<Public>

Power Electronic Reconnecting and Ceasing Load Model

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NERC Load Modeling Task Force Webinar

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First a Bit of Load Model History

< 1990

- 1990s and before
  - Interconnect-wide transient stability runs exclusively use algebraic functions of voltage and frequency for load models (IEEL, WSCC model)

$$P = P_{load}\left(a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}\right)\left(1 + a_7 \Delta f\right)$$

$$Q = Q_{load}\left(a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}\right)\left(1 + a_8 \Delta f\right)$$

  - Software tools had 3-phase induction motor models, but they were not typically used in large interconnection wide simulations

1996

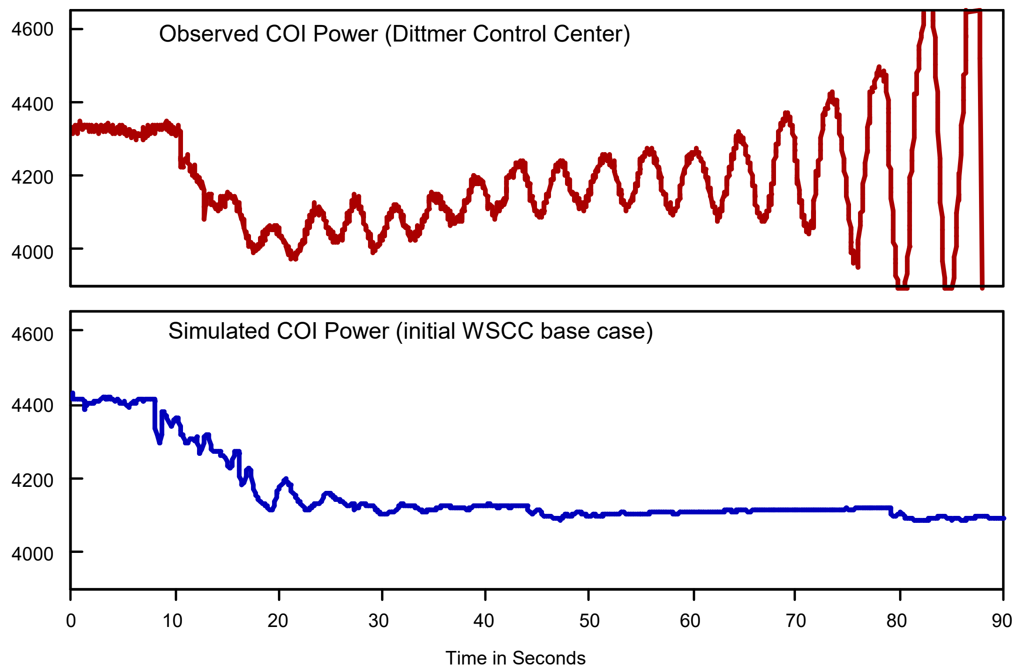
- 1996 – 1997 Blackouts in the Western Interconnect
  - Software simulations of the events leading up to the blackout did not show the same instability that occurred in the real event
  - One of the reasons for this deficiency was there were not any dynamics associated with loads
    - WECC added an “interim load model” named MOTORW from about 2000 until 2015 which treated a fractional part of the load as a single-cage induction motor

1996 Blackout Example Oscillations

- The below graph shows an oscillation that was observed during a 1996 WECC Blackout

Measurements → Unstable

Simulation → Stable



Journey to the Composite Load Model

1997-2012

- WECC utilities spent 15 years researching an appropriate new load model
  - BPA, PNNL, LBNL, Sandia, and other National Labs (I wasn't around, but others could speak to this work)
- WECC switched to using the CMPLDW model for interconnection wide studies in approximately 2015
  - Fractional 3-phase induction motor model included (with built in tripping and reconnection)
  - Fractional 1-phase induction motor model (performance model LD1PAC)
  - Fractional Electronic Load Model (LDELEC)
  - Fractional Algebraic function of Voltage and Frequency (IEEL)
  - Included an equivalent model of the distribution system

2015-2020

- Utilities within WECC work through the appropriate use of the CMPLDW model in interconnection wide models
  - Ongoing process
  - Nearly all WECC-wide transient simulation use CMPLDW

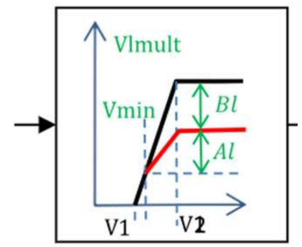
2025

- Eastern Inteconnection and ERCOT presently are in the 5-year "adoption period"

EPRI Work on modeling Electronic Load Models

2012

- LDELEC – This is in the composite load model now
  - A multiplier on a constant power
  - Frcel says what fraction reconnects
  - No concept of the timing of ceasing and reconnecting



$$Vrfrac = \frac{Al}{Al + Bl}$$

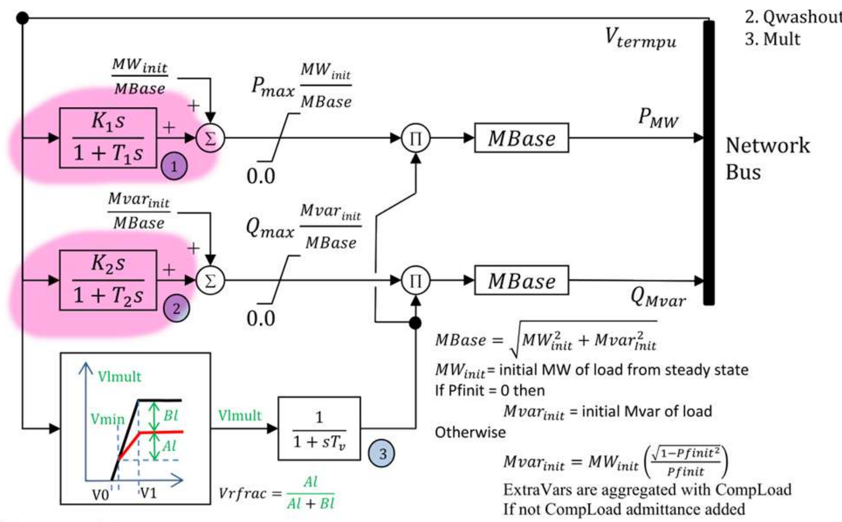
2019

- LDFVD_A – this was a Variable Frequency Drive model introduced by EPRI several years ago.
  - Same fractional voltage cease/reconnect as LDELEC
  - Adds some derivative blocks for characteristics related to variable frequency drives

Simple VFD Model: LDVFD_A
This model was never really adopted by industry

2019

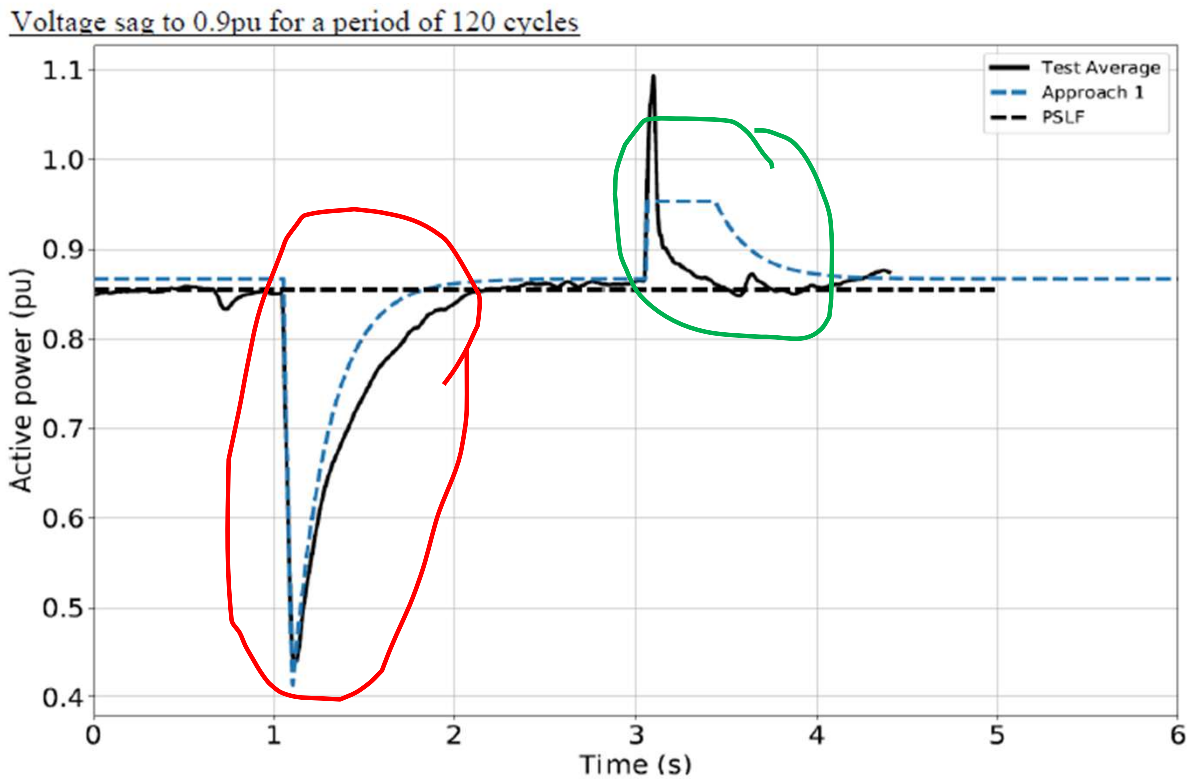
- https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20LDVFD_A.htm
- Derivative blocks come from original work EPRI did with a simple Variable Frequency Drive (VFD) models
  - The mechanical/energy system for VFD reduced power at fault inception, but then recovers some of the energy lost when the voltage recovers
- MW or Mvar vary with the derivative of the terminal voltage
  - Set Kvp=0 or Kvq=0 to disable this
- At fault inception the voltage drops, the derivative will be negative
  - MW and Mvar will reduce temporarily for a voltage drop
- At fault clearing the voltage increases, the derivative will be positive
  - MW and Mvar will increase temporarily at clearing



EPRI Presentation from March 2019 – LDVFD_A

- Testing on some Variable Frequency Drives

Load Decreases temporarily after a Fault, then recovers back



Load Increases temporarily immediately after the Fault Clears, then recovers back

Think of it as "buying back" the energy it lost after fault

1-Phase Induction Motor "Phasor-based" model INDMOT1P or MOTORC

2008

- An alternative to the LD1PAC model
  - Models the flux dynamics of the motor explicitly
  - Allows stalling and reacceleration to be modeled explicitly
  - Research by Bernie Lesieutre while he was at Lawrence Berkeley National Lab doing work with Joe Eto (Bernie is now at University of Wisconsin) (2008 time frame)

2021

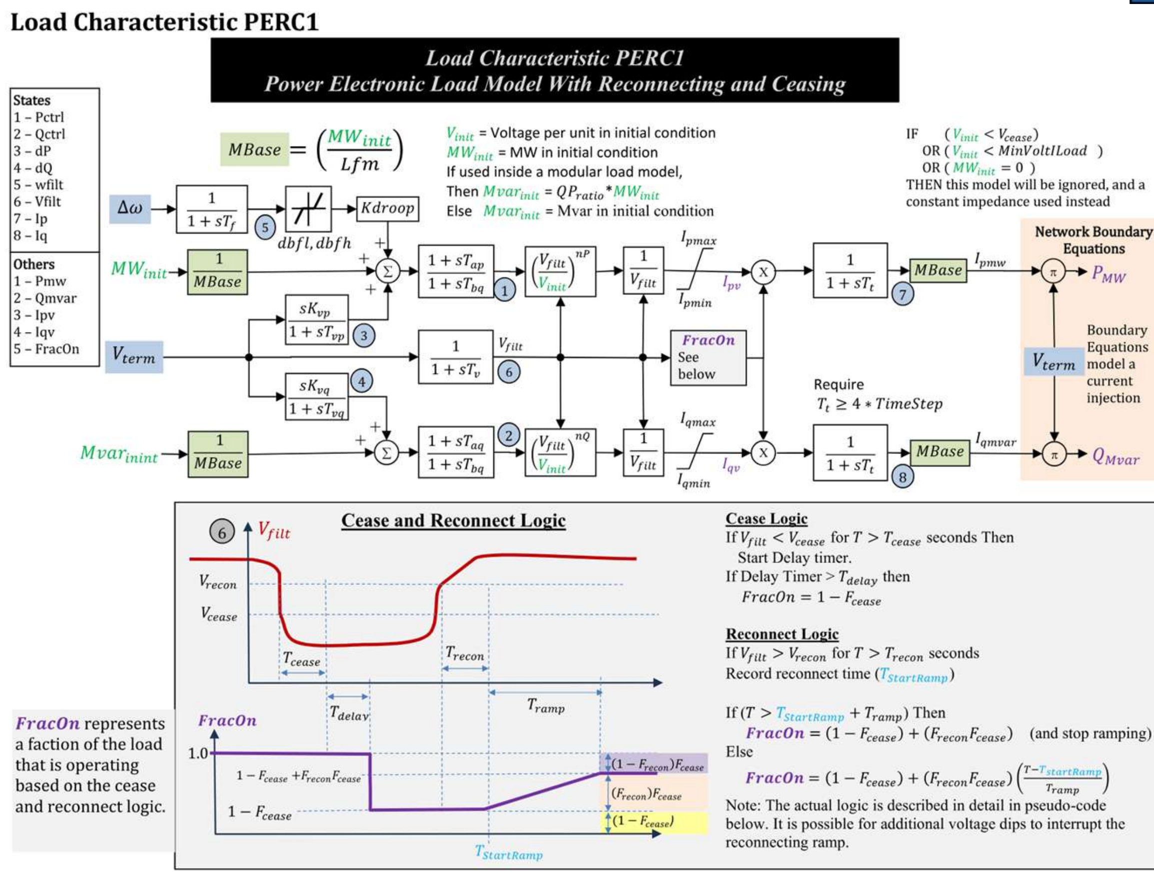
- Work done at PowerWorld with Joe Eto at LBNL fully documented the numerical implementation of this model
  - https://www.powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20INDMOT1P.htm

Power Electronic Reconnecting and Ceasing (PERC1)

https://powerworld.com/WebHelp/#TransientModels_HTML/Load%20Characteristic%20PERC1.htm

2022 EPRI introduces concept of Electric Vehicle Charger model"EV1"

2025 PERC1 is based on the EV1 model



Load Characteristic Model: PERC1

Model is under development, available in October 27, 2025 path of Version 24

PERC1 is an acronym for the **Power Electronic Reconnecting and Ceasing** load model. It is based on LDEV1 which was based on the model developed by EPRI summarized in the November 2022 report entitled

"A Positive Sequence Model for Aggregated Representation Electric Vehicle Chargers"

EPRI Project 1-116982

written by L. Sundaresh and P. Matra

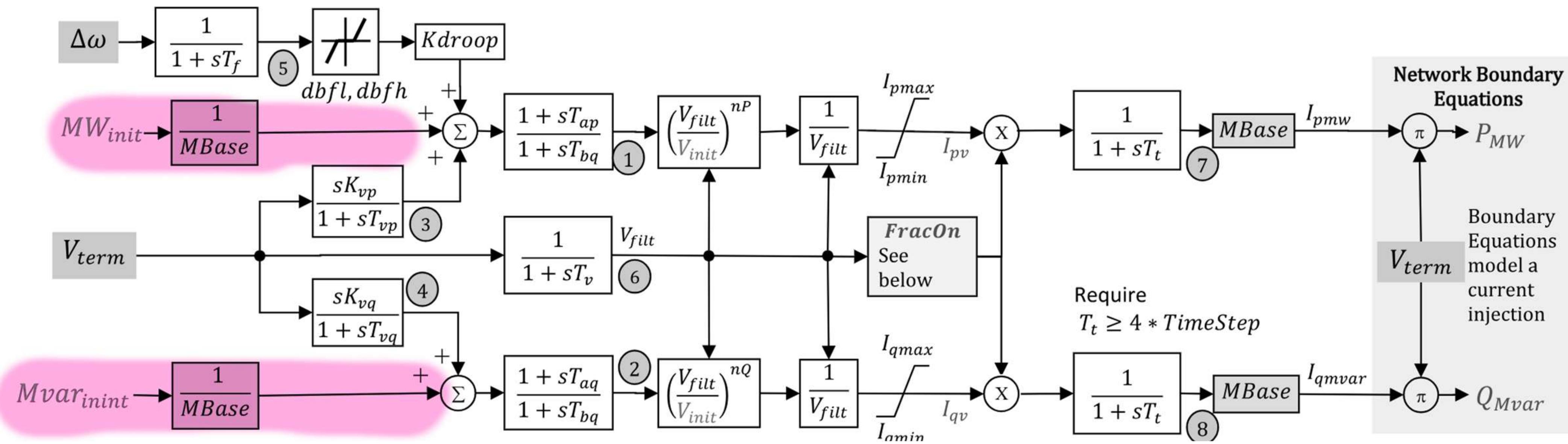
Power Electronic Ceasing and Reconnecting PERC1

- Model was originally developed by EPRI for use in Electric Vehicle Charging loads
  - It has been modified slightly to add a Frecon parameter (fraction that reconnects)
- Model is very generic
  - Power is an exponential function of voltage, and adds current limits
  - Derivative Blocks (same as LDVFD_A)
  - Frequency Droop with dead-band
  - Special Reconnecting and Ceasing timing logic
    - Timing will be useful in modeling behavior of Uninterruptible Power Supply in the context of computing loads such as Crypto mining, Data Centers, AI loads
- Goal is to represent how the load impacts the AC transmission system
  - Not representing all the details of the load itself

Initial Condition

- Under a minor disturbance where
  (1) frequency recovers back to 60 Hz
  (2) voltage recovers to the same per unit values
  (3) no permanent fractional tripping occurs

Model brings the MW and Mvar back to the same value as the initial condition



Temporarily reduced load at Fault Inception, Temporarily increased load at Fault Clearing

- Derivative blocks come from original work EPRI did with a simple Variable Frequency Drive (VFD) models
  - The mechanical/energy system for VFD reduced power at fault inception, but then recovers some of the energy lost when the voltage recovers
- MW or Mvar vary with the derivative of the terminal voltage
  - Set Kvp=0 or Kvq=0 to disable this
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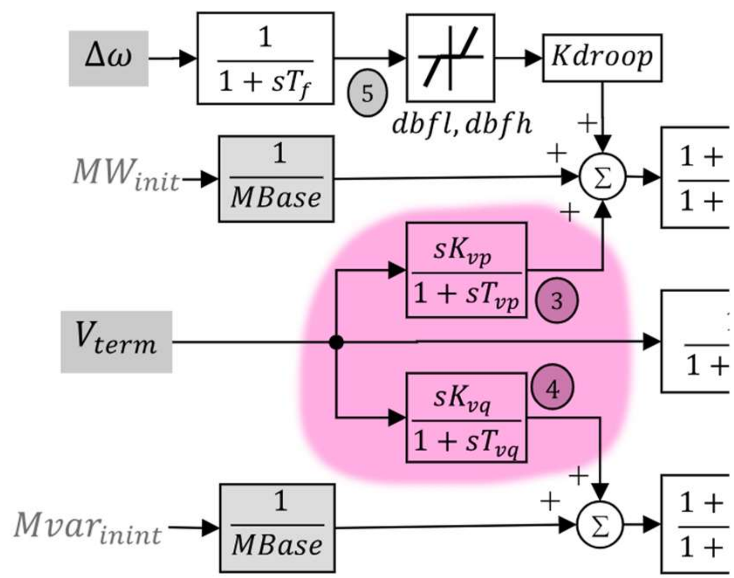
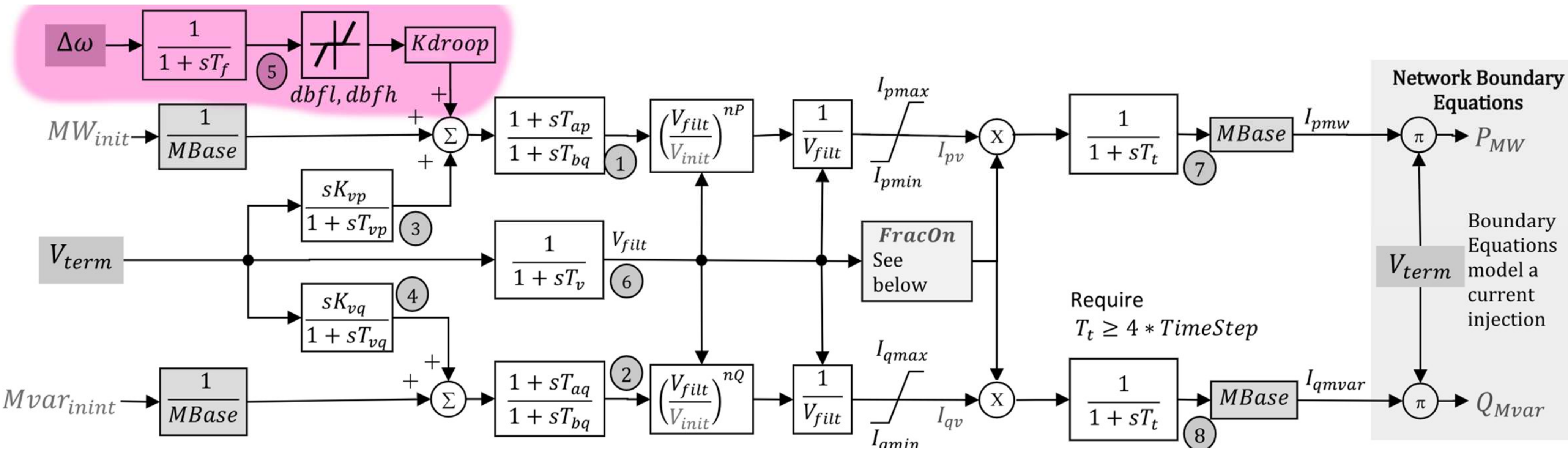


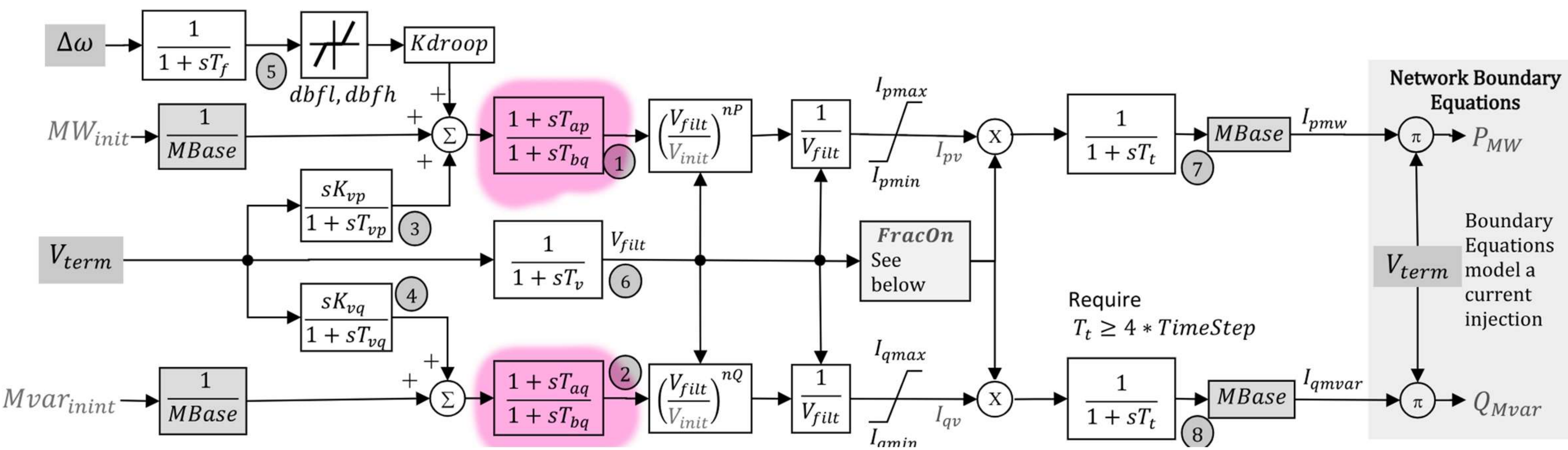
Real Power Frequency Droop

- Real power may respond with a Frequency Droop with deadband characteristic
  - As frequency increases, the load would increase
- Typical input data will not use this feature right now (Kdroop = 0)



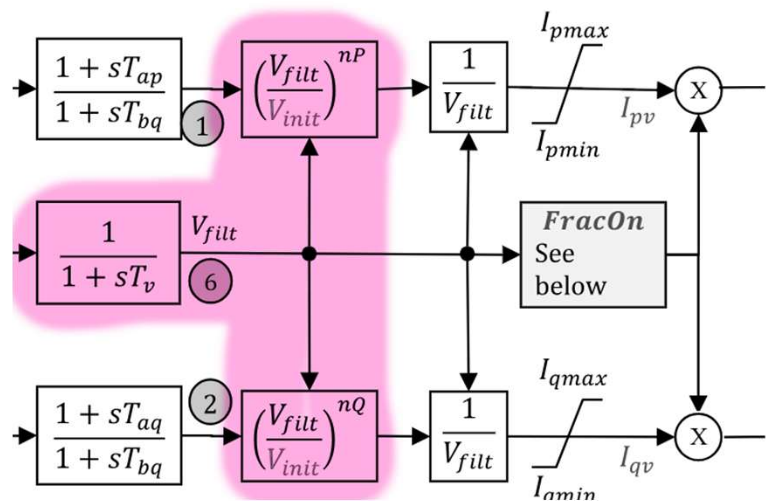
Dynamic Response

- Lead-Lag blocks added to allow modeling of some dynamic response
  - This is “future-proofing the model”
  - Typical input data will not use this feature right now (Tap=Tbp= 0)



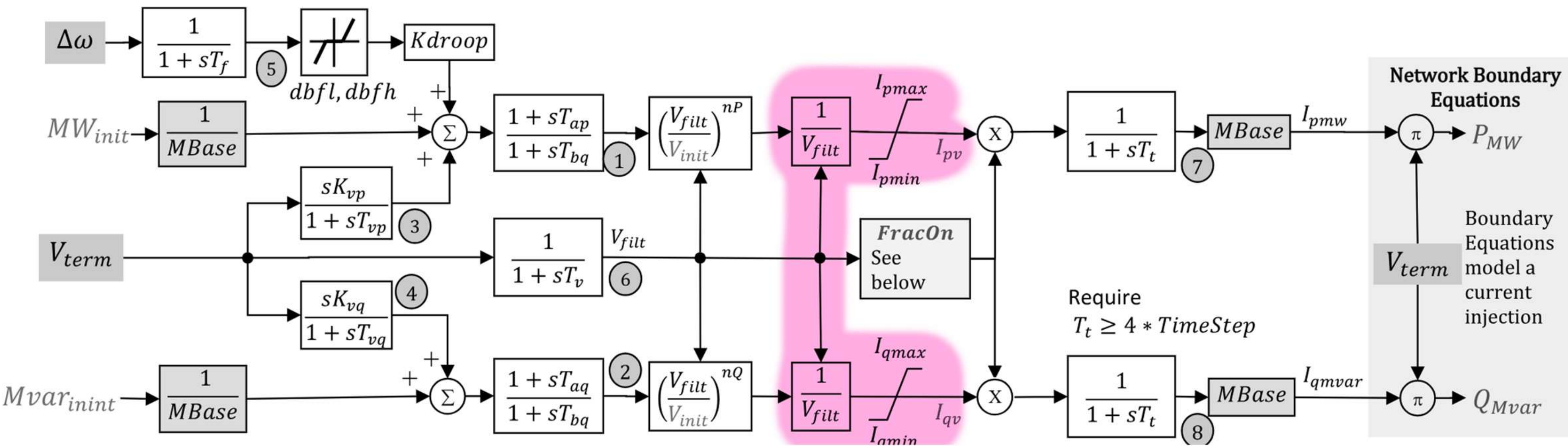
Steady-State Behavior as a function of voltage

- At the core of this model, it is just an algebraic load model which is a function of voltage
  - nP and nQ exponents as input
    - Modeling the **Power** as voltage raised to an exponential
  - nP=nQ=2 means Constant Impedance
  - nP=nQ=1 means Constant Current
  - nP=nQ=0 means Constant Power



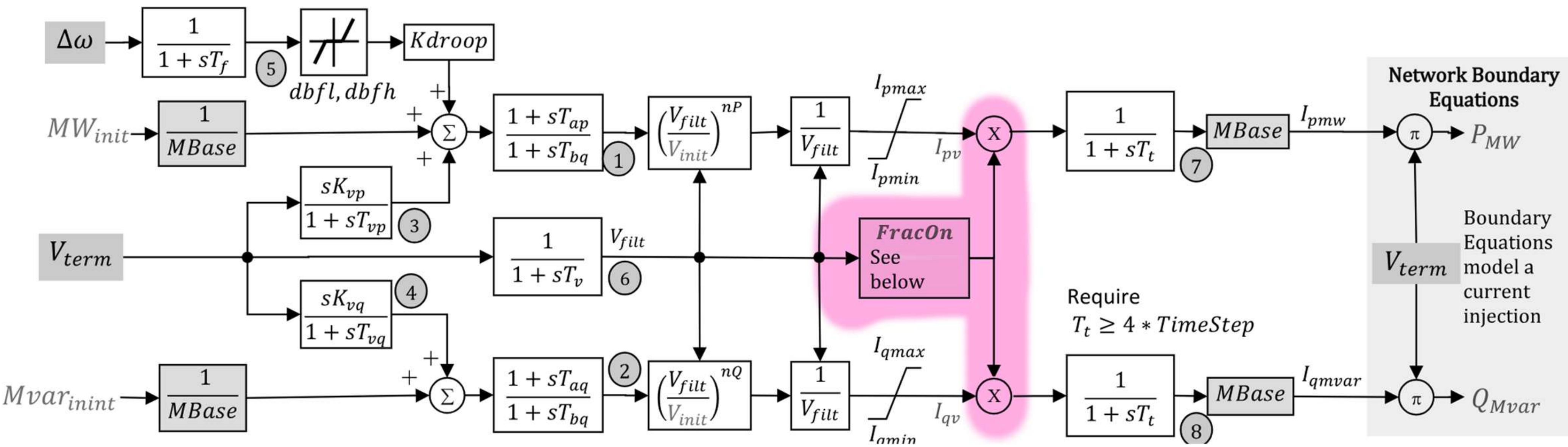
Convert to a Current Signal and Apply Limits

- Convert Power value to a current by dividing by voltage
- Apply Ipmax/Ipmin and Iqmax/Iqmin current limits



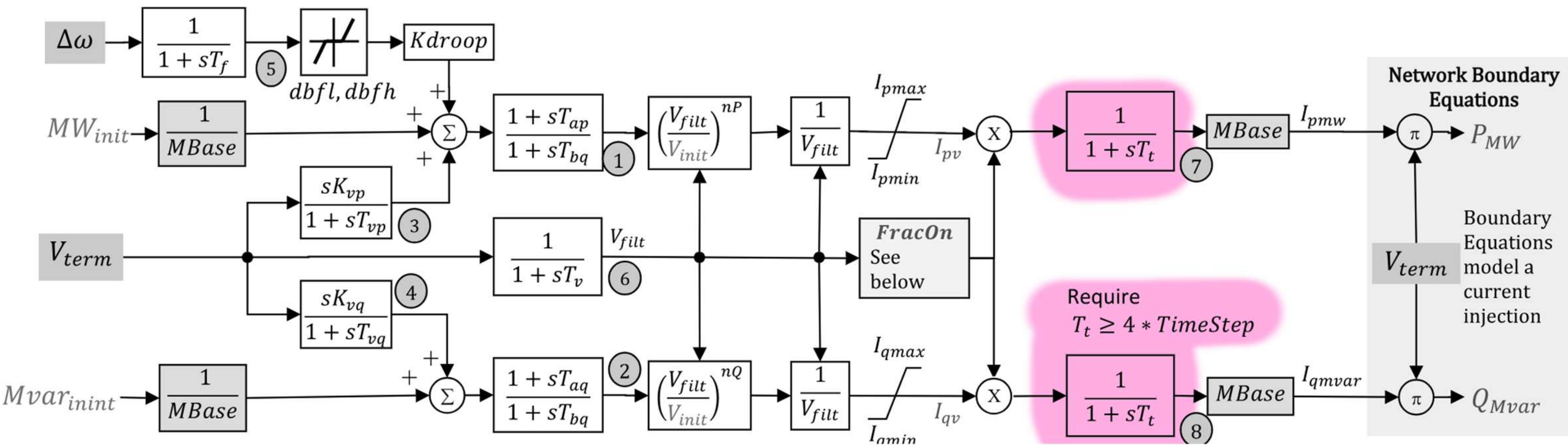
FracOn = Reconnecting and Ceasing Modeled

- This is the most important part of the model – thus why it has the name "Reconnecting and Ceasing"
- FracOn = the fraction of the load the remains connected



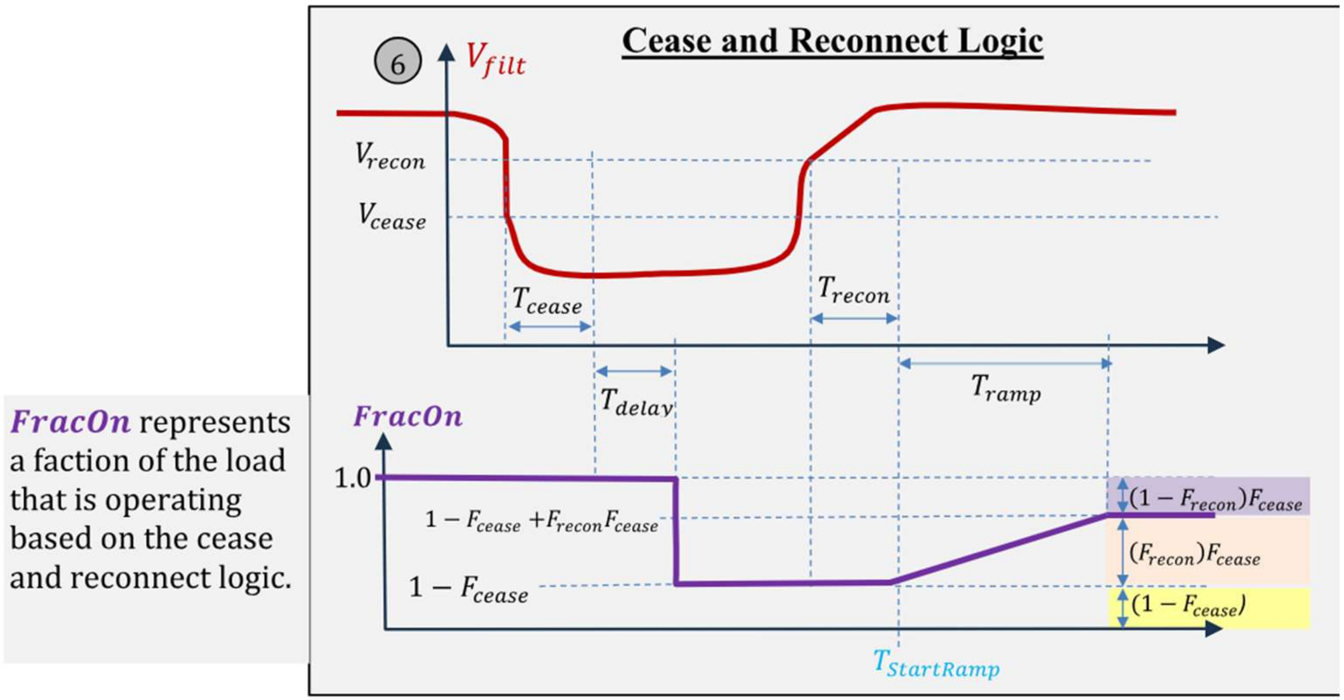
Short Delays on Output

- Delay Blocks on the output added to help with numerical stability
  - Must be set larger than 4*TimeStep



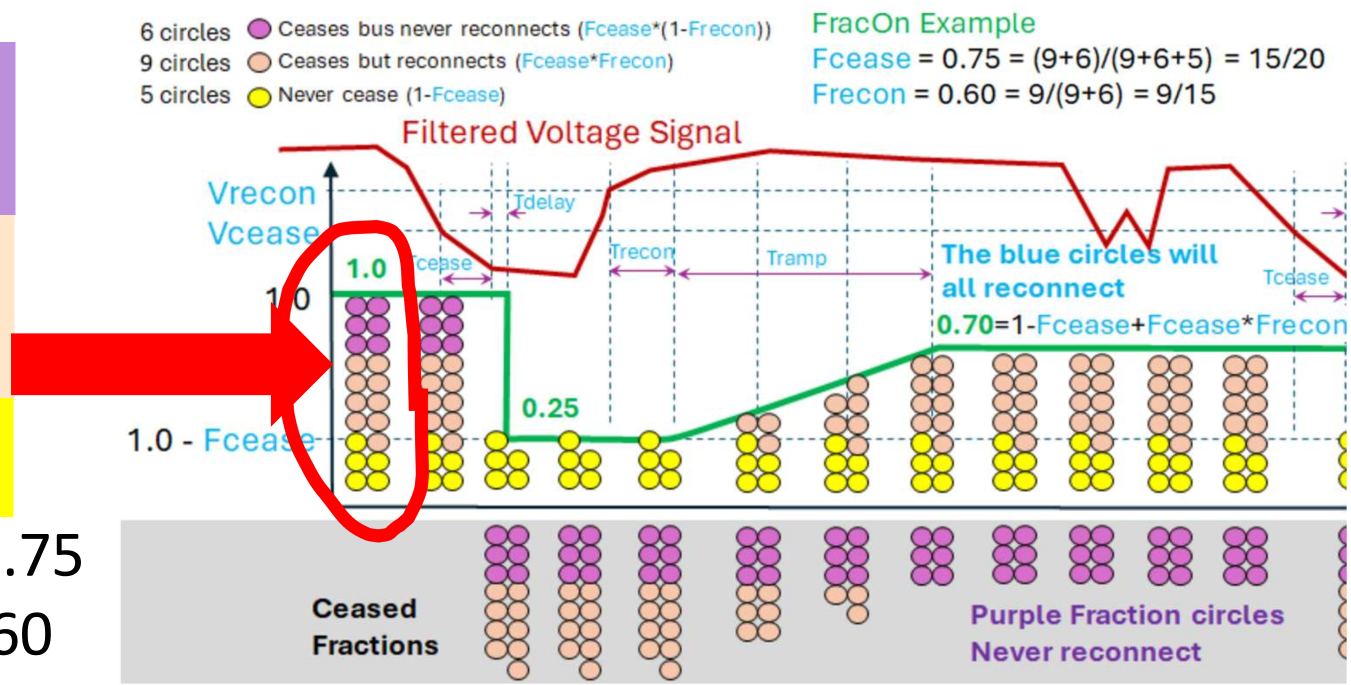
Reconnecting and Ceasing

- This is adding the concept of timing to the ceasing and reconnecting which was missing in LDELEC model used inside Composite model



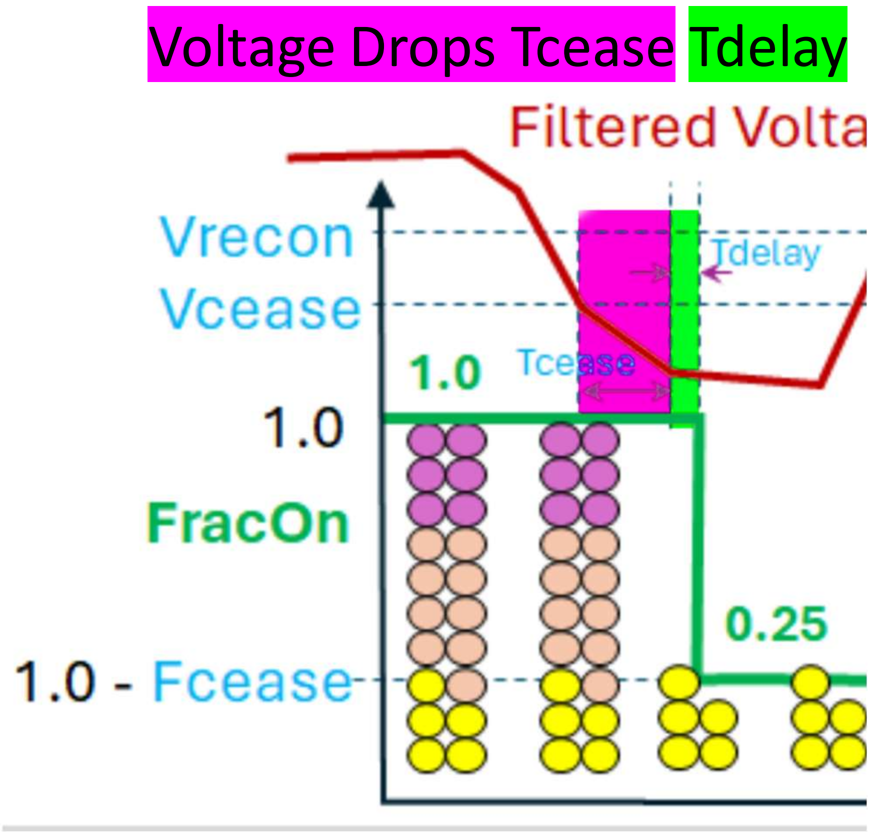
Visualization of Ceasing and Reconnecting

- Imagine we have 20 “fractional parts” of the load represented by 20 circles
  - 6 Purple circles Cease and NEVER reconnect
  - 9 orange circles Cease but MAY reconnect
  - 5 yellow circles Never Cease
- Fcease = 15/20 = 0.75
- Frecon = 9/15 = 0.60



Vcease/Tcease Timer

- Filtered Voltage Drops below Vcease for Tcease seconds
- Starts a timer Tdelay
  - Tdelay represents how long it takes the fractional load to turn itself off (very small)
- After Tdelay expired FracOn multiplier drops to FracOn = (1 – Fcease)



Vrecon/Trecon

- Filtered Voltage recovered above Vrecon for Trecon seconds, then FracOn starts ramping back up over Tramp seconds

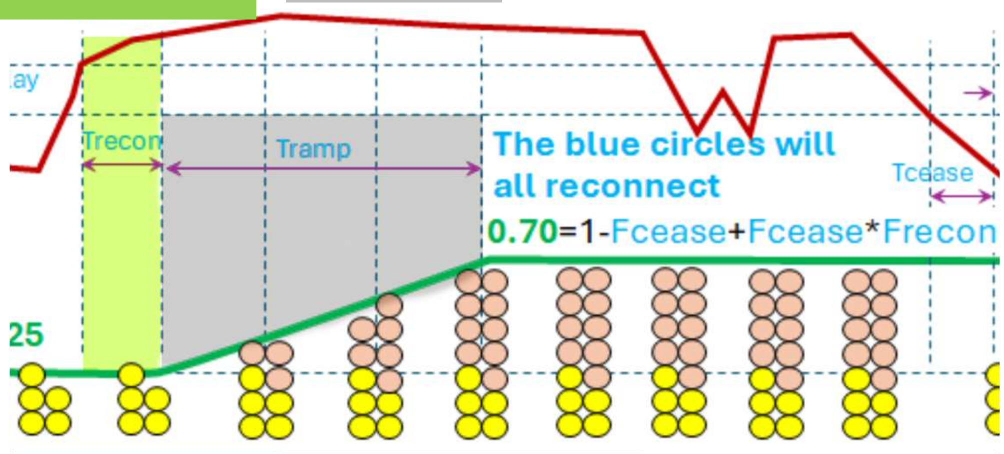
Voltage above for Trecon

Tramp

Purple Circles never come back

Orangle Circles Fractionally Reconnect

Yellow Circles Never Cease



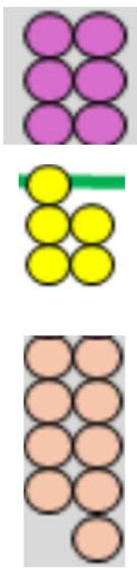
$$FracOn = (1 - Fcease) + Frecon * Fcease * \left(\frac{PresentTime - T_{startramp}}{T_{ramp}}\right)$$

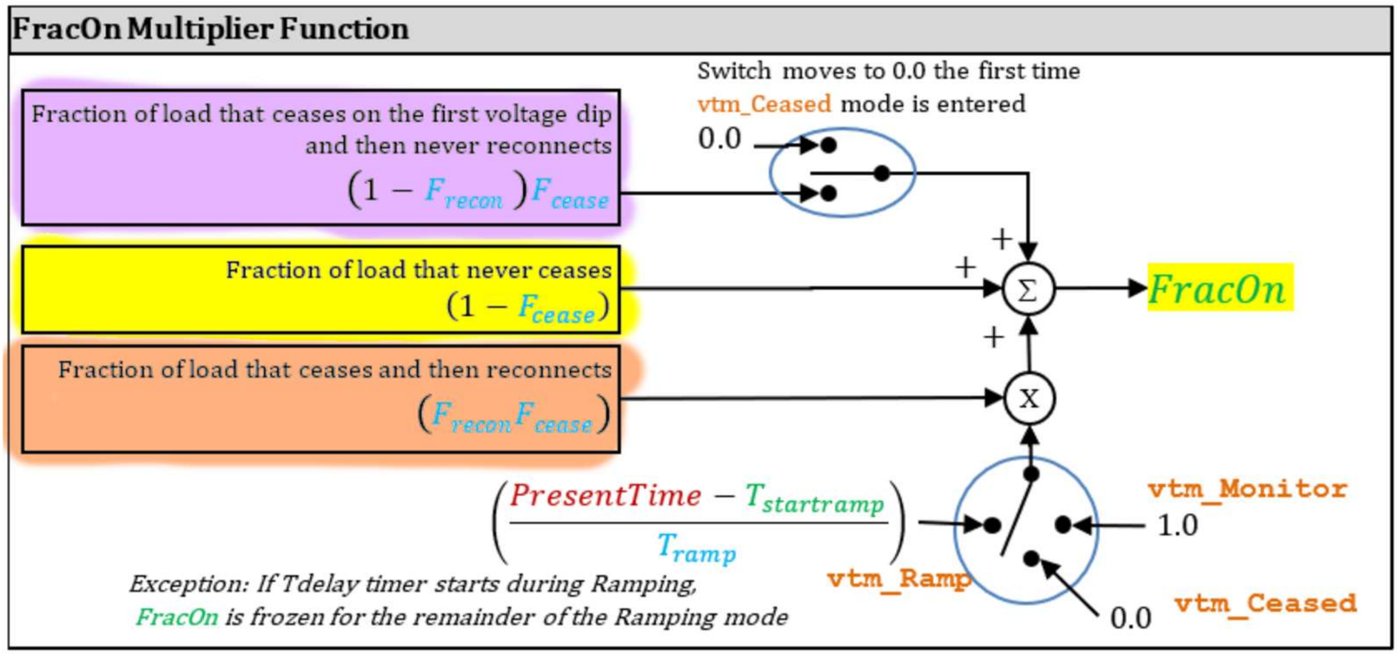
FracOn Calculation

Cease,
Never reconnect

Never Cease

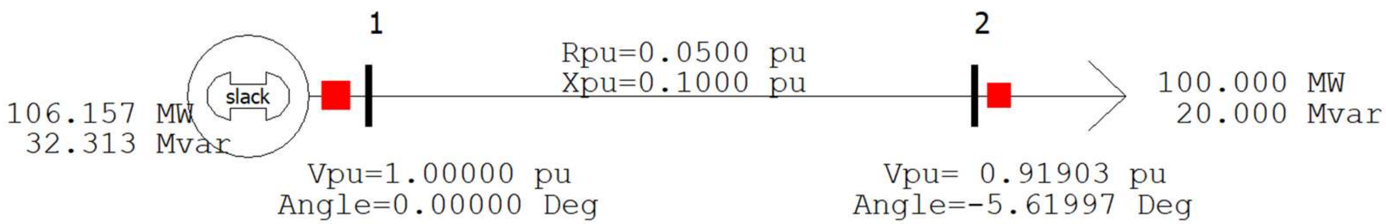
Cease,
Then Reconnect





2-Bus Test System

- 2-bus Test System

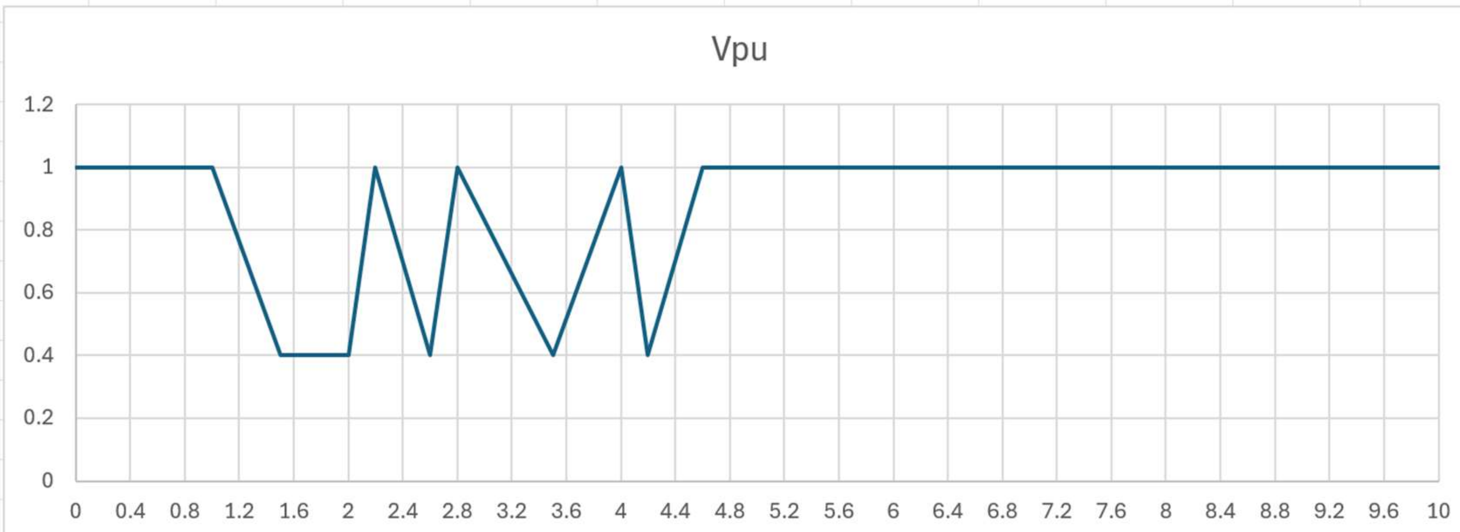


- Generator on the left has a PlayIn Voltage and a flat 60 Hz frequency
- Load model on the right configured with a PERC1 model

Voltage Test Signal

- Test is intentionally designed to test the resetting of timers and behavior of FracOn calculation for multiple voltage dips
- I really hope your systems never see this voltage trace!

	A	B	C
1	PlayInSignal		
2	Name	Time	Vpu
3	VoltRamp	0	1
4	VoltRamp	1	1
5	VoltRamp	1.5	0.4
6	VoltRamp	2	0.4
7	VoltRamp	2.2	1
8	VoltRamp	2.6	0.4
9	VoltRamp	2.8	1
10	VoltRamp	3.5	0.4
11	VoltRamp	4	1
12	VoltRamp	4.2	0.4
13	VoltRamp	4.6	1
14	VoltRamp	10	1



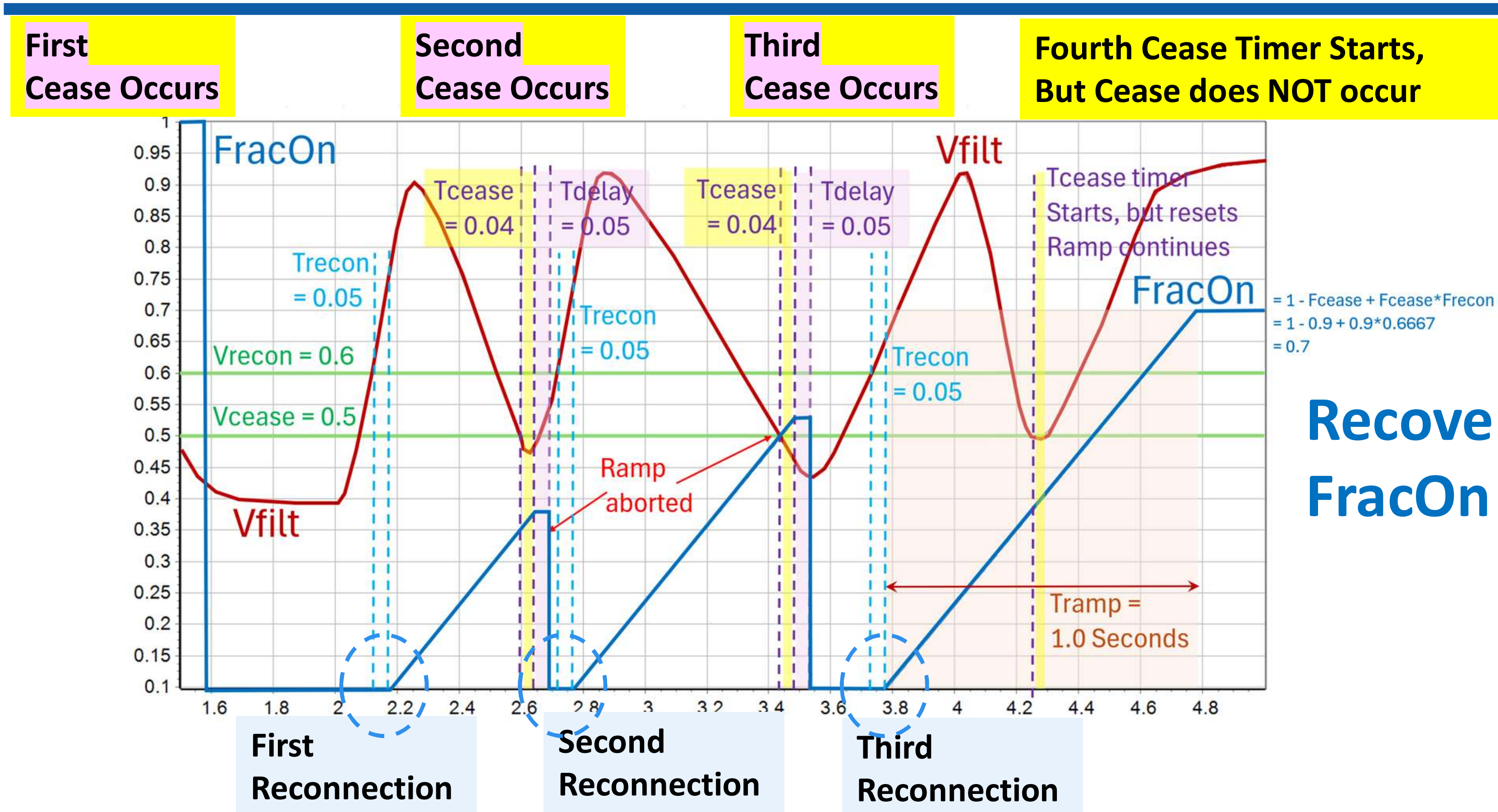
PERC1 Input Parameters

Lfm	0.8
QPratio	0.2
Dbfl	0
Dbfh	0
Kdroop	10
Kvp	0.2
Tvp	0.05
Kvq	0.5
Tvq	0.1
Tap	0
Tbp	0
Taq	0
Tbq	0

nP	2
nQ	1
Ipmax	1
Ipmin	0
Iqmax	0.66
Iqmin	-0.66

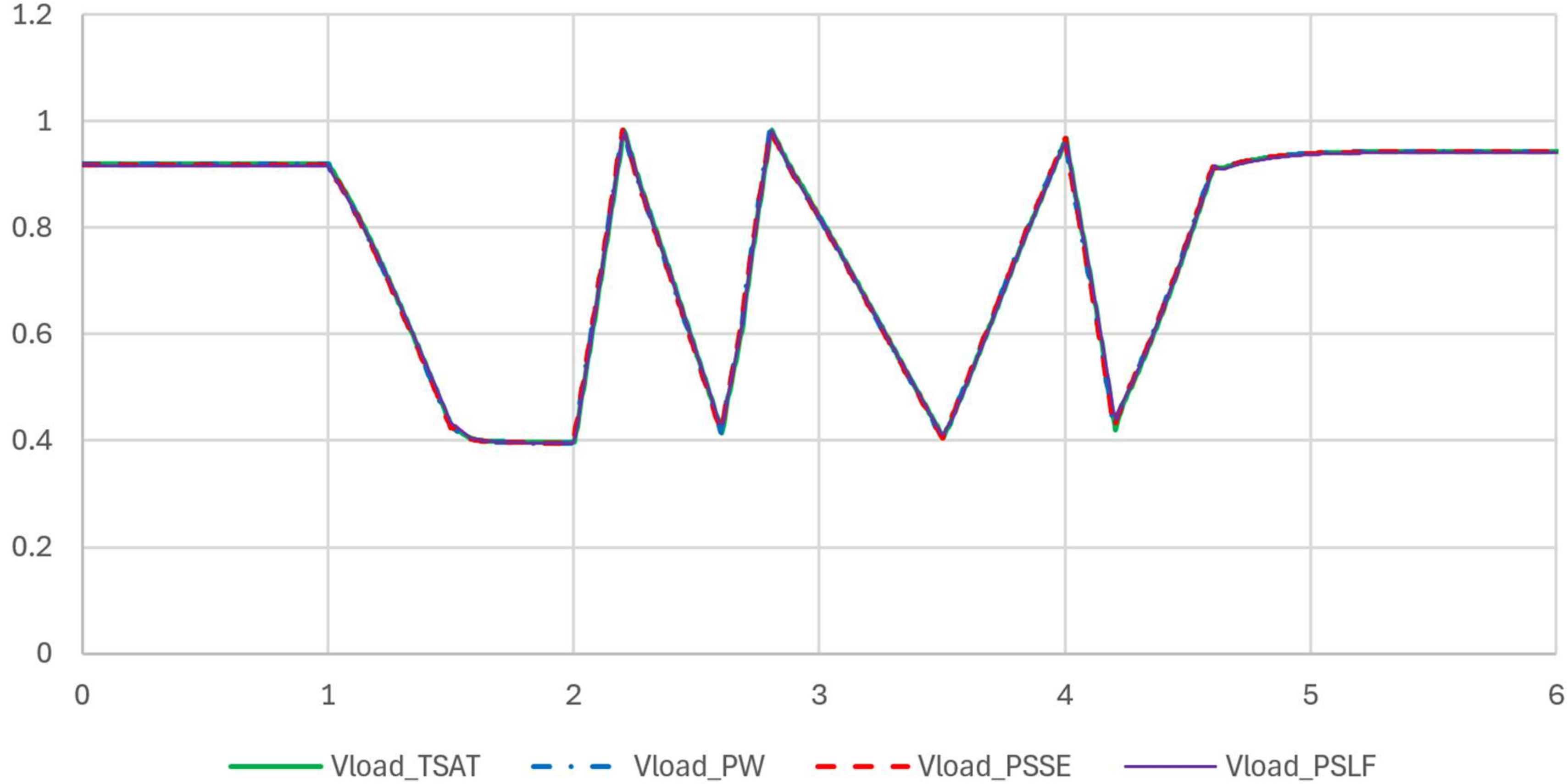
Fcease	0.9
Vcease	0.5
Tcease	0.04
Tdelay	0.05
Vrecon	0.6
Trecon	0.05
Tramp	1
Frecon	0.6667
Tt	0.02
Tv	0.05
Tf	0.02

Detailed Look at FracOn calculation for Test

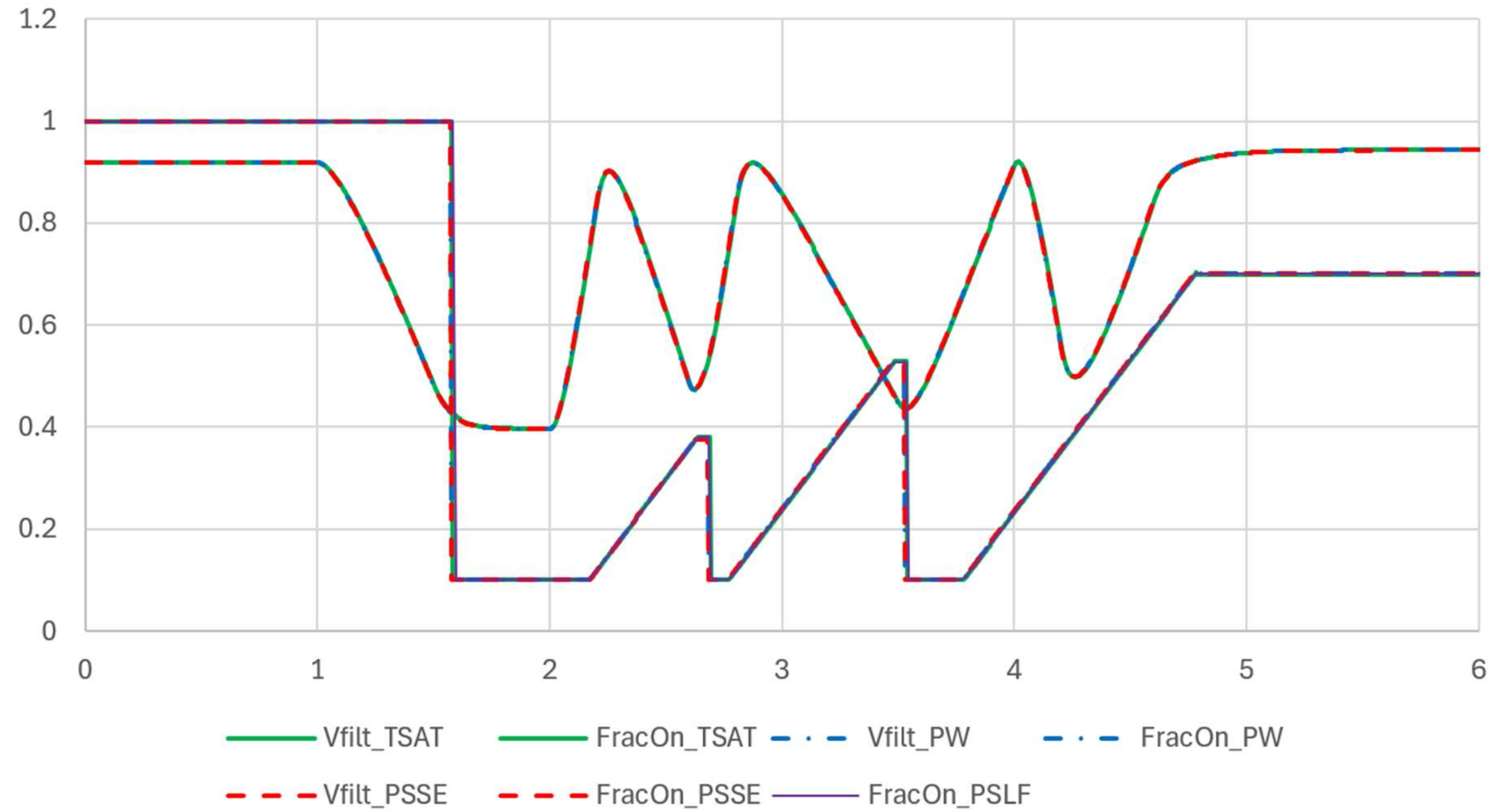


Recovers to final FracOn = 0.70

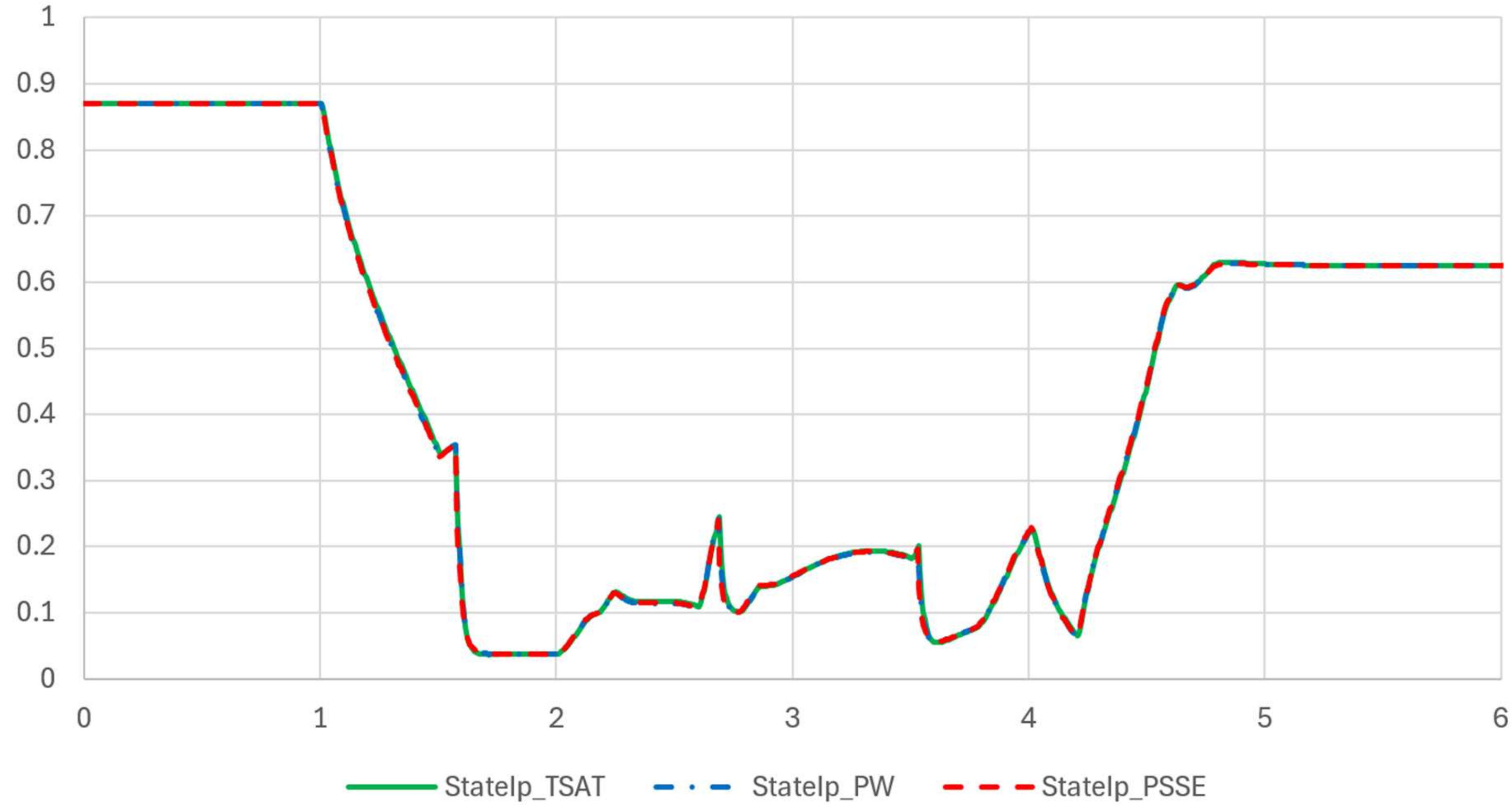
PowerWorld, TSAT, PSSE , and PSLF Results Vpu at Load – Identical



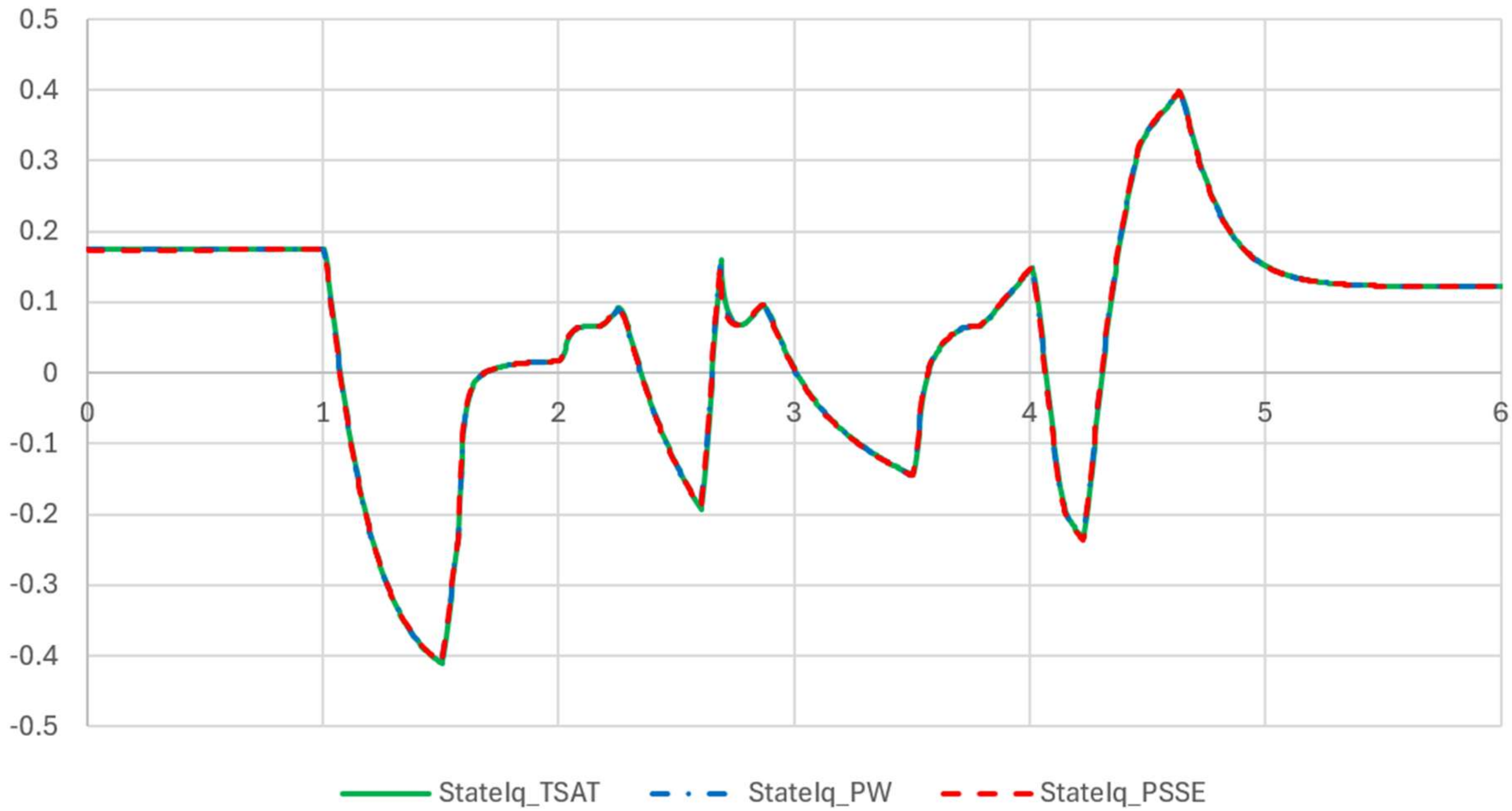
PowerWorld, TSAT, PSSE , and PSLF Results Vfilt and FracOn –Identical



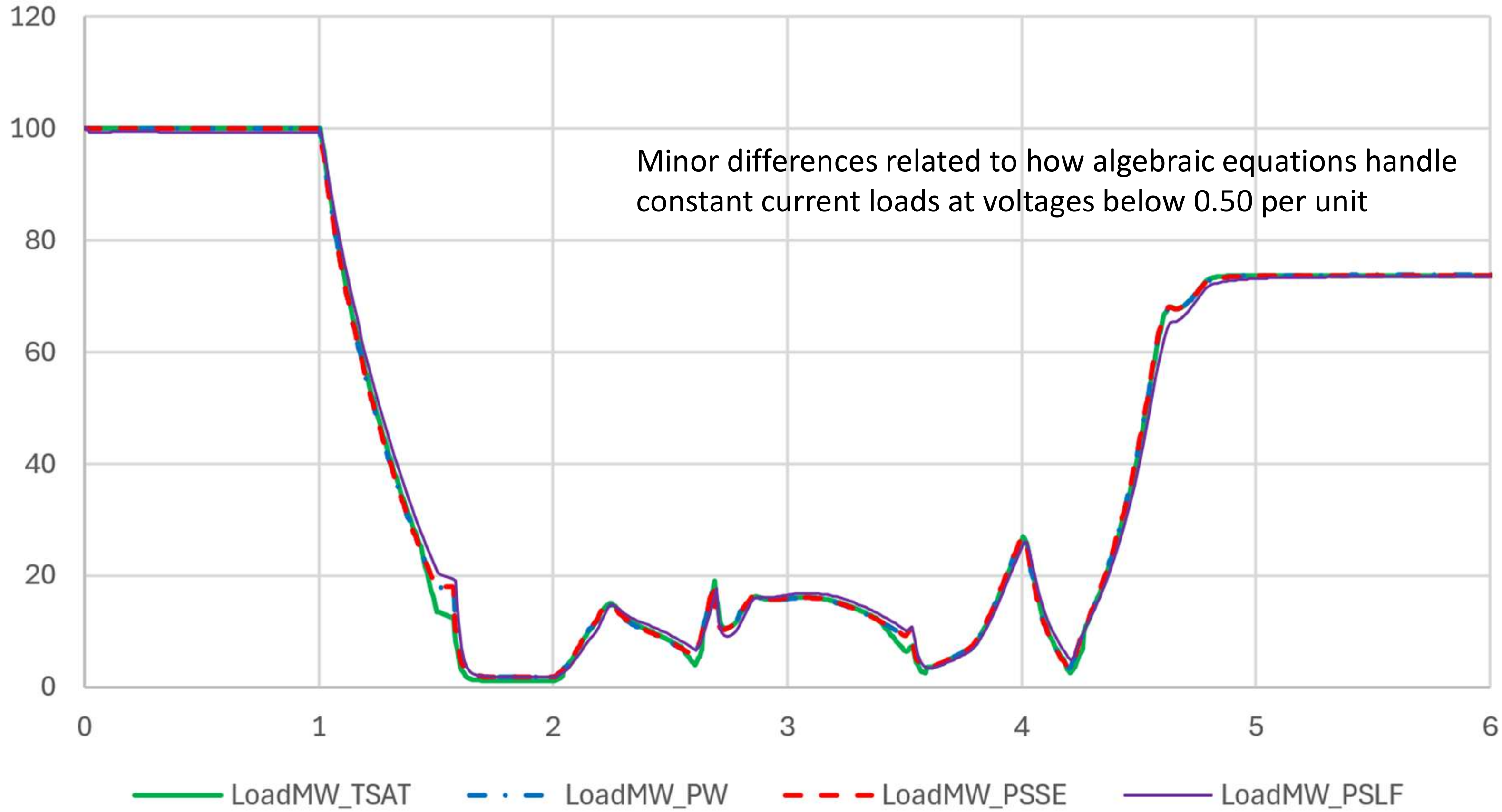
PowerWorld, TSAT, and PSSE Results
State Ip output of Dynamic Model – Identical



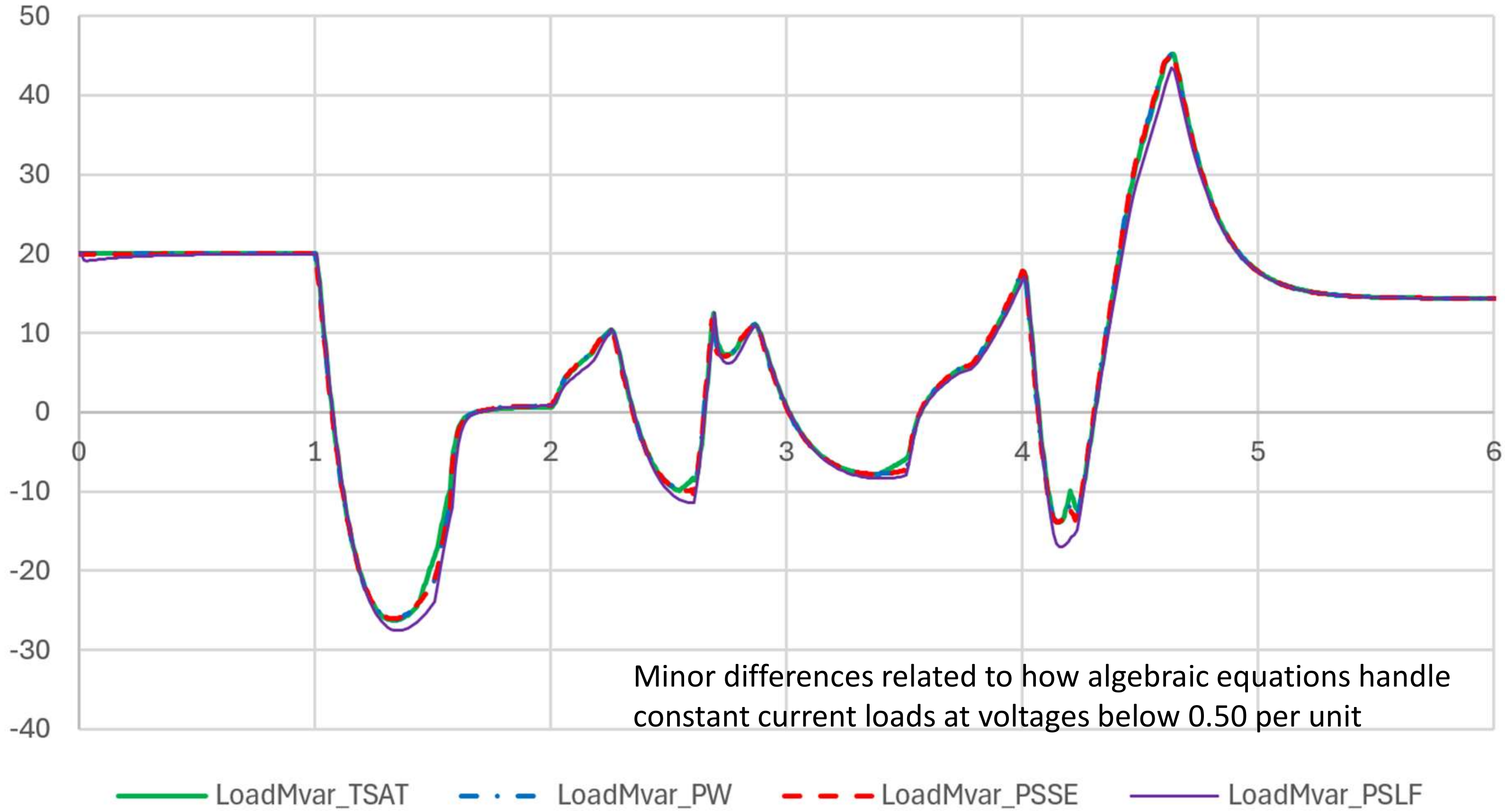
PowerWorld, TSAT, and PSSE Results State Iq output of Dynamic Model – Identical



PowerWorld, TSAT, PSSE, and PSLF Results Load MW Results – Almost Identical



PowerWorld, TSAT, PSSE , and PSLF Results
Load Mvar Results – Almost Identical



Pseudo-Code for the FracOn Timer

```
Variable Names in the Pseudo-Code Below
  Fcease, Vcease, Tcease, Tdelay : input parameters control Ceasing
  Frecon, Vrecon, Trecon, Tramp : input parameters control Reconnecting
  Vfilt       : State variable of the filtered voltage
  FracOn      : Multiplier representing the fraction of the load that remains connected
  Mode        : 3 possible modes:  vtm_Monitor, vtm_Ceased, vtm_Ramp
  TimerActive : 4 possibilities determine if any timer is active (only one timer can be active)
                vtt_None, vtt_Tcease, vtt_Tdelay, vtt_Trecon
  Timer       : Float number used to keep track of timing for Tcease, Tdelay and Trecon
  TStartRamp  : Float number used to keep track of timing during ramping

Initialize the following before simulation starts
  FracOn = 1.0
  Mode = vtm_Monitor
  TimerActive = vtt_None
  Timer = 0
  TStartRamp = 0
```

```
Run the following at each time step
  If Fcease > 0 Then // Ignore all this stuff if Fcease <= 0
    If (Mode == vtm_Ramp)
       AND (TimerActive <> vtt_Tdelay) // FracOn is frozen during Tdelay
    Then  // update the value of FracOn
      If PresentTime >= TStartRamp + Tramp Then
        FracOn = 1 - Fcease + Frecon*Fcease
        Mode = vtm_Monitor
      Else
        FracOn = 1 - Fcease + Frecon*Fcease*(PresentTime - TStartRamp)/Tramp
      EndIf
    EndIf

    // Tcease and Tdelay timers are counting the same whether we are in Monitor or Ramp
    If Mode <> vtm_Ceased Then // handled in both Monitor and Ramp modes
      If TimerActive <> vtt_Tdelay Then
        If (Vfilt >= Vcease) Then
          TimerActive = vtt_None
        ElseIf (TimerActive <> vtt_Tcease) Then
          Timer = PresentTime
          TimerActive = vtt_Tcease
        EndIf
      EndIf

      If (TimerActive = vtt_Tcease) AND (PresentTime - Timer) >= Tcease) Then
        Timer = PresentTime
        TimerActive = vtt_Tdelay
      EndIf

      If (TimerActive = vtt_Tdelay) AND (PresentTime - Timer) >= Tdelay Then
        TimerActive = vtt_None
        Mode = vtm_Cease
        FracOn = 1 - Fcease
      EndIf
    Else // (Mode == vtm_Cease)
      If (Vfilt < Vrecon) Then
        TimerActive = vtt_None
      ElseIf (TimerActive <> vtt_Trecon)
        Timer = PresentTime
        TimerActive = vtt_Trecon
      EndIf

      If (TimerActive = vtt_Trecon) AND (PresentTime - Timer) >= Trecon) Then
        TimerActive = vtt_None
        If Tramp == 0 then // skip over Ramp Mode and jump to Monitor
          Mode = vtm_Monitor
          FracOn = 1 - Fcease + Frecon*Fcease
        Else
          Mode = vtm_Ramp
          TStartRamp = PresentTime
        EndIf
      EndIf
    EndIf
  EndIf // If Fcease > 0
```

PERC1 Today

- Industry/Software Vendor Decision
  - We have this model implemented and it works identically across all 4 software platforms
  - Should we release this model now as a standard model?
  - It is ready for use.
- Pieces we need to discuss more
  - High Voltage ceasing and reconnecting
  - Frequency deviation ceasing and reconnecting
    - Remember any frequencies outside about 59.5 to 60.5 Hz are frequencies we just won't see in any but the most extreme interconnection wide simulations
  - We are still deciding whether to just release
- Remember we can always have a PERC2 in a year or so that includes additional functionality