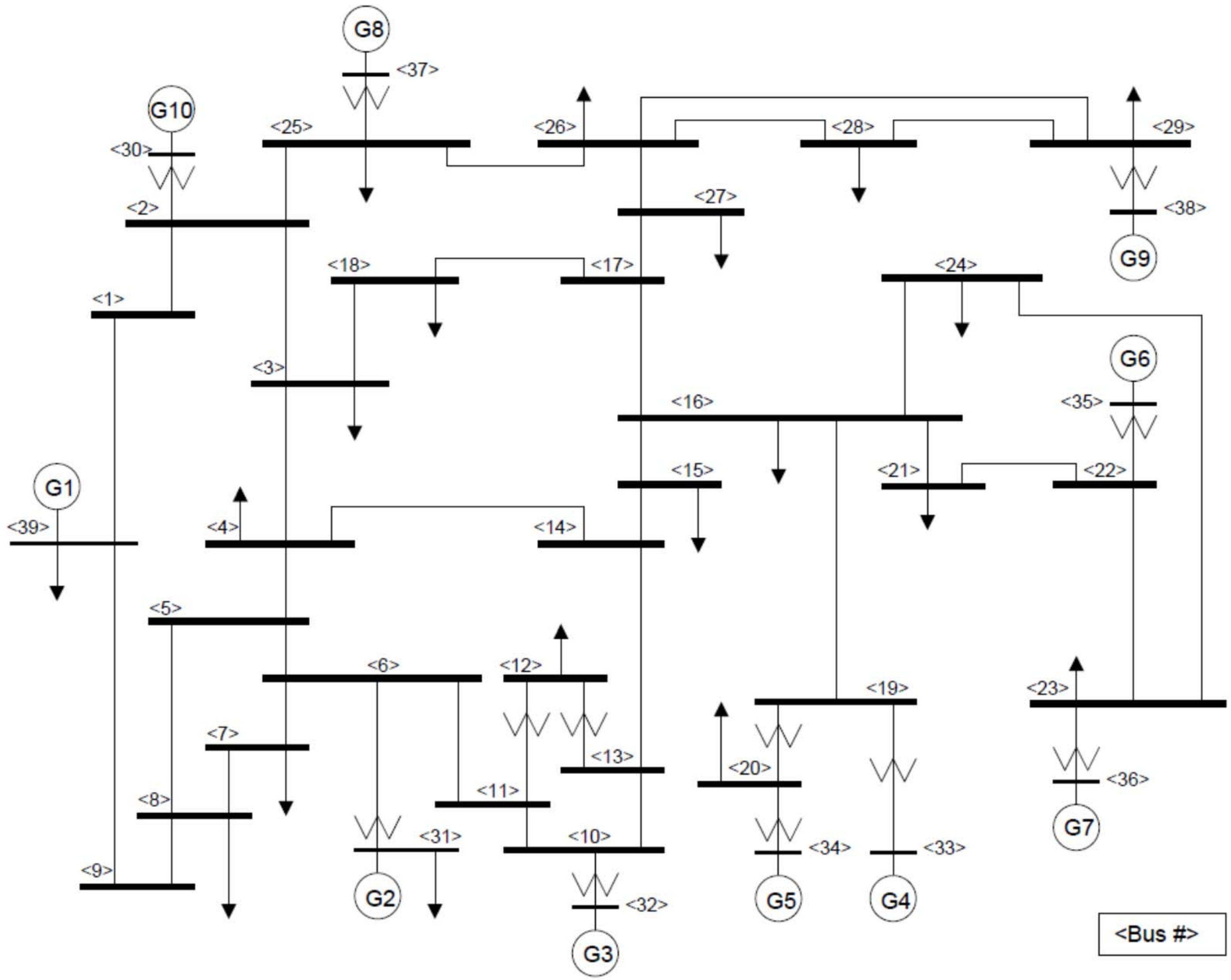
1) G.T. Wrate, B.A. Mork, and K.K. Mustaphi, "**A New Method to Determine Frequency Characteristics of a Power System Including Nonlinear Effects**," Proceedings of IPST, pp. 11-16, Seattle, WA, June, 1997.
2) B.A. Mork, D. Ishchenko, X.Wang, A.D. Yerrabelli, R.P. Quest, C.P. Kinne, "**Power Line Carrier Communications System Modeling**," Proceedings of IPST, Paper No. IPST05-247, Montreal, June 19-23, 2005.
3) A.P. Kunze, B.A. Mork, "**Prediction of Ferroresonance Using Moving Window Techniques**," European EMTP Users Group Meeting, Leon, Spain, September 24-26, 2007.
4) Today's presentation on Voltage Collapse…

Project Work

- **Developing different indices to predict voltage collapse**
  - Fast and accurate recognition of voltage degrading
  - Multi-variable indices
  - Different test systems
- **Wide-area feedback control**
  - Develop a control decision algorithm
  - Considering different wide-area system parameters
  - Feed-back from the system to upgrade the control action
- **Time-domain modeling of the power system**
  - Different load types
  - Shunt compensators; TCR, SVC
  - Phasor Measurement Unit (PMU)
- **Time-domain method to identify voltage collapse**
  - Use actual voltage and current waveforms
  - Plot P-V curve, identify operating point, and available power margin
  - Verify time-domain method accuracy

IEEE 39 Bus System (New-England Power System)

- 39 bus system
- 10 generators
- 29 load buses
- 46 transmission lines



Monitor available power margin using Thevenin equivalent

- Maximum power transfer occurs when the load impedance is equal to Thevenin equivalent impedance
- The ratio of Thevenin equivalent impedance and the load impedance reveals the operating point and power margin.
- Thevenin equivalent impedance is calculated using two consecutive voltage and current measurements.

$$V_L = E_{th} - Z_{th} I_L \qquad Z_{th} = \frac{V_{L2} - V_{L1}}{I_{L1} - I_{L2}}$$

- Based on the distance to maximum power transfer point, a multi-level alert is generated.

Monitor rate of change of voltage

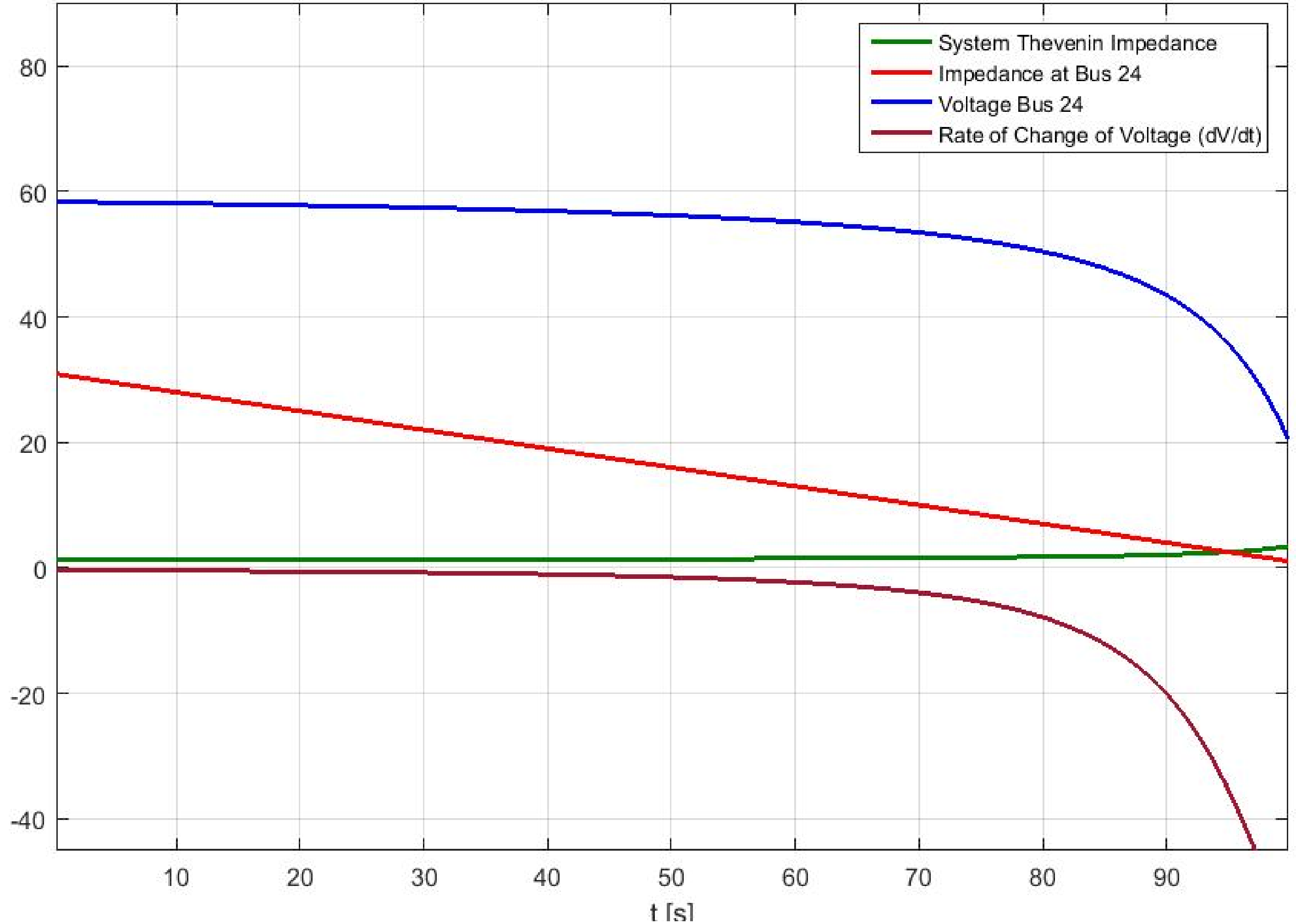
- The average of three consecutive changes in peak voltage is considered as the rate of change of voltage
- Different threshold are considered to activate a multi-level alert

Monitor magnitude of voltage

- Magnitude of voltage is also monitored to track very fast changes
- Different threshold are considered to activate a multi-level alert

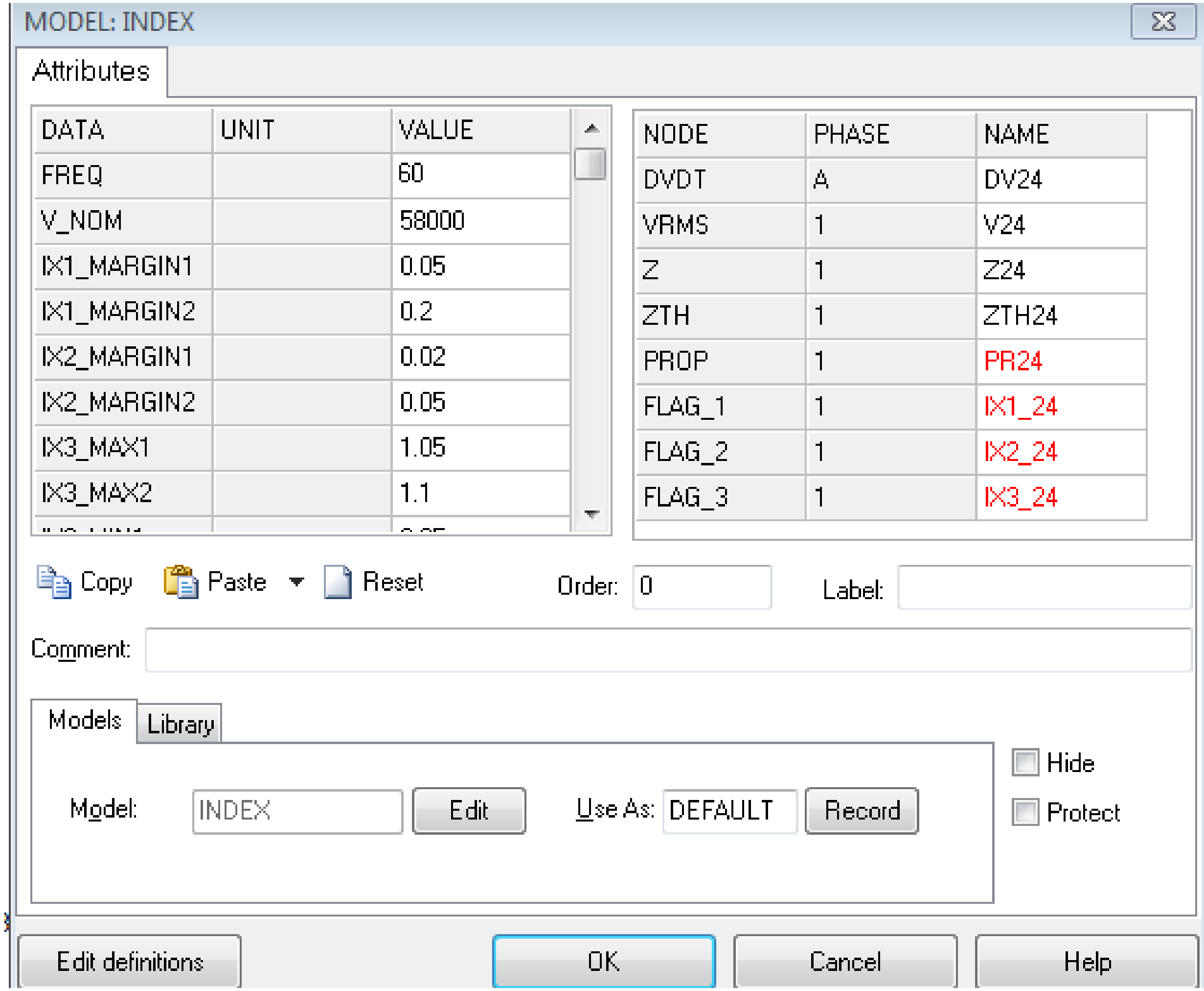
Case Study

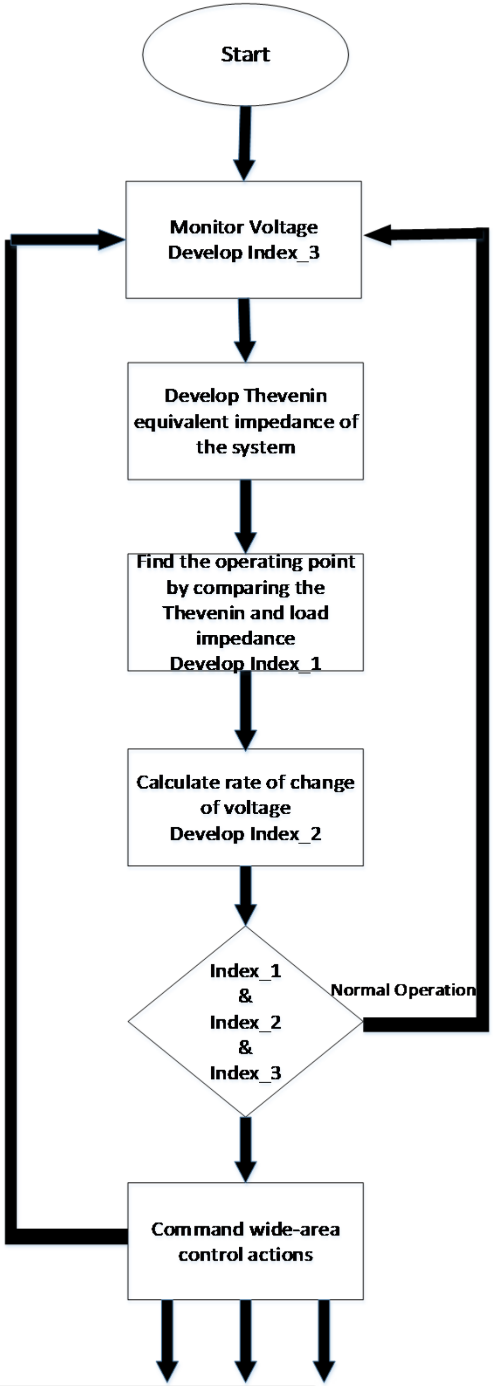
- Load at Bus 24 is increasing
- Index monitor at bus 24 and bus 16



Different monitored parameters (normalized plot)

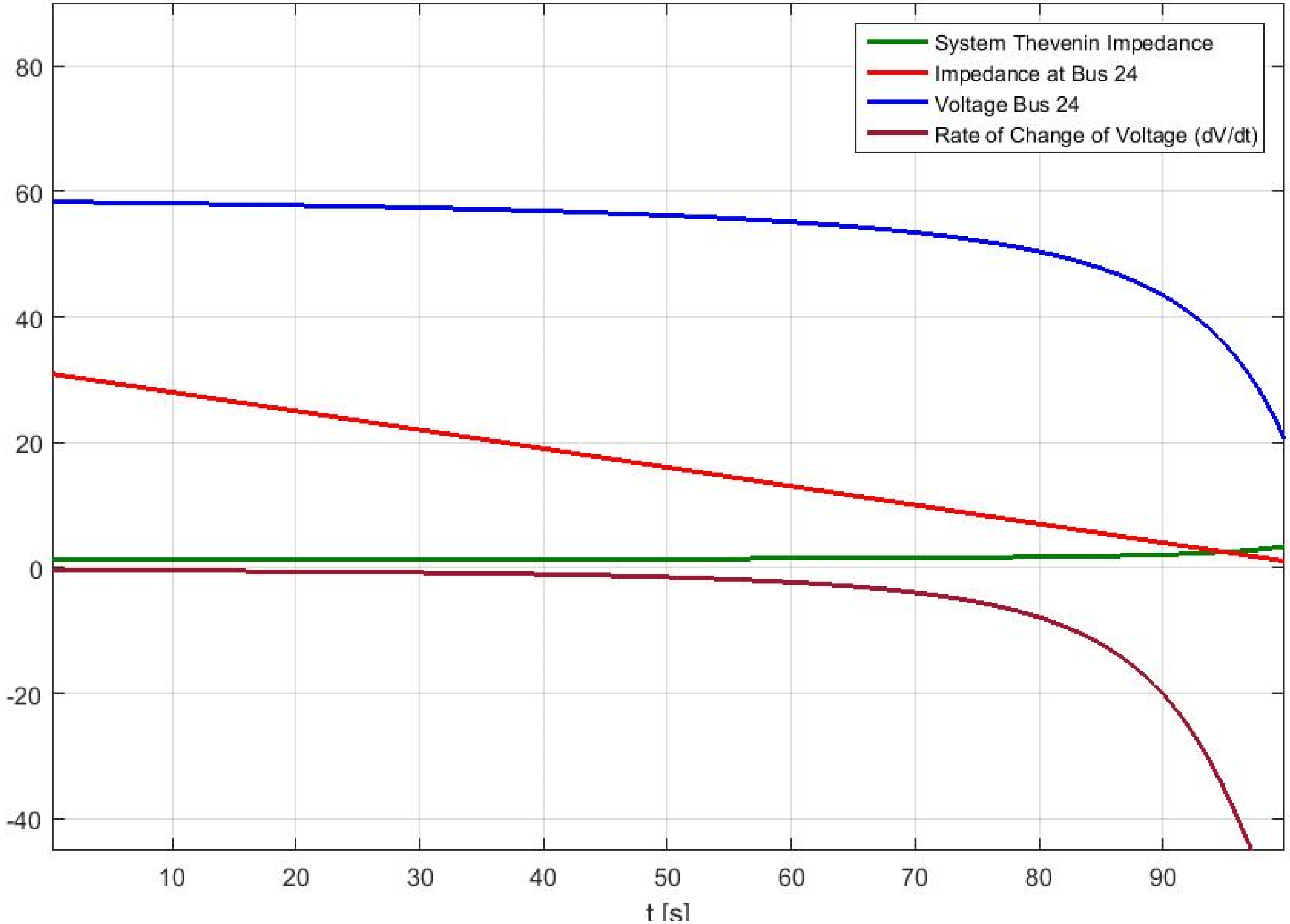
Flag-1	Flag-2	Flag-3
0 **Normal operation** Z/Zth<0.05	**0** **Normal,** voltage increase or drop less than 5% in 10 second	**0** **Normal operation,** Voltage between 0.95 and 1.05 PU
	1 **Caution,** voltage drop between 5-10% in 10 second	
	2 **Action,** voltage drop more than 10% in 10 second	
1 **Caution** 0.05<Z/Zth<0.2	**0** **Normal,** voltage increase or drop less than 2% in 10 second	**1** **Caution,** Voltage between 0.9 and 0.95 PU or Voltage between 1.05 and 1.1 PU
	1 **Caution,** voltage drop between 2-5% in 10 second	
	2 **Action,** voltage drop more than 5% in 10 second	
2 **Action** Z/Zth>0.2	**2** **Action**	**2** **Action,** Voltage less than 0.9 or greater than 1.1


MODEL: INDEX
Attributes
DATA | UNIT | VALUE
FREQ | | 60
V_NOM | | 58000
IX1_MARGIN1 | | 0.05
IX1_MARGIN2 | | 0.2
IX2_MARGIN1 | | 0.02
IX2_MARGIN2 | | 0.05
IX3_MAX1 | | 1.05
IX3_MAX2 | | 1.1
NODE | PHASE | NAME
DVDT | A | DV24
VRMS | 1 | V24
Z | 1 | Z24
ZTH | 1 | ZTH24
PROP | 1 | PR24
FLAG_1 | 1 | IX1_24
FLAG_2 | 1 | IX2_24
FLAG_3 | 1 | IX3_24
Copy
Paste
Reset
Order: 0
Label:
Comment:
Models
Library
Model: INDEX
Edit
Use As: DEFAULT
Record
Hide
Protect
Edit definitions
OK
Cancel
Help

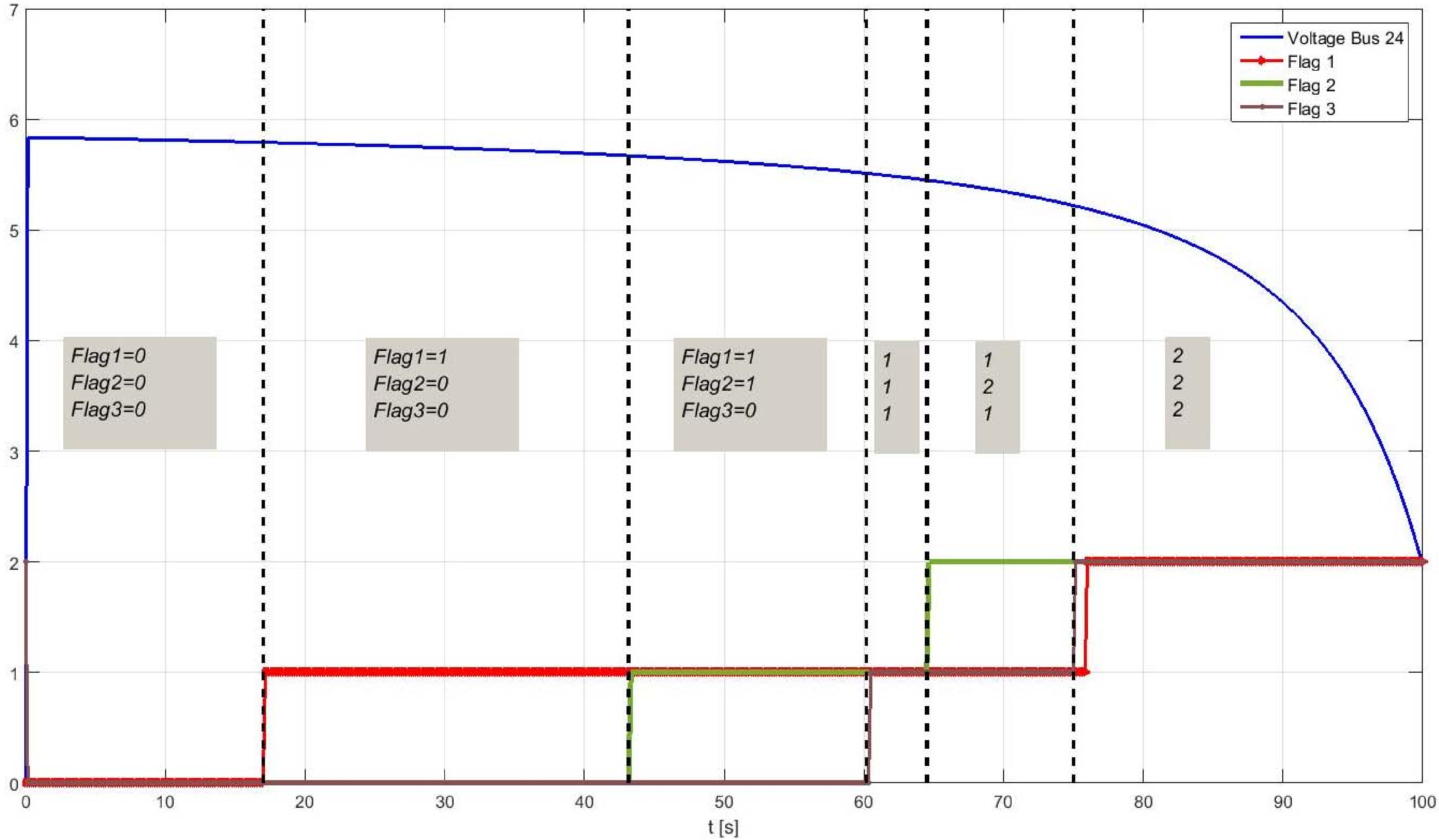

Start
Monitor Voltage
Develop Index_3
Develop Thevenin equivalent impedance of the system
Find the operating point by comparing the Thevenin and load impedance
Develop Index_1
Calculate rate of change of voltage
Develop Index_2
Index_1 & Index_2 & Index_3
Normal Operation
Command wide-area control actions

Case Study

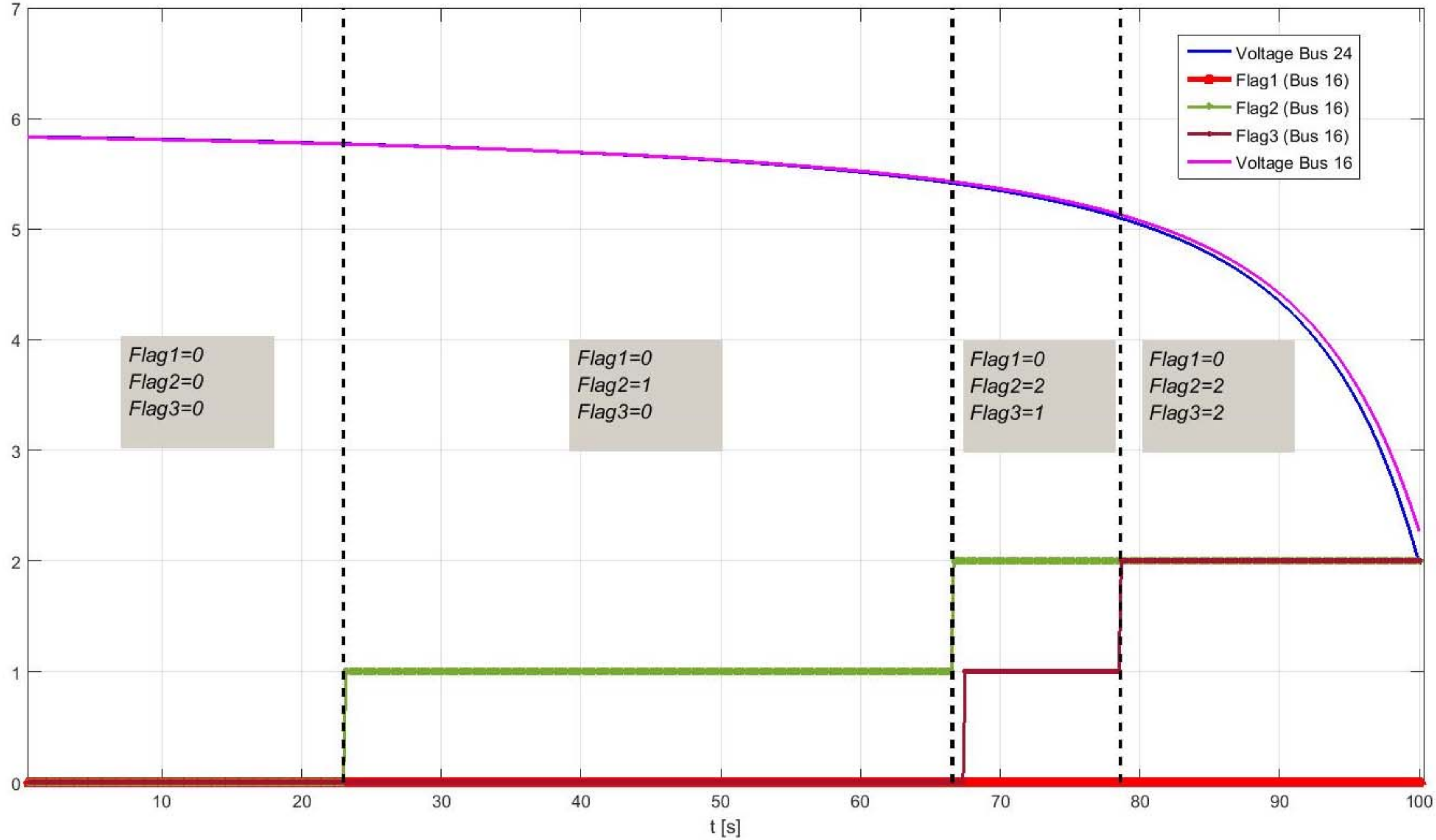
- Load at Bus 24 is increasing
- Index monitor at bus 24 and bus 16



Different monitored parameters (normalized plot)



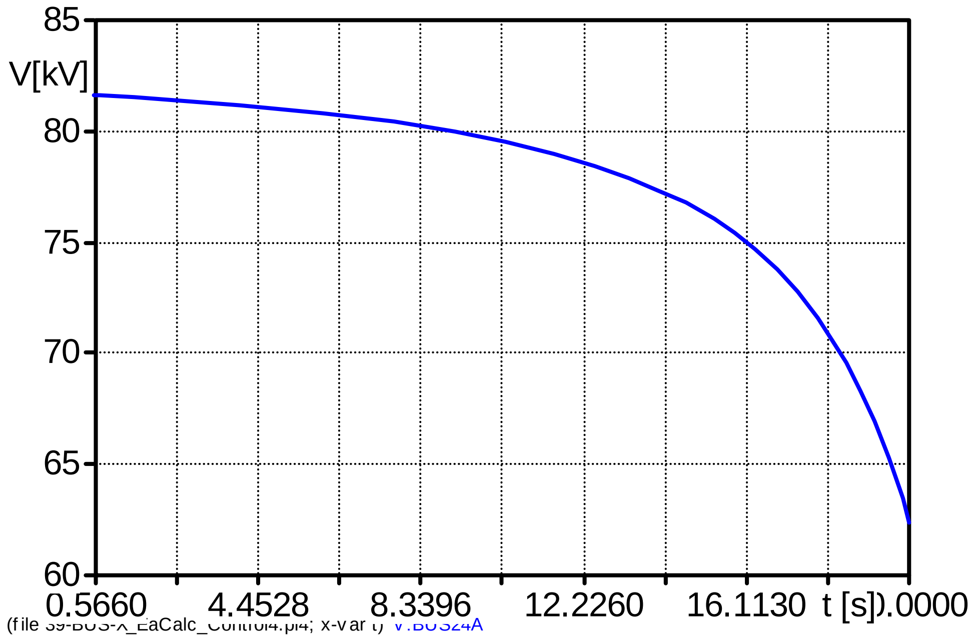
Bus 24 voltage (normalized) and indices at Bus 24



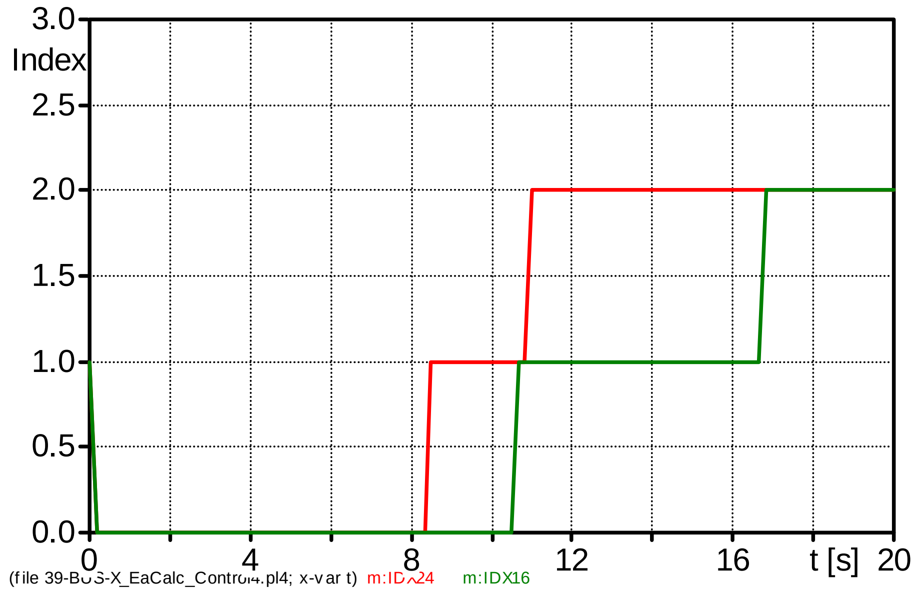
Bus 24 and 16 voltages (normalized) and indices at Bus 16

Overall Voltage Stability Index at Each Bus

Flag 1	Flag 2	Flag 3	Overall Index
0	0	0	**0**
1	0	0	
0	1	0	
0	0	1	
1	1	0	**1**
1	0	1	
0	1	1	
2	0	0	
0	2	0	
0	0	2	
1	1	1	
Any combinations in which one of the flags is 2 and another is 1. If all flags are 2.			**2**



Voltage at Bus 24



Stability indices at bus 24 snd bus 16

NTNU

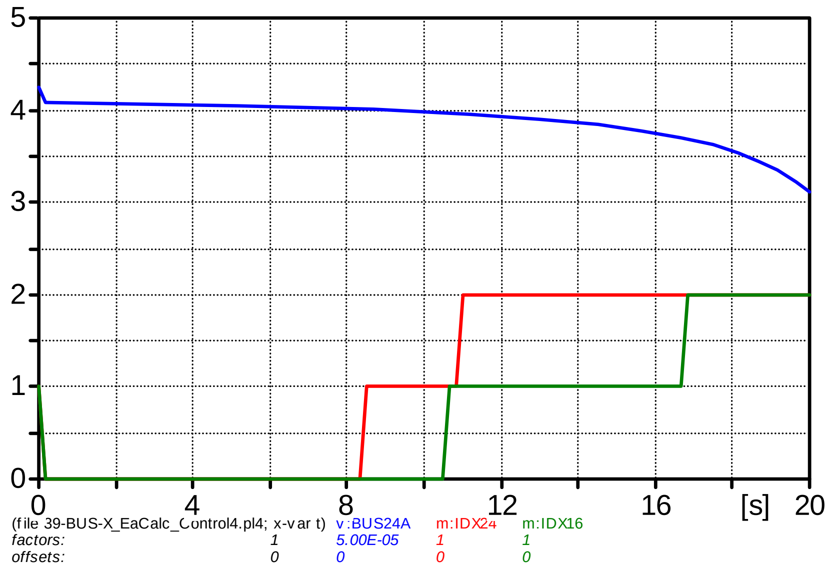
Michigan Tech
Create the Future

Wide-area control actions

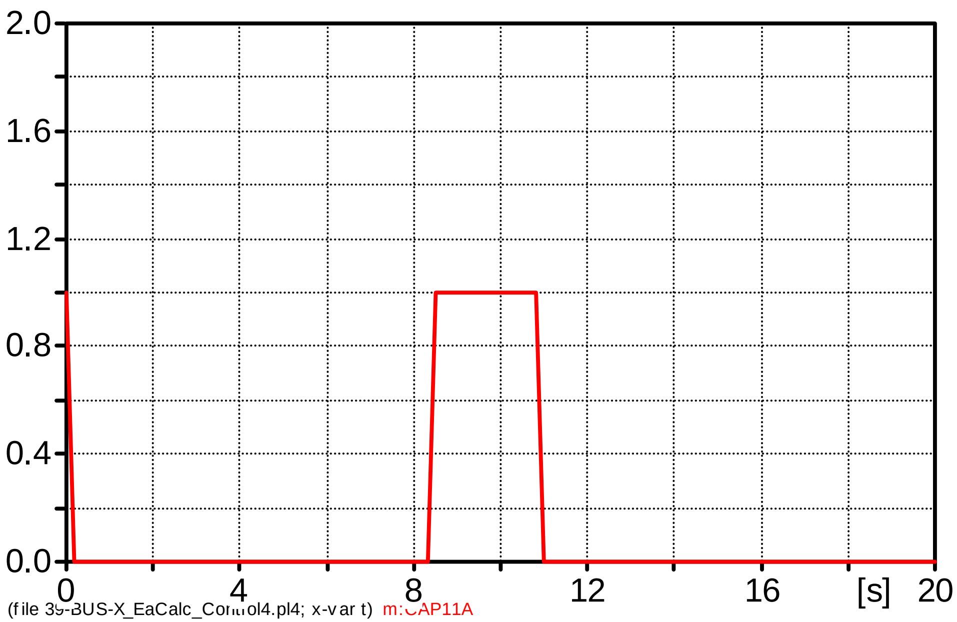
- All voltage stability indices transferred to wide-area control center
- Control commands issued based on stability indices and available control actions
- If two control options available, capacitor bank and load shedding, a control table example would be as:

Wide-Area Control Commands

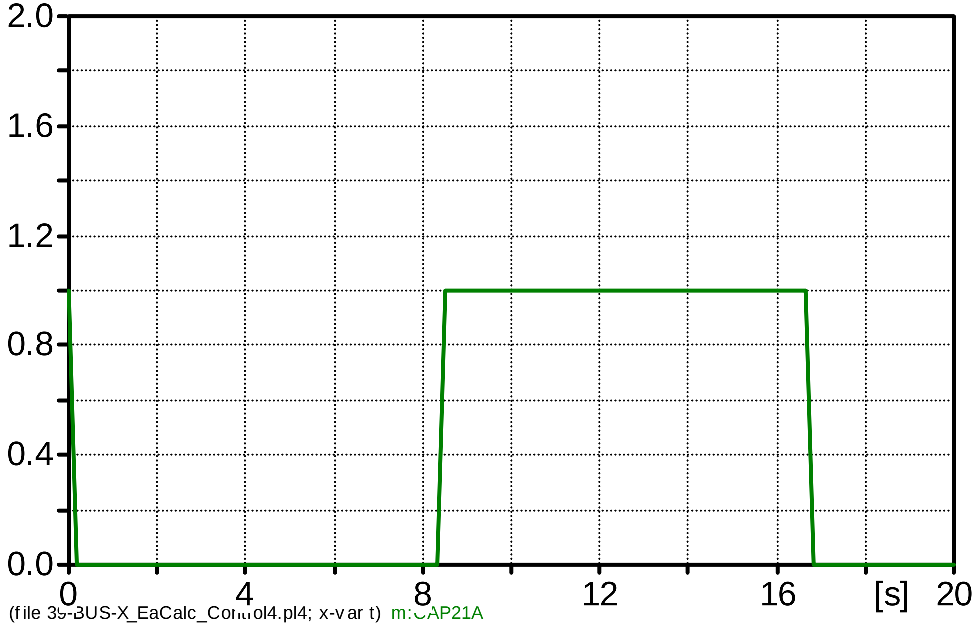
Stability Index Bus 24	Stability Index Bus 16	Cap Bank Bus 24	Cap Bank Bus 16	Load Shedding Bus 24	Load Shedding Bus 16
0	0	✗	✗	✗	✗
1	0	✓	✗	✗	✗
0	1	✗	✓	✗	✗
1	1	✓	✓	✗	✗
2	0	✗	✓	✓	✗
0	2	✓	✗	✗	✓
2	1	✗	✓	✓	✗
1	2	✓	✗	✗	✓
2	2	✗	✗	✓	✓



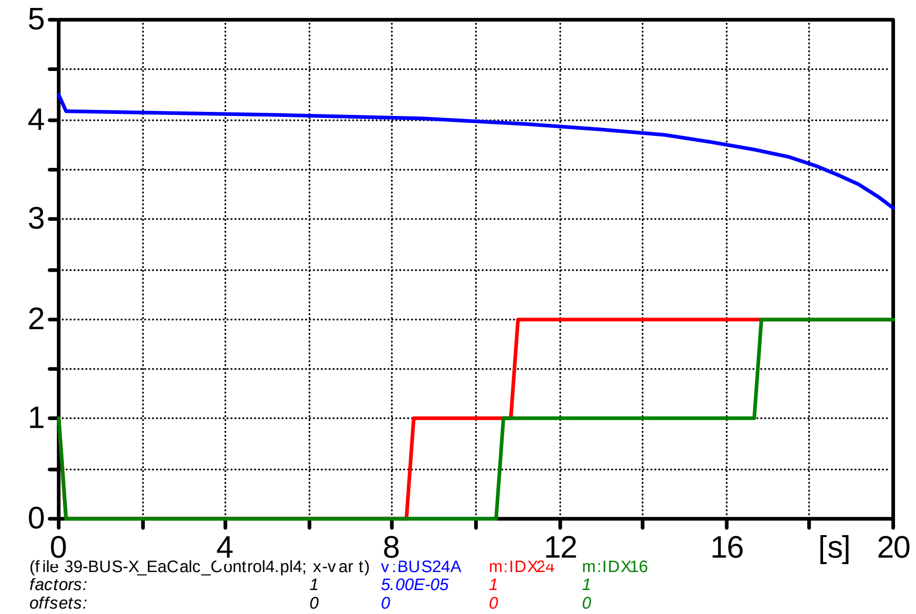
Voltage (normalized) and indices at Bus 24



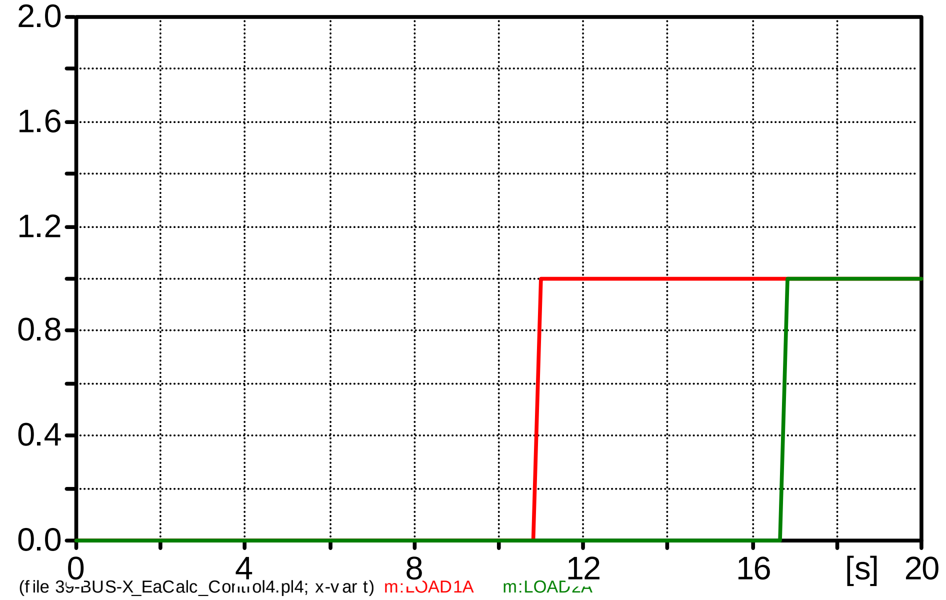
Control command for Capacitor Bank at Bus 24



Control command for Capacitor Bank at Bus 16



Voltage (normalized) and indices at Bus 24



Control command for load shedding at Bus 24 and Bus 16

Variable Inductive Load

Time-varying magnetic flux induces a voltage across the inductor.

$$v_l = \frac{d\phi}{dt} \quad \text{and} \quad L(t) = L_0 + Kt$$

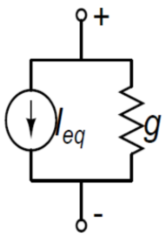
$$v_l = \frac{\partial L i}{\partial t} \Rightarrow \frac{v_{l,k} + v_{l,k-1}}{2}\Delta t = L_k i_k - L_{k-1} i_{k-1}$$

$$i_k = \left(\frac{L_{k-1}}{L_k} i_{k-1} + v_{l,k-1}\frac{\Delta t}{2L_k}\right) + v_{l,k}\frac{\Delta t}{2L_k}$$

We can model the time-varying inductance using a Norton current source and an equivalent conductance.

$$i_{eq} = \left(\frac{L_{k-1}}{L_k} i_{k-1} + v_{l,k-1}\frac{\Delta t}{2L_k}\right)$$

$$g_k = \frac{\Delta t}{2 L_k}$$



Inductance equivalent circuit

Variable Capacitive Load

Time-varying electric charge develops a current flow through the capacitor.

$$i = \frac{\partial C v}{\partial t} \quad \text{and} \quad C(t) = C_0 + kt$$

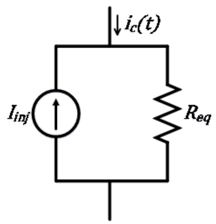
$$\frac{i_{c,k} + i_{c,k-1}}{2}\Delta t = C_k v_k - C_{k-1} v_{k-1}$$

$$i_{c,k} = v_k \frac{2C_k}{\Delta t} - \left(\frac{2C_{k-1}}{\Delta t} v_{k-1} + i_{c,k-1}\right)$$

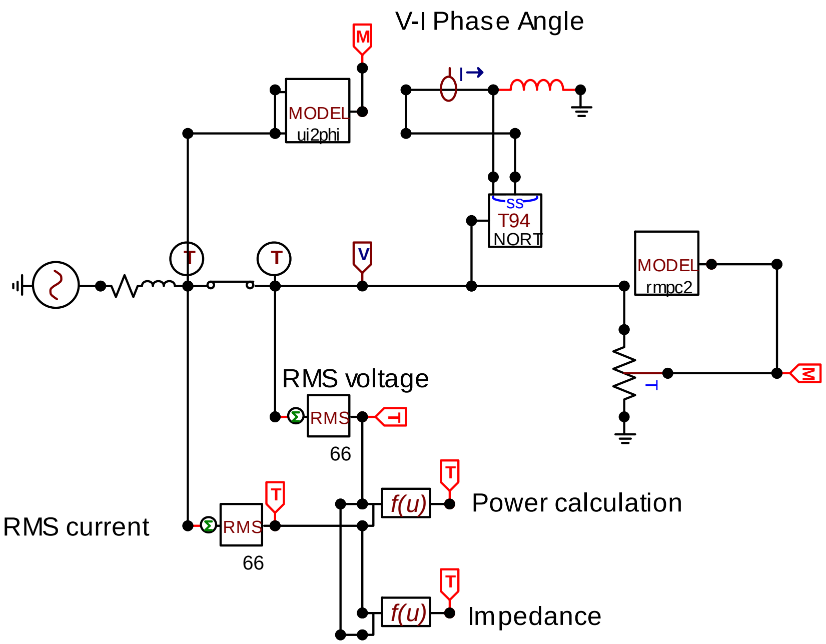
We can develop an equivalent Norton current source and a resistance to model time-varying capacitor.

$$I_{inj} = \frac{2C_{k-1}}{\Delta t} v_{k-1} + i_{c,k-1}$$

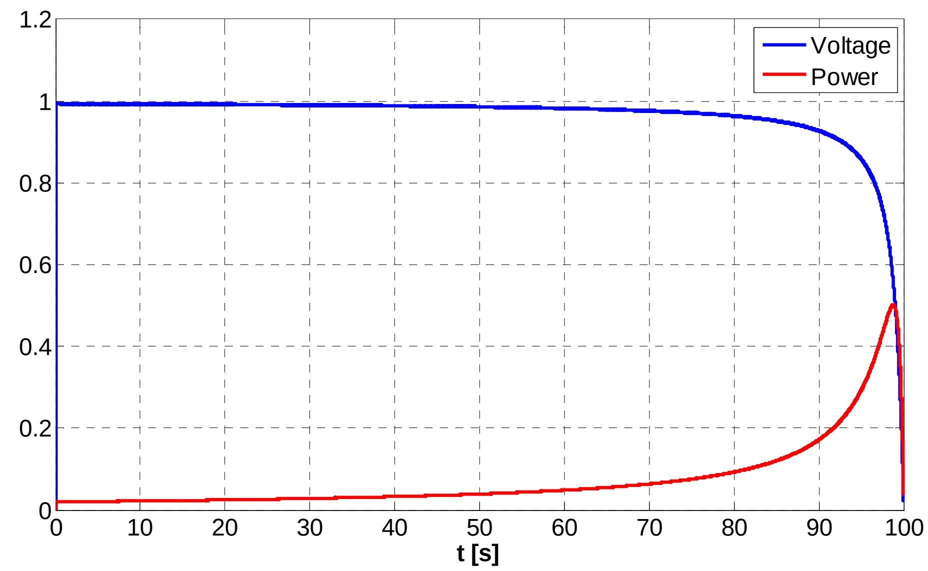
$$R_{eq,k} = \frac{\Delta t}{2C_k}$$



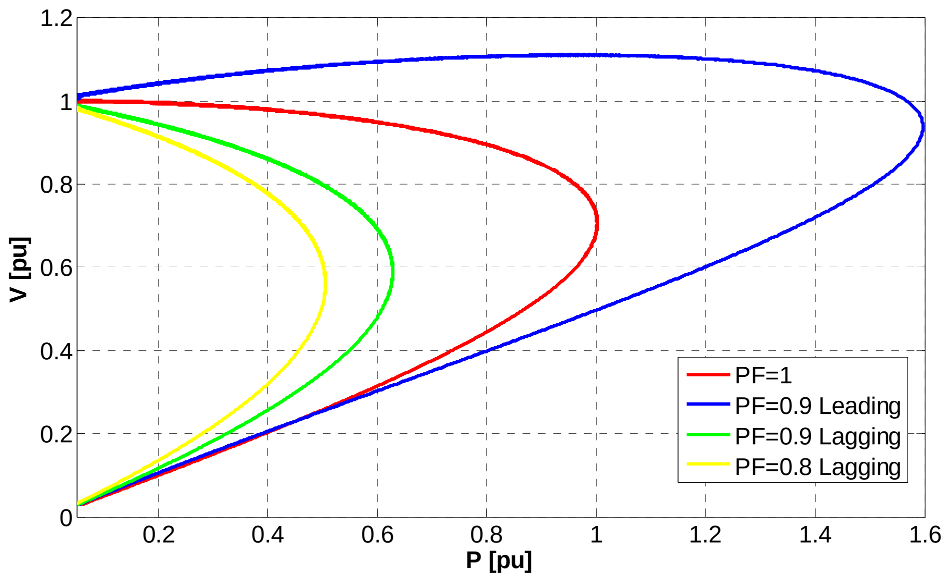
Capacitor equivalent circuit



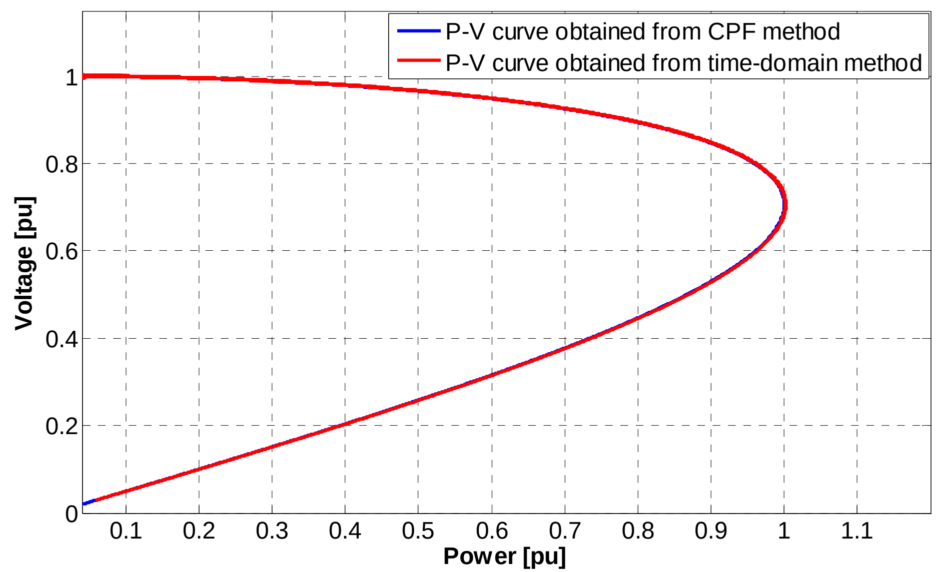
Simulated system with time-varying lagging load model



Load power and RMS voltage



P-V curve of loads with different power factors



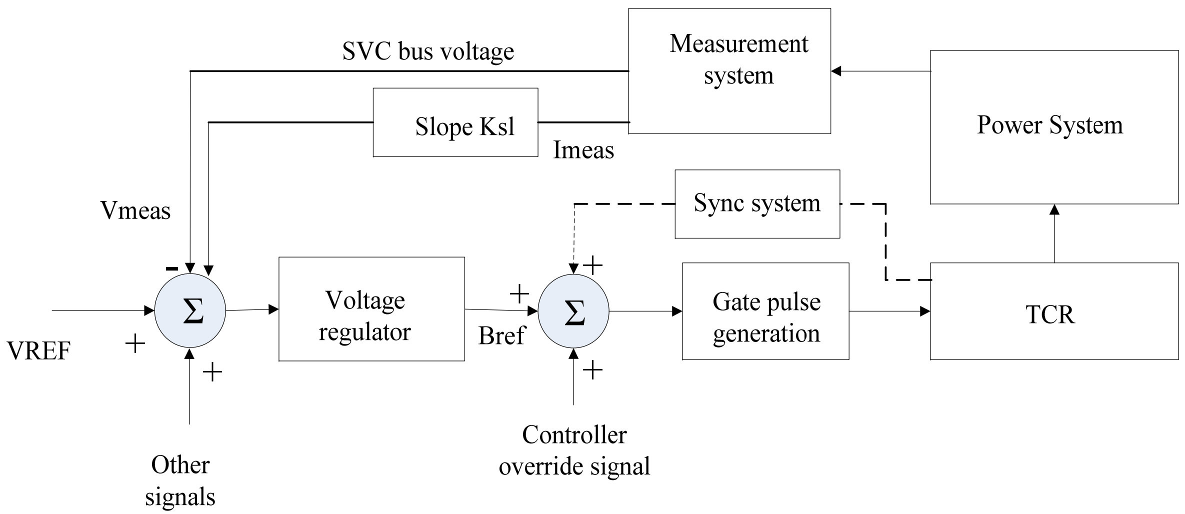
P-V curves plotted using time-domain method and CPF

Modeling SVC

- Considering compensation limits
- Effects on voltage stability
- Compare PV curves

Developed Model for SVC in ATPDraw

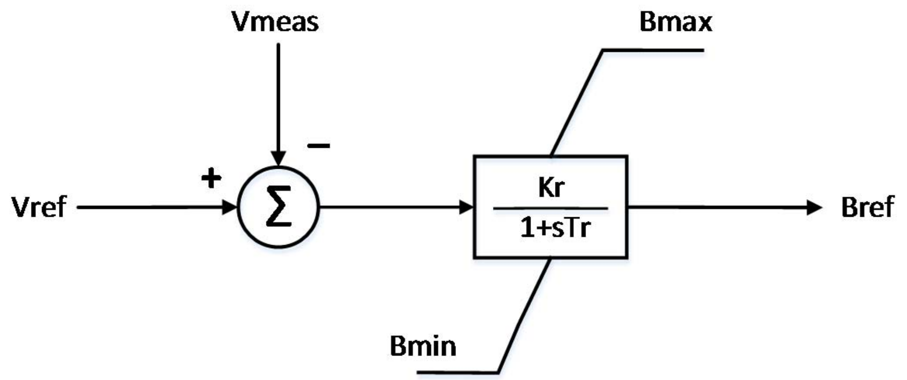
- **Phase-Locked Loop (PLL)**
- **Voltage Regulator**
- **Pulse Generator**
- **TCR/FC**



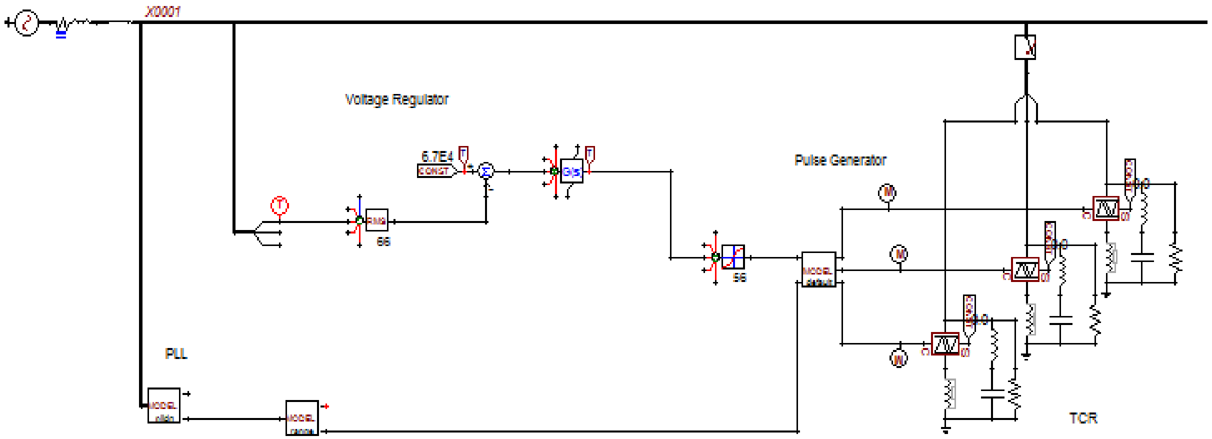
General SVC Schematic

Voltage Regulator

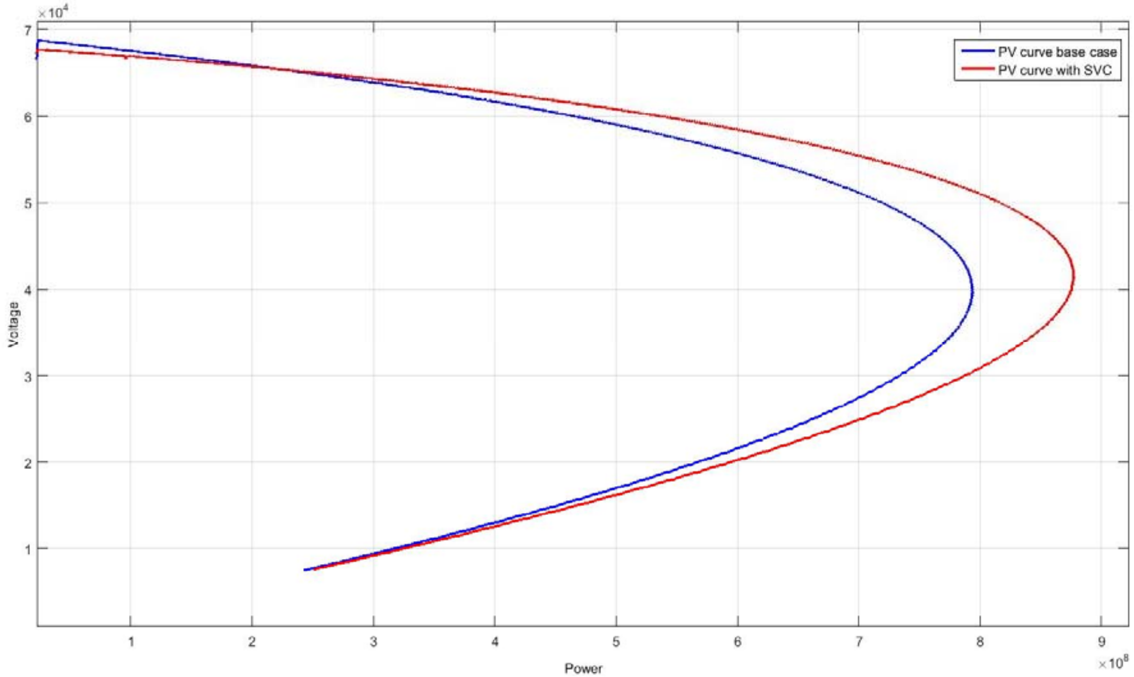
- Input: measured voltage
- Output: a signal proportional to the required reactive power compensation to maintain system voltage at the reference value
- Output of the controller would be the desired susceptance value
- Measured voltage > the reference value, then B would be a negative value showing inductive compensation;
- Measured voltage < the reference value, the output of voltage regulator would be a positive value showing capacitive compensation to increase the voltage.



- Bus P-V curve with SVC
- Increase maximum power transfer capability



Developed SVC model in ATPDraw



Modeling PMU

- Extract a single frequency component of the signal
- Using sampled system data

Phasor Estimation at Off-Nominal Frequency

- Sampling rate is constant and it is multiple of the nominal frequency.

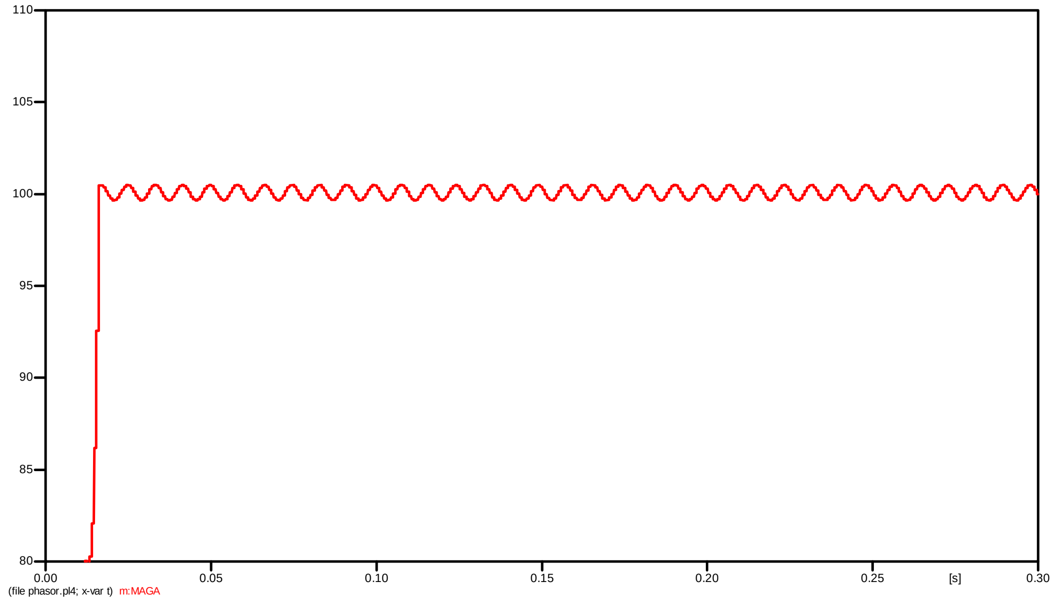
$$\omega = \omega_0 + \Delta\omega \qquad x(t) = X_m \cos(\omega t + \phi)$$

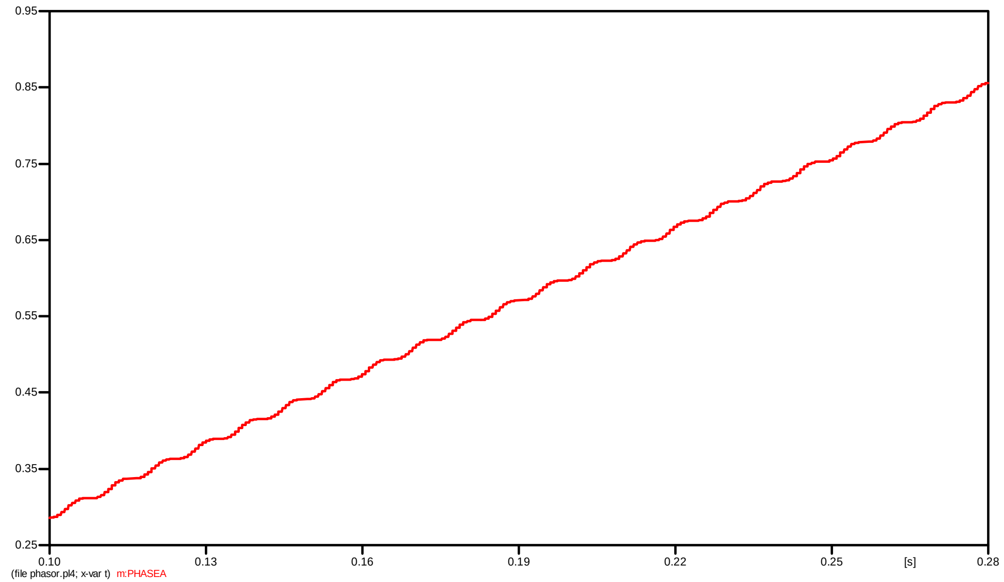
- Correct phasor representation for this input signal $\frac{X_m}{\sqrt{2}} e^{j\phi}$
- Phasor estimation error depends on the difference between the nominal frequency and actual frequency.
- phasor estimate at off-nominal frequency

$$X'_r = PXe^{jr(\omega-\omega_0)\Delta t} + QX^* e^{-jr(\omega+\omega_0)\Delta t}$$

- P and Q coefficients, their values depends upon the nominal frequency and the actual signal frequency and also the sampling rate

- Using a recursive DFT algorithm for phasor estimation with nominal frequency of 60HZ while the signal frequency is 60.5 Hz

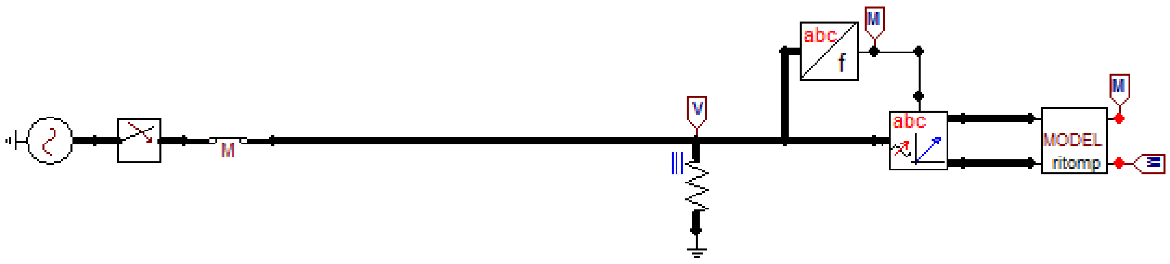


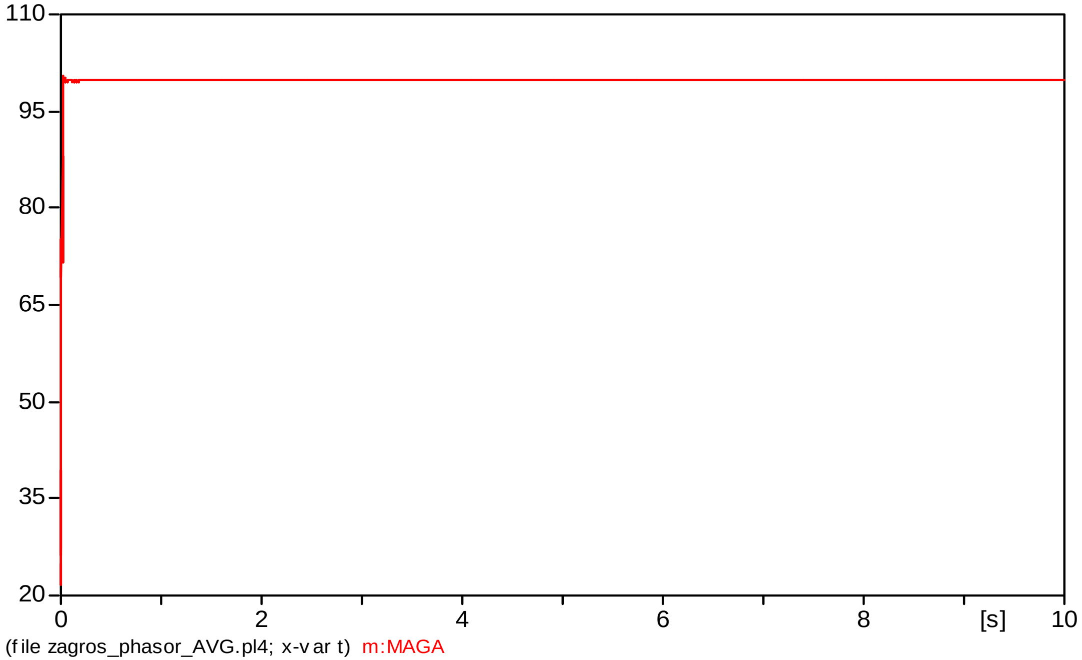


Magnitude and angle of phasor - Using 60Hz recursive DFT algorithm to estimate the input signal with f=60.5Hz

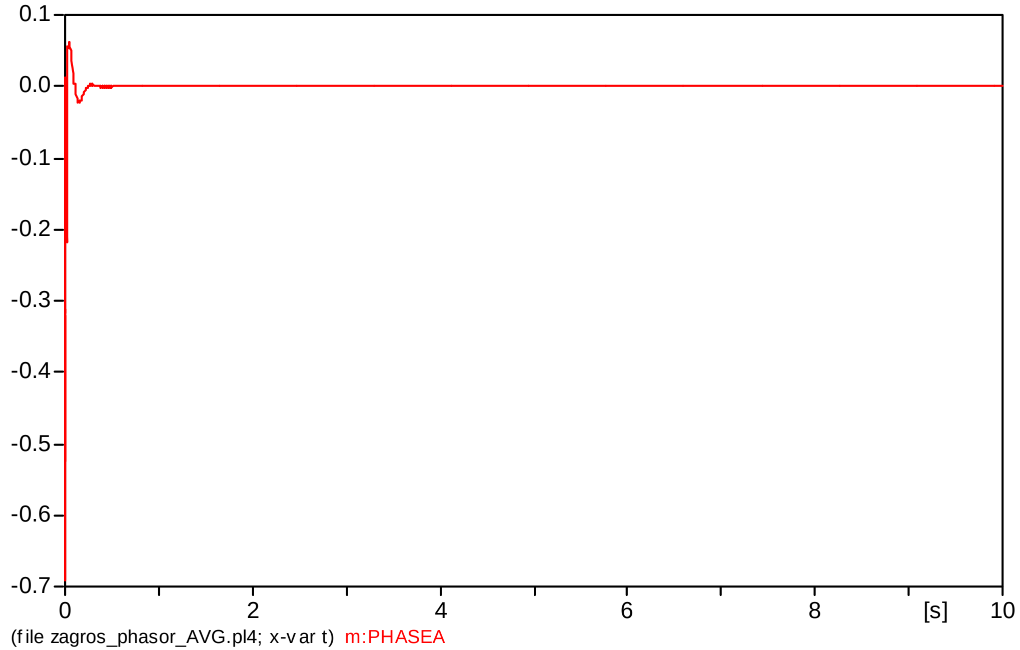
Modeling with Frequency Estimation and FFT Algorithm

- Use a PLL block to estimate the frequency
- Phasor estimation using an 8-point FFT algorithm
- In each time step new time delays are calculated and the phasor is estimated.





Phasor Magnitude Estimation

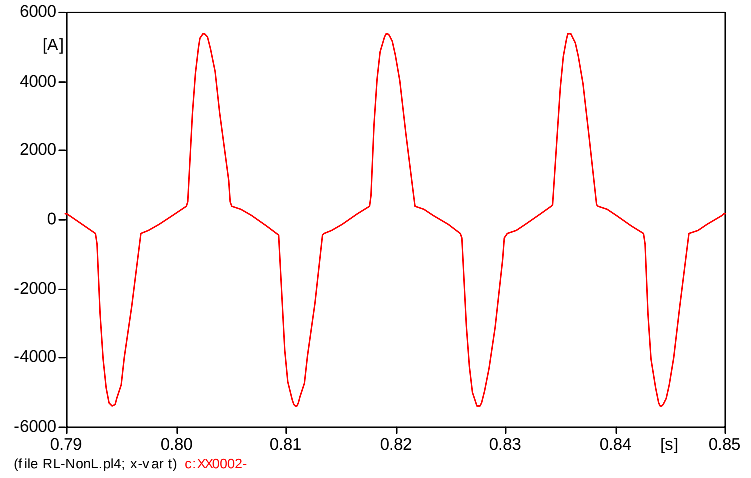


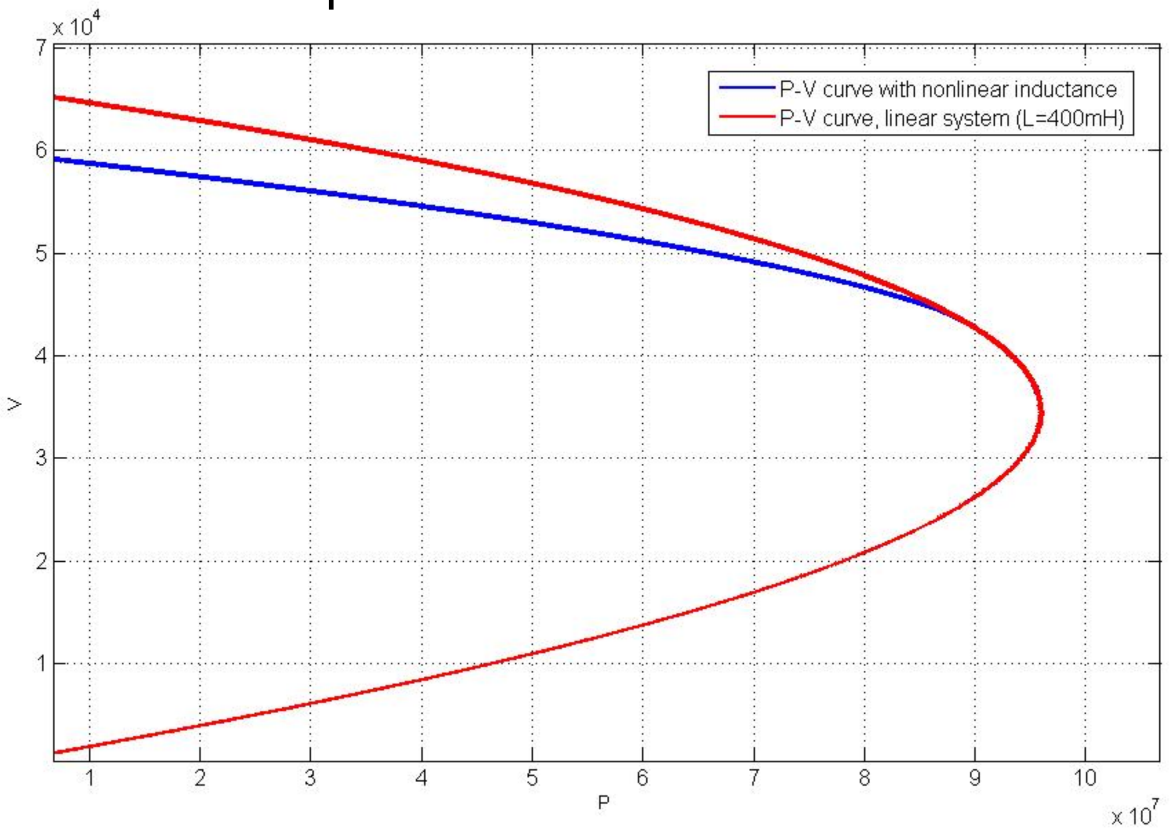
Phasor Angle Estimation

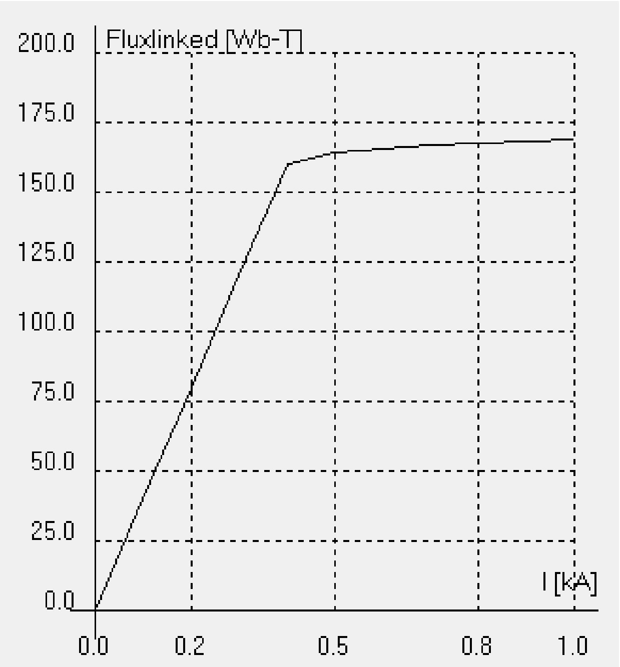
Applications of Time-Domain Analysis

❑ Nonlinear Component in Power System

- Nonlinear inductance (Saturable Transformer)
- Observe saturation effects
- Effect on voltage stability
- Compare PV curves.



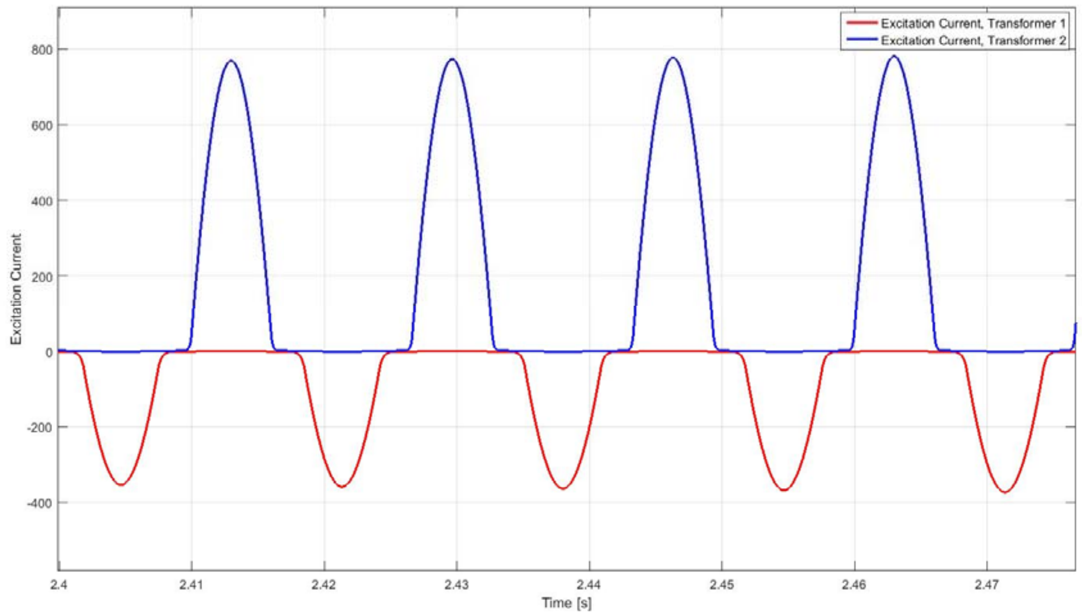




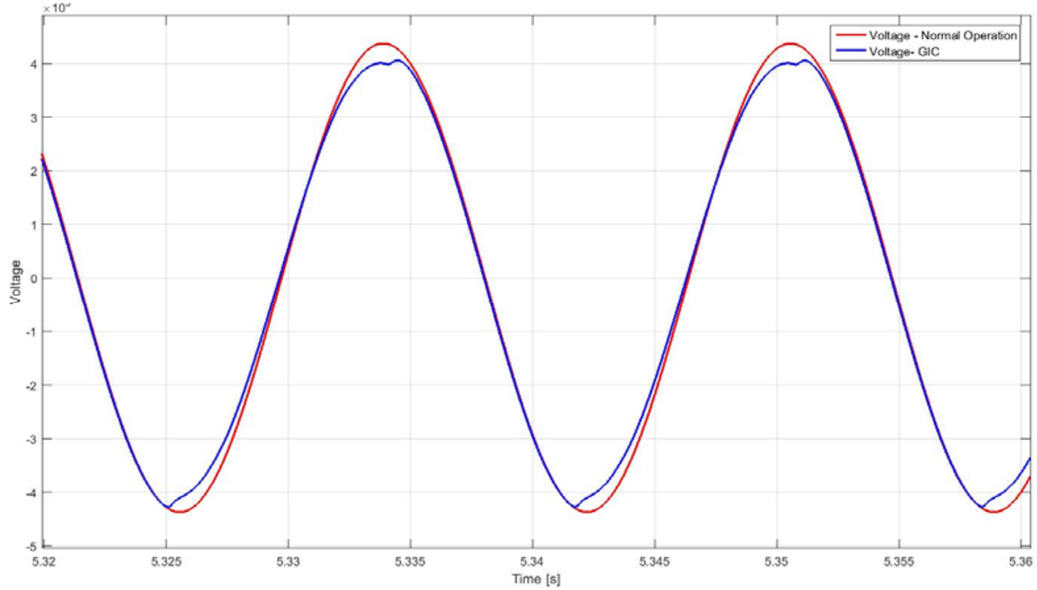
Applications of Time-Domain Analysis

❑ Geomagnetice Induced Current (GIC)

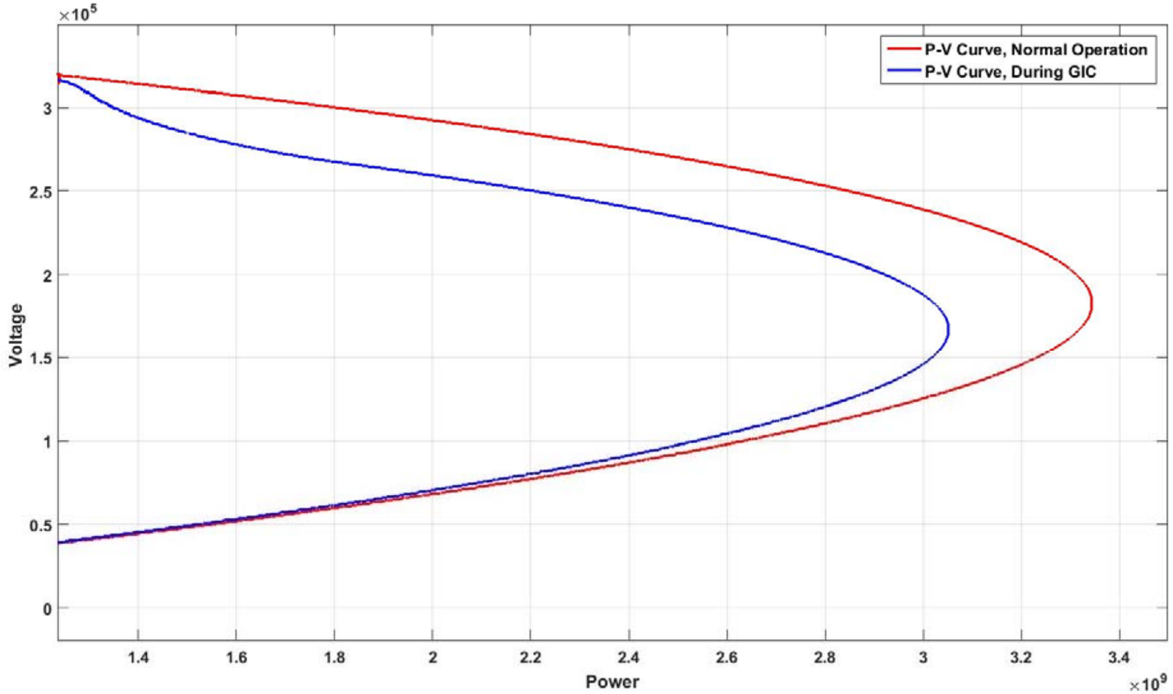
- Voltage Gradients of 3-6 Volts/Km
- DC Voltage at transformer neutrals
- Severe offset and continuous saturation on transformers
- Half-cycle saturated excitation currents
- Transmission line between Bus 1 and Bus 2: 400 Km
- 4 Volts/Km voltage gradient



Transformers excitation currents



Voltage during normal operation and GIC

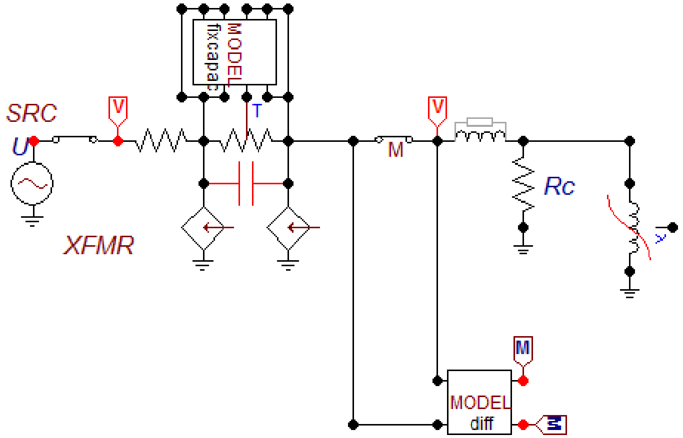


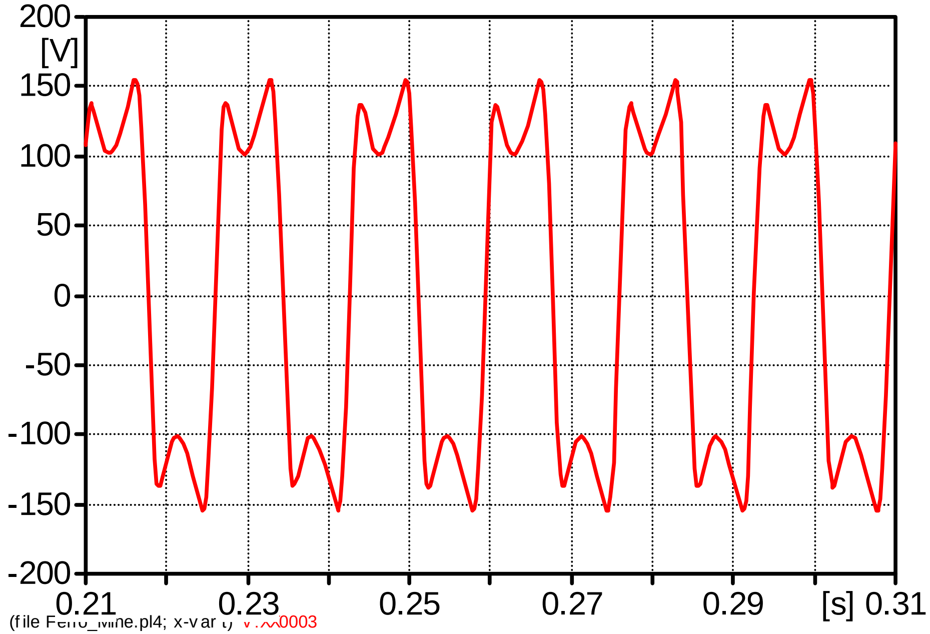
P-V during normal operation and GIC

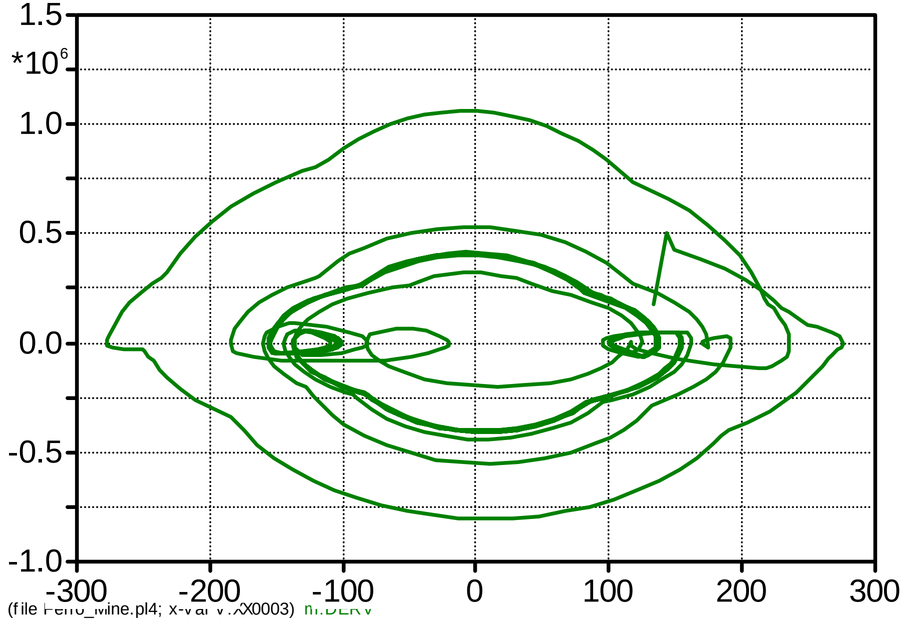
Applications of Time-Domain Analysis

❑ Ferroresonance

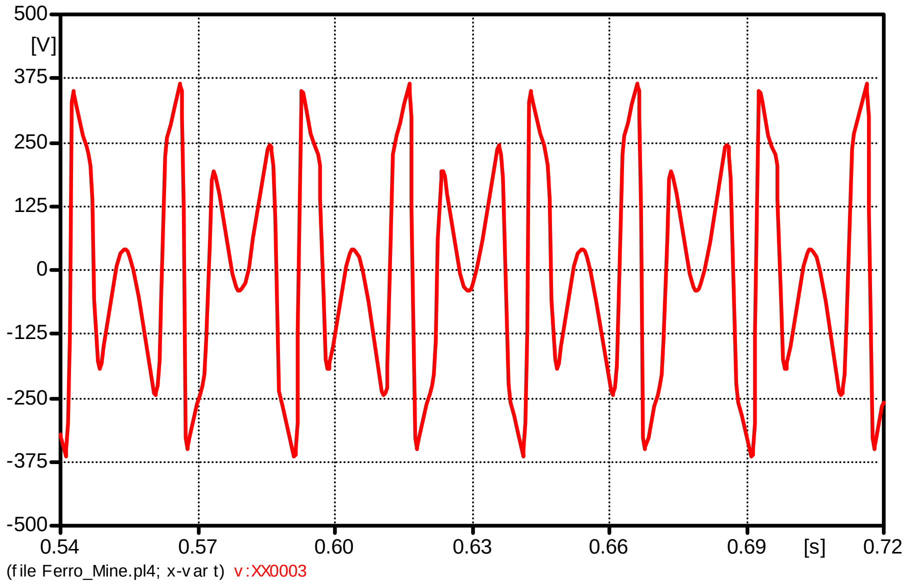
- Oscillating phenomena occurring in a power system which contains a nonlinear saturable transformer and series capacitance.
- Ferroresonance especially occurs when the circuit is subjected to a transient disturbance such as switching.
- voltage and current jump between different stable operating states.
- Ferroresonance characteristics depend on several parameters:
  - Initial conditions of the capacitance and transformer magnetizing inductor
  - Voltage magnitude and initial source phase angle
  - Total loss of the system.

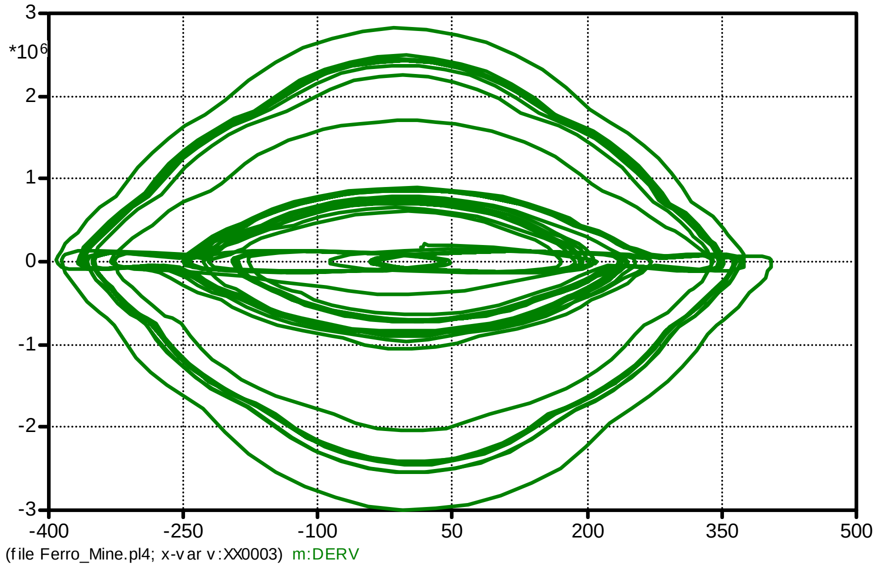






Fundamental mode ferroresonance





Sub-harmonic mode ferroresonance

Thank You