Transient Stability Model of a Series Capacitor Metal Oxide Varistor (SCMOV)

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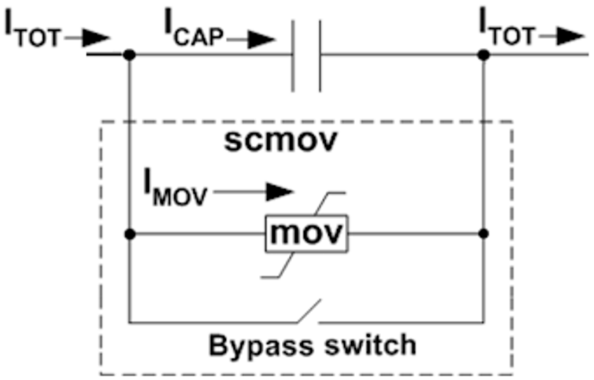
Reference for SCMOV Model

- SCMOV stands for Series Capacitor Metal Oxide Varistor (MOV)
- This models combines a set of protection equipment for over-current protection on a series capacitor
  - MOV is a device with a highly nonlinear impedance
    - At small voltage differences, the MOV exhibits very high impedance
    - As the voltage difference increases the impedance of the MOV drops quickly
    - Placing an MOV in parallel with a Series Capacitor will protect the Series Cap
      - As current on Capacitor increase, voltage drop across series cap increase → The MOV in parallel will thus have its impedance drop which pushes more of the current to the MOV
  - A bypass switch is also coupled with this MOV/Cap pair so that if the current gets high enough the bypass switch will short out both the MOV and Cap thus protected both MOV and Capacitor

Goldsworthy Paper from 1987

- D. L. Goldsworthy, “A linearized model for MOV-protected series capacitors”, IEEE Transactions on Power Systems, Vol. PWRS-2, No. 4, November 1987
  - Describes a model that has transitions between 3 operating modes
    - NORMAL (Mode 0): use the Rcap + jXcap from the power flow case
    - CAP+MOV (Mode 1): use a special Rpc + jXpc curve empirically determined and presented in the 1987 paper
    - BYPASS (Mode 2): Assume the bypass switch has operated and treat as a near zero impedance



Mode 0 (NORMAL)	I_{TOT}	$R_{cap} + jX_{cap}$
Mode 1 (CAP+MOV)	I_{TOT}	$R_{pc} + jX_{pc}$
Mode 2 (BYPASS)	I_{TOT}	$0 + j0.00001$

Empirically Derived Impedance

- When the MOV is conducting the Goldworthy 1987 paper found that the equivalent impedance of the CAP+MOV was consistently a multiple function of the nominal series Reactance we will call Xcap (Figure 6 in the paper on page 956)
- The paper empirically curve fits this function as follows

$$I_{pux} = \frac{I_{totAmps}}{I_{cappro} I_{crated}}$$

Restrict Ipux to between 0.94879 and 17.5684
to prevent MultR and MultX from being negative values

$$MultR(I_{pux}) = 0.0745 + 0.49e^{-0.243*I_{pux}} - 35.0e^{-5.0*I_{pux}} - 0.60e^{-1.4*I_{pux}}$$

$$MultX(I_{pux}) = 0.1010 - 0.005749 * I_{pux} + 2.088e^{-0.8566*I_{pux}}$$

Figure 6 from Goldsworthy 1987 Paper

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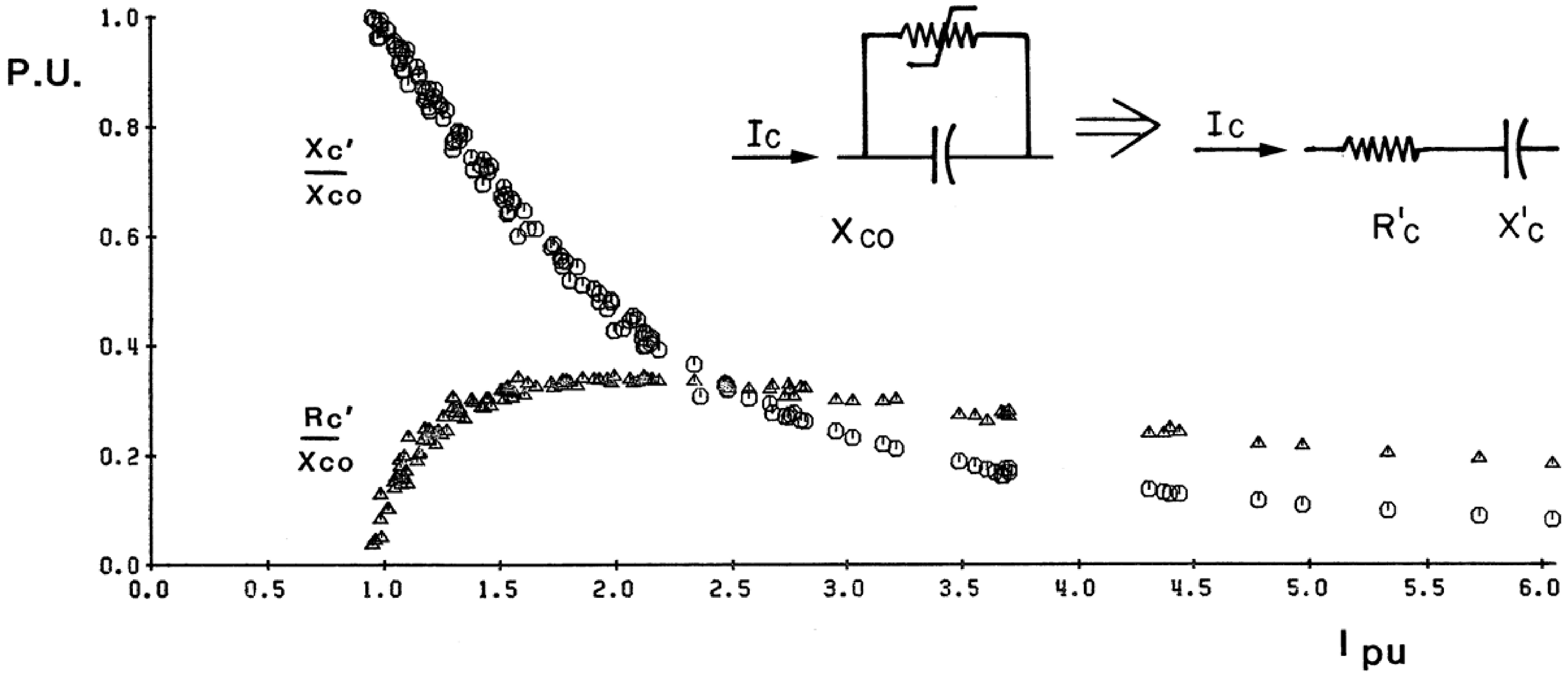
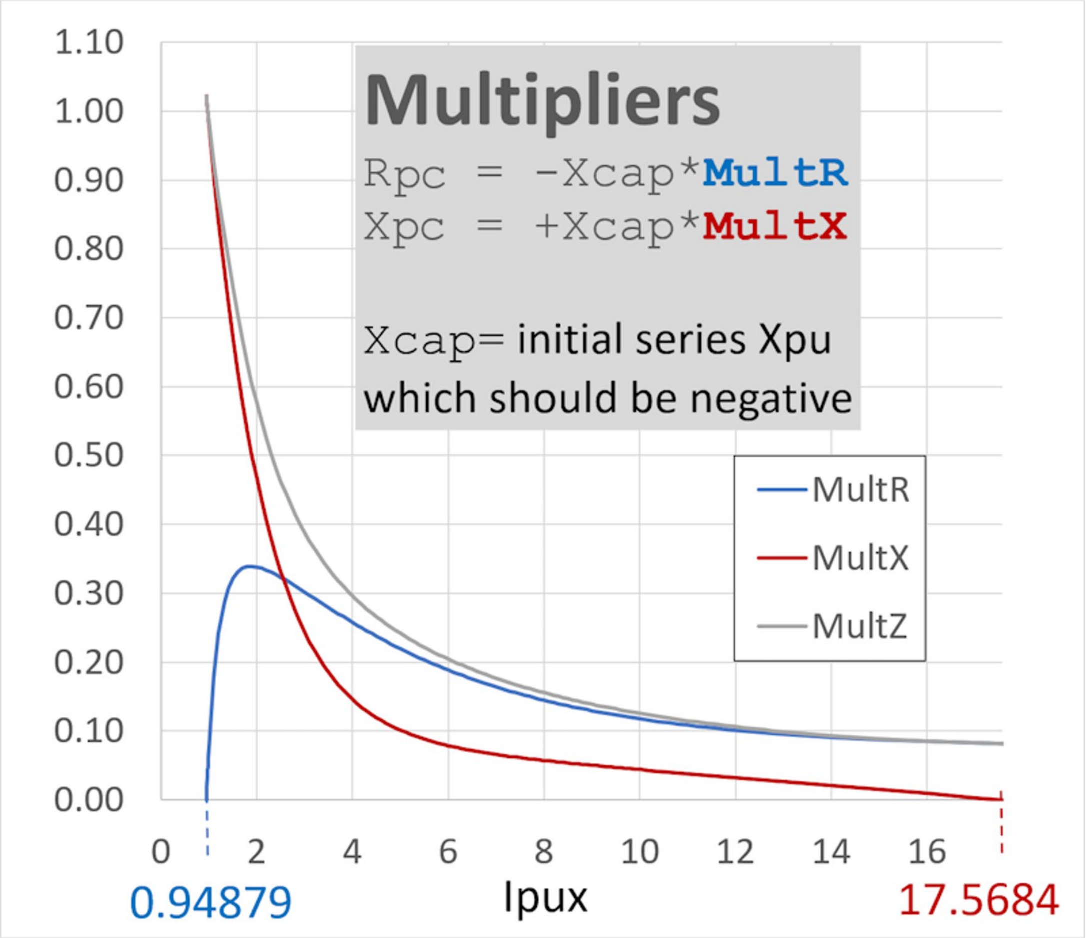


Figure 6. Normalized equivalent reactance and resistance vs. normalized current.

Graph of Multipliers

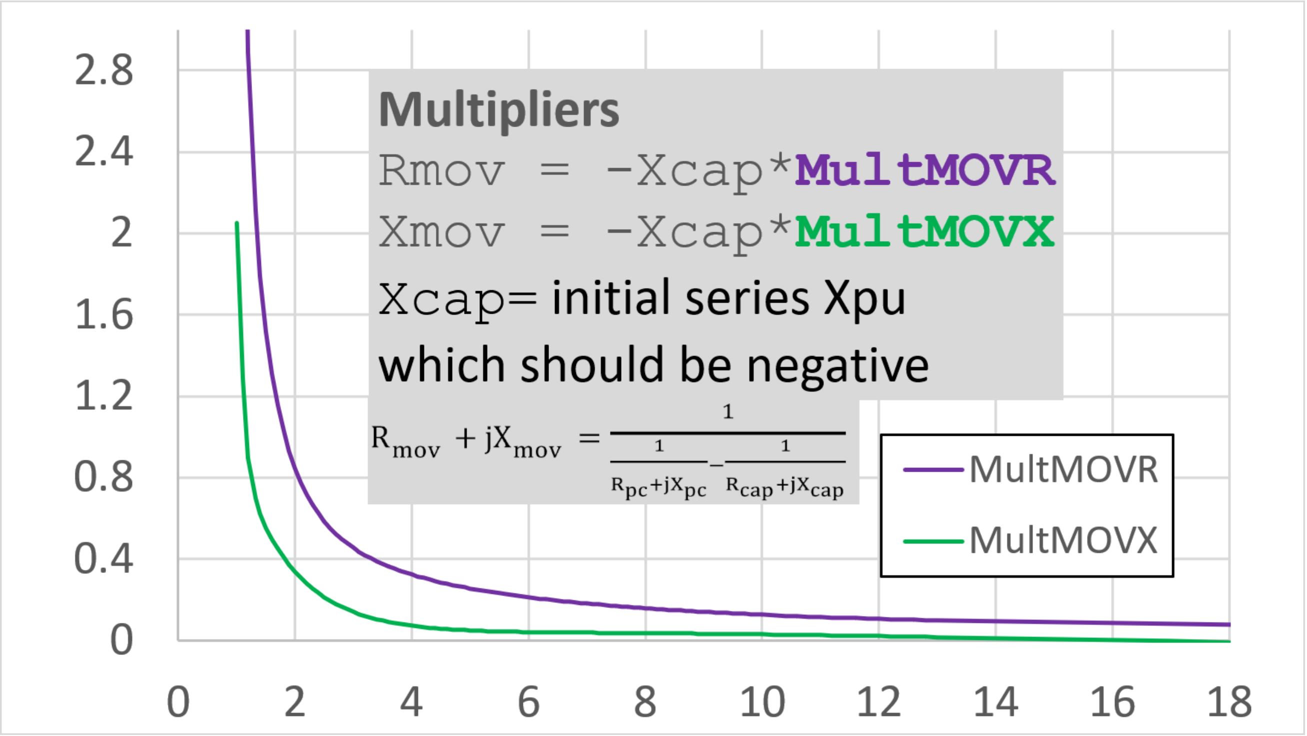
- Notice at about 0.94879
  - MultR = 0.000
  - MultX = slightly bigger than 1.000
    - (MultX = 1.000 at 0.97648)
- When calculating multipliers, we restrict Ipux to between 0.94879 and 17.5684
  - The empirical data is in Figure 6 of the paper only has data from 0.95 to 6.00
  - Negative multipliers do not make sense, so restrict the range to prevent them



Graph of the Rmov + jXmov

- Previous Graph was for Equivalent Impedance of the CAP+MOV
  - We can calculate the MOV impedance using equation
- Near value of Ipux = 0.94879 the impedance goes towards infinite
- As Ipux increases the impedance gets smaller and smaller
  - Eventually the SCMOV model will bypass it

$$R_{mov} + jX_{mov} = \frac{1}{\frac{1}{R_{pc}+jX_{pc}} - \frac{1}{R_{cap}+jX_{cap}}}$$



Input Parameters

- Icrated
  - Current Base in Amps for the mode
- Icappro
  - Uused in Ipux calculation
- Ithresh
  - Value of Ipux at which we assume the MOV begins conducting
  - PowerWorld requires that Ithresh >= 0.94879
- All other values are used in transitions between the 3 modes of operationing

Icrated	Capacitor Rated current in Amps
Icappro	Capacitor protective level current, pu on Icrated base
Ithresh	Threshold value for MOV activation. Any value smaller than 0.94879 will be ignored and treated as equal to 0.94879.
Enerlim	MOV energy limit in Mjoules
Enerdly	Bypass delay associated with Enerlim in seconds
Imovlim	MOV current limit in pu of Icrated
Imovdly	Bypass delay associated with Imovlim in seconds
Icaplim	Capacitor current limit in pu of Icrated
Icapdly	Bypass delay associated with Icaplim in seconds
Iinsert	Insertion current in pu of Icrated
Tinsert	Insertion time in seconds

NORMAL (Mode 0)

- The original Rpu and Xpu of the series capacitor is used
- Currents used in reporting and mode transitions
  - Itot = magnitude of current through the branch
  - Icap = Itot
  - Imov = 0

CAP+MOV (Mode 1)

- The Rpc + jXpc is calculated (see earlier multipliers)
- Also, while operating in this mode, the energy absorbed by the MOV is calculated by using the resistance of the equivalent impedance Rpc + jXpc and the Rcap+jXcap

$$R_{mov} + jX_{mov} = \frac{1}{\frac{1}{R_{pc}+jX_{pc}} - \frac{1}{R_{cap}+jX_{cap}}}$$

- The power absorbed over a time step is the resistive loss calculated as

  MegaWattMOV = (Rmov*Imovpu*Imovpu)*SystemMVABase

- Energy absorbed by MOV is integrated by accumulating using the function

  EnergyMOV = EnergyMOV + MegaWattMOV * TimeStep

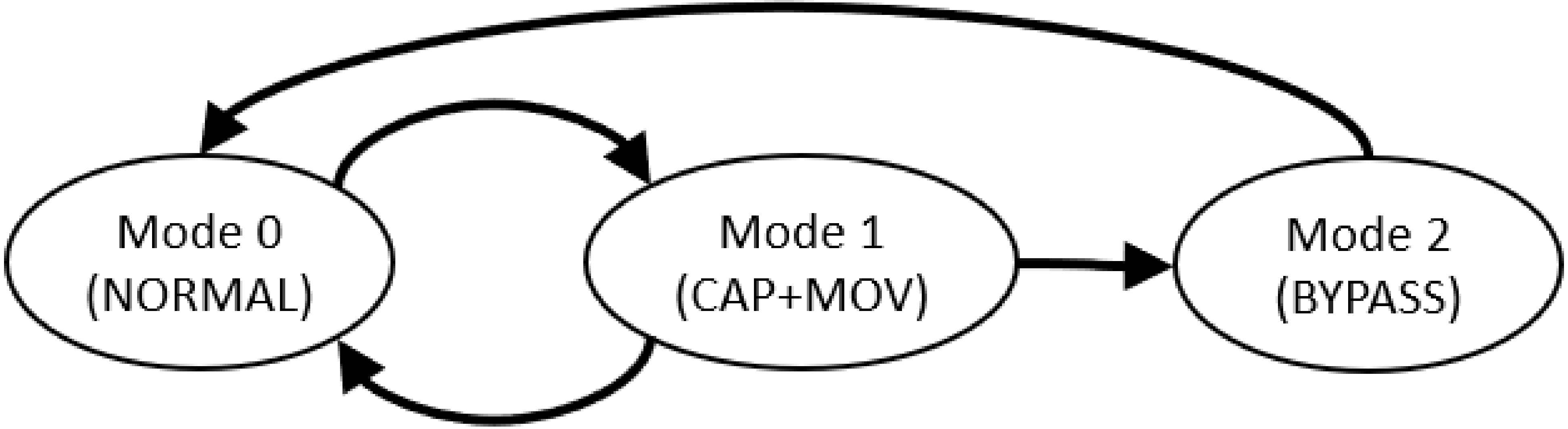
- Currents used in reporting and mode transitions
  - Itot = magnitude of current through the branch
  - Icap = current calculated from terminal voltage and original Rcap + jXcap
  - Imov = magnitude of complex current calculation (Itot – Icap)

BYPASS (Mode 2)

- When a decision to bypass the capacitor and the MOV, then the impedance is replaced by the very small impedance 0.0000001 + j0.00001
- Currents used in reporting and mode transitions
    - Itot = magnitude of current through the branch
    - Icap = 0
    - Imov = 0

Mode Transitions

- Direct transition from NORMAL to BYPASS is not allowed
- Direct transition from BYPASS to CAP+MOV is not allowed



Mode Transition
NORMAL (Mode 0) to CAP+MOV (Mode 1)

- When in Mode 0 (NORMAL), at the end of each time step of the simulation if the following condition is met then the device will switch to Mode 1 (CAP+MOV)
- Ipux > Ithresh , where Ipux = ItotAmp/(Icappro*Icrated) .
    - Note that the current base for getting Ipux in per unit is different than the per unit for comparisons to Icaplim and Imovlim described later because the multiplier Icappro is used with Ipux.

Mode Transition
CAP+MOV (Mode 1) to NORMAL (Mode 0)

- When in Mode 1 (CAP+MOV), at the end of each time step, if Ipux <= Ithresh then the device transitions to Mode 0 (NORMAL) at next time step.

Mode Transition
CAP+MOV (Mode 1) to BYPASS (Mode 2)

- When in Mode 1 (CAP+MOV), at the end of each time step, three different checks are done to determine if a transition to Mode 2 (BYPASS) is made.
  - Enerlim If the accumulated energy absorbed by the MOV stored in EnergyMOV exceeds the MOV energy limit Enerlim for more than Enerdly seconds, then the device will bypass. Ignore if Enerlim = 0.
  - Imovlim: If the current passing through the MOV exceeds Imovlim, the capacitor and MOV are bypassed after a delay of Imovdly seconds. Ignore If Imovlim = 0.
  - Icaplim: If the current passing through the capacitor exceeds Icaplim, the capacitor and MOV are bypassed after a delay of Icapdly seconds. Ignore if Icaplim = 0.

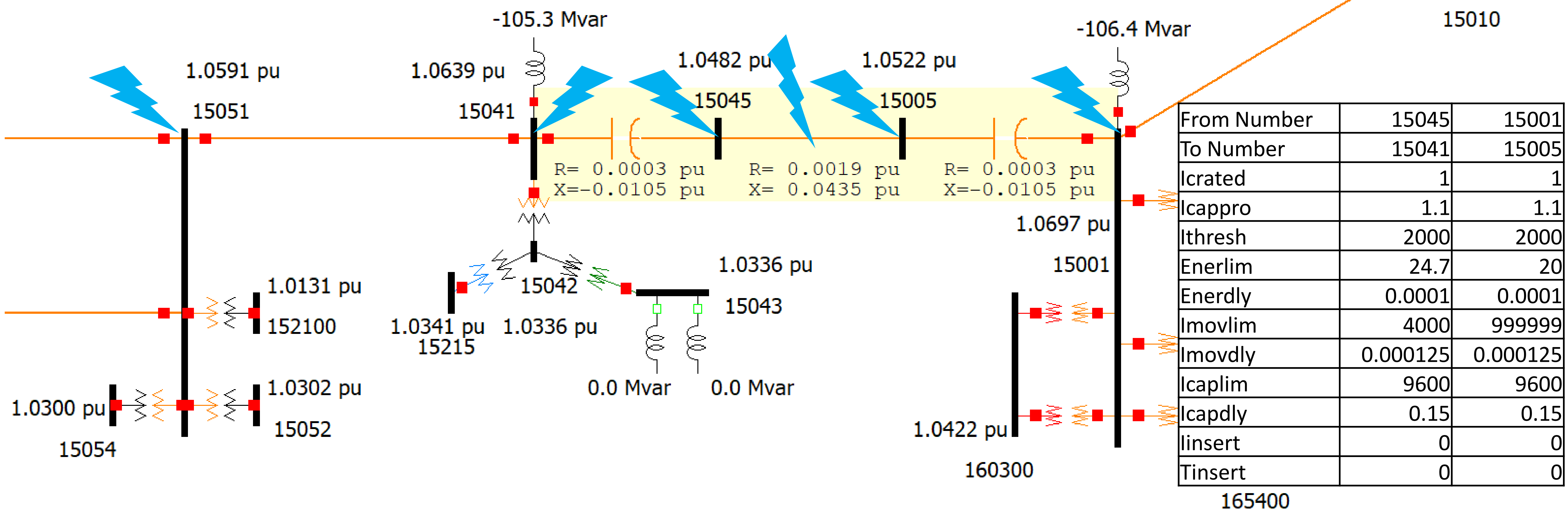
Mode Transition

BYPASS (Mode 2) to NORMAL (Mode 0)

- When in Mode 2 (BYPASS), the model allows for reinsertion of the device if the bypass decision was made due to the Imovlim or the Icaplim. Reinsertion will occur if all other bypass conditions are not met and the current is below the Iinsert for Tinsert seconds.
- When this transition occurs the Enerdly timer for Enerlim is reset and will start counting again
- If the device was set to BYPASS due to the EnerLim, then the device will not reinsert the capacitor and MOV.
  - One exception to this is if another stability model or a user event has intentionally removed the Bypass, then this transition will reset the EnergyMOV = 0 and reset the Enerdly timer.
  - *** Should we do this? We will discuss this at the end of this presentation***

Large System Example from WECC

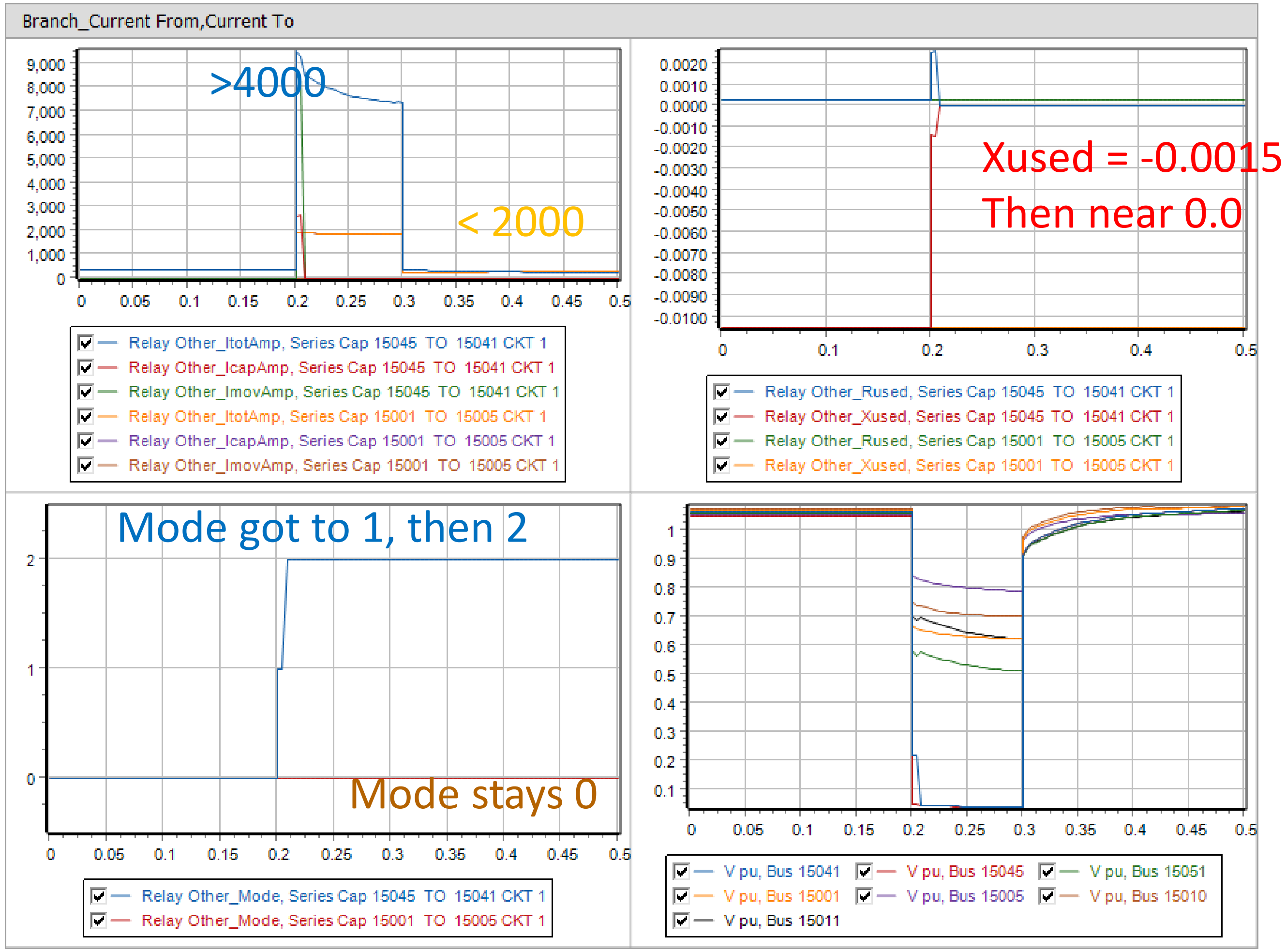
- Series caps on either end of branch from 15045 to 15005
- Study fault at the 7 lightning bolt locations



From Number	15045	15001
To Number	15041	15005
Icrated	1	1
Icappro	1.1	1.1
Ithresh	2000	2000
Enerlim	24.7	20
Enerdly	0.0001	0.0001
Imovlim	4000	999999
Imovdly	0.000125	0.000125
Icaplim	9600	9600
Icapdly	0.15	0.15
Iinsert	0	0
Tinsert	0	0

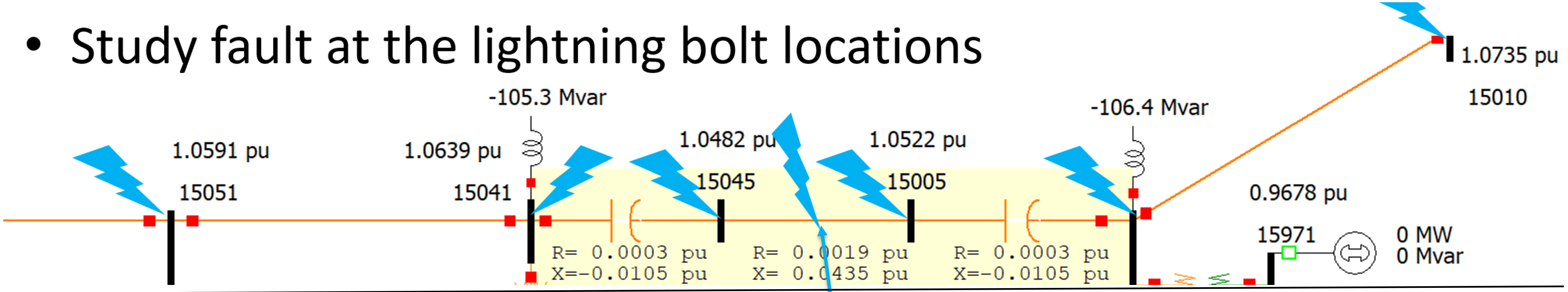
Example Simulation Result for Fault at 15045 (Line side terminal of Series Capacitor)

- Fault At Bus 15045
- 15045 – 15041
  - Current goes to above 9000 Amps
  - Mode = 1 (CAP+MOV)
  - Current is > Imovlim (4000
  - Go to Mode = 2 (BYPASS) quickly
- 15001 – 15005
  - Current stays below 2000 Amps
  - Mode = 0 (NORMAL) entire time



Used Input Parameters from Utility

- Study fault at the lightning bolt locations



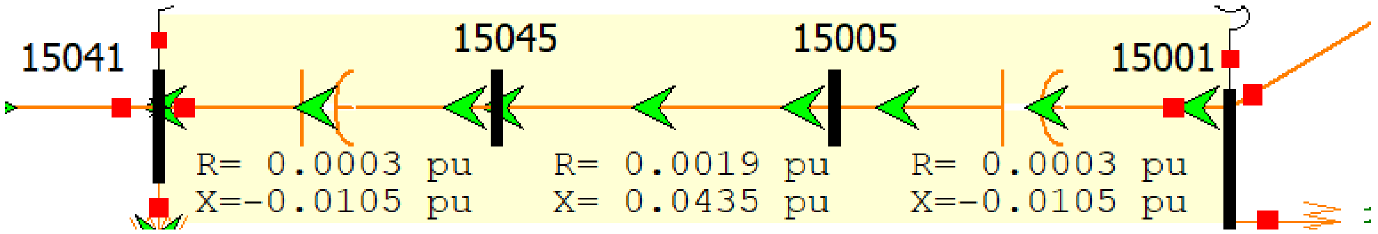
15051	15041	15045	15005	15001	15010
None	-19% (-0.0085)	-86% (-0.0015)	-78% (-0.0023)	-17% (-0.00875)	None
NORMAL	CAP+MOV/NORMAL	CAP+MOV/NORMAL	NORMAL/CAP+MOV	NORMAL/CAP+MOV	NORMAL
NORMAL	NORMAL/NORMAL	BYPASS/NORMAL	NORMAL/BYPASS	NORMAL/NORMAL	NORMAL

Fault Location
Change in Series X
FaultMode for Left Cap/FaultMode for Right Cap
Post Fault Mode for Left Cap/Post Fault Mode for Right Cap

15045-15005 50% of branch
-38% (-0.0065)
CAP+MOV/CAP+MOV
BYPASS/BYPASS

Summary

- Faulting anywhere except directly at terminals (15054 or 15010)
  - The SCMOV does ***nothing***
- Faulting the system-side of the series caps (15041 or 15001)



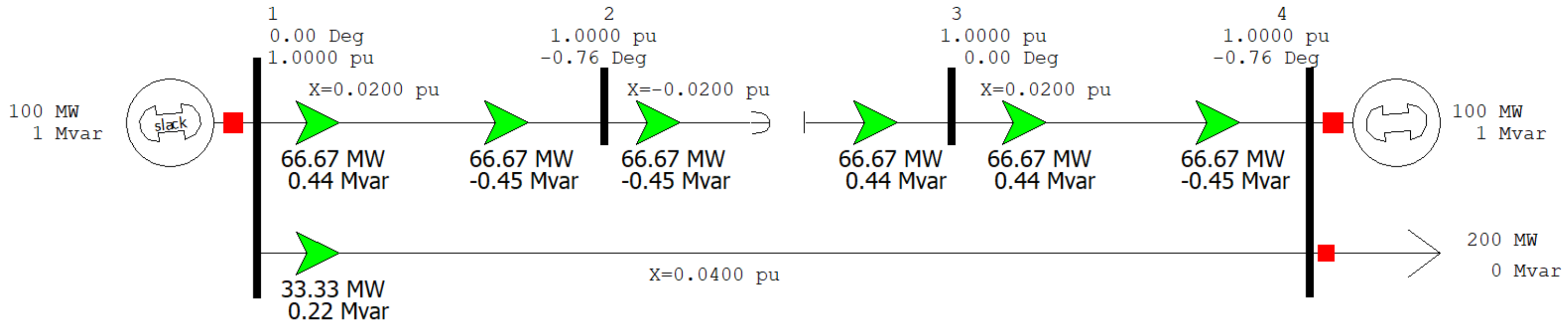
  - Small (about 20%) impedance drop during the fault, immediately recovers after clearing
  - Only adjacent series cap responds, the other cap does not respond
  - This is close to having nothing happen
- Faulting the line-side of the series caps (15045 or 15005)
  - Large (about 80%) impedance drop on fault and then very quickly a bypass of device
  - Only adjacent series cap responds, the other cap does not respond
- Faulting in the middle of the branch from 15045 to 15005)
  - Medium (about 40%) impedance drop on fault and then very quickly a bypass of device
  - BOTH series cap respond this way

What did we learn from this example?

- SCMOV only responded to faults inside the network bounded by these example series capacitors
  - Properly functioning relays would *trip all these devices for these faults*
- This SCMOV is primarily important for a very specific study
  - Faults on the line-side of the series caps
  - Even then, if we assume the devices trip it will only change the behavior during the fault time, unless we assume *primary protection fails*
- This is a very localized and specific study

Small Test Example Simulation

- Following sample system has all 230 kV buses. All resistances are 0.0. Other information needed for network model is in picture.



- The Series Cap from bus 2-3 has the SCMOV parameters below. A constant impedance model is used for the load at bus 4.

Dynamic Model Parameters for Test System

- Generator MVABase for both generators is 500 MVA and the following GENROU Machine, ESAC1A Exciter and TGOV1 Governor models and parameters.

GENROU

H	3
D	0
Ra	0
Xd	2.1
Xq	0.5
Xdp	0.2
Xqp	0.5
Xdpp	0.18
Xl	0.15
Tdop	7
Tqop	0.75
Tdopp	0.04
Tqopp	0.05
S1	0
S12	0
RComp	0
XComp	0

ESAC1A

Tr	0
Tb	0
Tc	0
Ka	200
Ta	0.02
VaMax	7.5
VaMin	-7.5
Te	0.8
Kf	0.03
Tf	1
Kc	0.2
Kd	0.38
Ke	1
E1	3
SE1	0.03
E2	4
SE2	0.1
Vrmax	14
Vrmin	-14
Spdmlt	0

TGOV1

Trate	0
R	0.05
T1	0.5
Vmax	1
Vmin	0
T2	2.5
T3	7.5
Dt	0

SCMOV

Icrated	1000
Icappro	1
Ithresh	0.98
Deaccel	0.1
Enerlim	100
Enerdly	1
Imovlim	2
Imovdly	1
Icaplim	1.1
Icapdly	0.8
Operdly	0
Iinsert	0.3
Tinsert	2

Imovlim*Icrated = 2000 Amps

Icaplim*Icrated = 1100 Amps

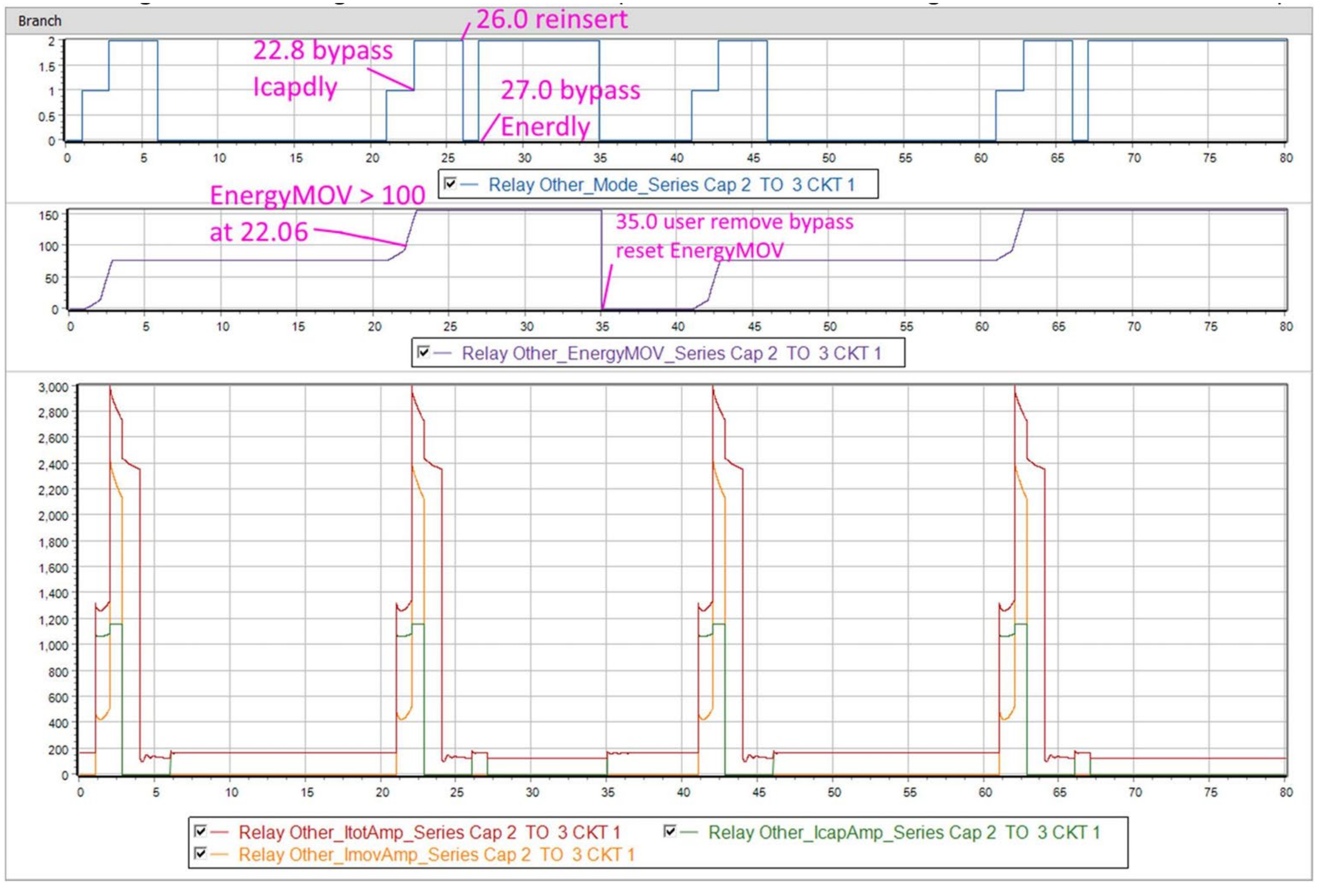
Iinsert*Icrated = 300 Amps

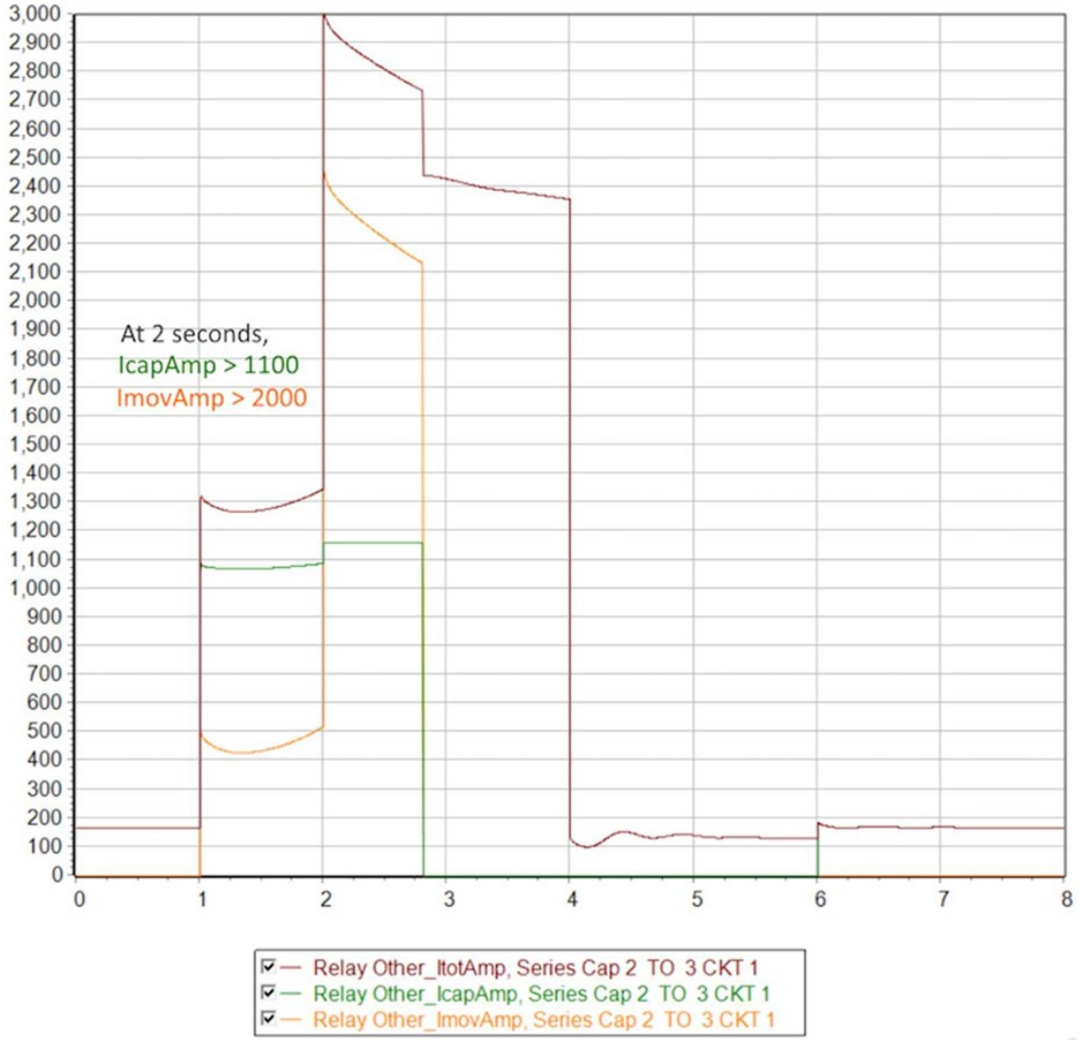
Example Simulation Run

- A Simulation is run that applies a fault at Bus 3 with fault impedance 0.1 per unit at 1.00 second. Fault impedance is changed to 0.02 at 2.00 seconds. Fault is cleared at 4.00 seconds. This sequence 3 events is then repeated at 20, 40, and 60 seconds. Finally, a user entered removal of the bypass is added at 35 seconds.

Time	Object	Action
1.0	Bus 3	FAULT 3PB IMP 0 0.1
2.0	Bus 3	FAULT 3PB IMP 0 0.02
4.0	Bus 3	CLEARFAULT
21.0	Bus 3	FAULT 3PB IMP 0 0.1
22.0	Bus 3	FAULT 3PB IMP 0 0.02
24.0	Bus 3	CLEARFAULT
35.0	Branch 2 3 1	NOTBYPASS
41.0	Bus 3	FAULT 3PB IMP 0 0.1
42.0	Bus 3	FAULT 3PB IMP 0 0.02
44.0	Bus 3	CLEARFAULT
61.0	Bus 3	FAULT 3PB IMP 0 0.1
62.0	Bus 3	FAULT 3PB IMP 0 0.02
64.0	Bus 3	CLEARFAULT

Example Simulation Results





Description of the First 35 seconds

- Simulation Start
  - At 1.0 seconds the fault is applied and the current immediately exceed the Ithresh value and we transition to CAP+MOV mode, but we do NOT exceed any of the values that would cause bypassing.
  - At 2.0 second the fault impedance decreases causing currents to increase. Immediately the Imovlim and the Icaplim thresholds are exceeded and bypass events are scheduled with a delay of 0.8 and 1.0 seconds.
  - At 2.8 seconds, the series cap is bypassed due to the 0.8 second time delay for Icapdly.
  - At 3.0 seconds, the 2nd bypass event from Imovdly is ignored because bypassing has already occurred.
  - At 4.0 seconds the fault clears and the total EnergyMOV accumulated by that point is 78 MJ which is not enough to cause a permanent bypass
  - At 4.0 seconds, the ItotAmp drops below Iinsert and the timer for Tinsert starts
  - At 6.0 seconds the Tinsert timer expires and the series cap is reinserted
- This sequence of events is then repeated at time 21 seconds, however this time the EnergyMOV has continued to accumulate and will change the response
  - At 22.06 seconds the EnergyMOV > Enerlim value and if it stayed there until 23.06 seconds it would have done a permanent bypass, however the model bypasses before this at 22.8 seconds due to the Icapdly again.
  - At 24.0 seconds the Tinsert timer starts again and the device is inserted at 26.0 second
  - At 26.0 seconds the EnergyMOV>Enerlim still so the Enerdlg timer starts
  - At 27.0 seconds the Enerdly timer expires and a permanent bypass is done.

Now a model design question?

- Once EnergyMOV>Enerlim SCMOV bypasses the entire device
- The only way the bypass can be removed is if the user specifically tells the simulation to remove the bypass
- If the user chooses to remove the bypass, I suggest we should reset the EnergyMOV = 0.00 and reset the EnerDly timer