

# Power Electronic Reconnecting and Ceasing Load Model

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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)
$$P = P_{load} (a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}) (1 + a_7 \Delta f)$$
$$Q = Q_{load} (a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}) (1 + a_8 \Delta f)$$
  - 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

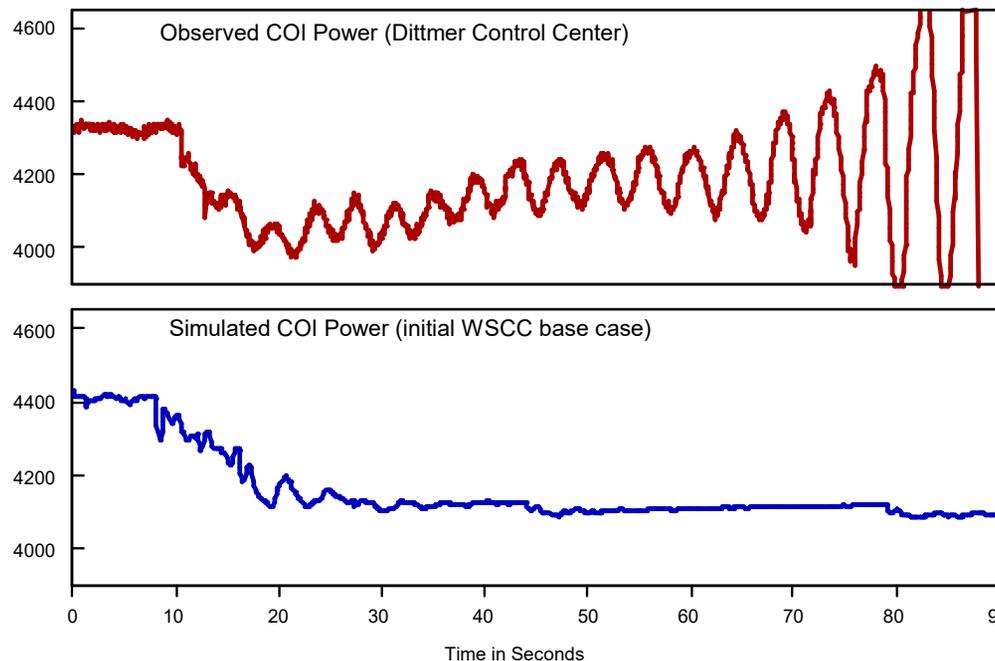
# 1996 Blackout Example Oscillations



- 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

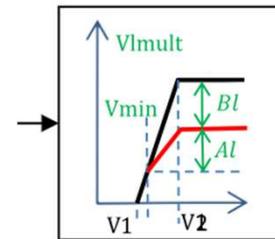
- Eastern Inteconnection and ERCOT presently are in the 5-year “adoption period”

# 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

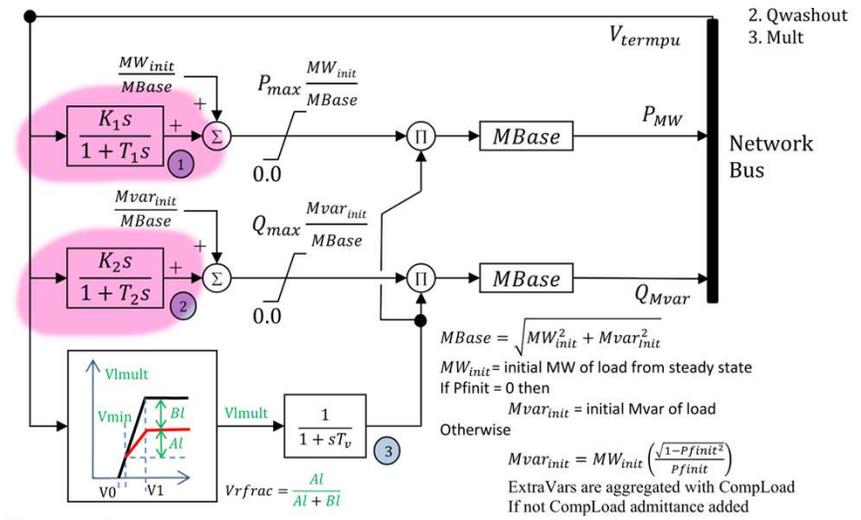
# Simple VFD Model: LDVFD\_A

This model was never really adopted by industry



2019

- [https://powerworld.com/WebHelp/#TransientModels\\_HTML/Load%20Characteristic%20LDVFD\\_A.htm](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

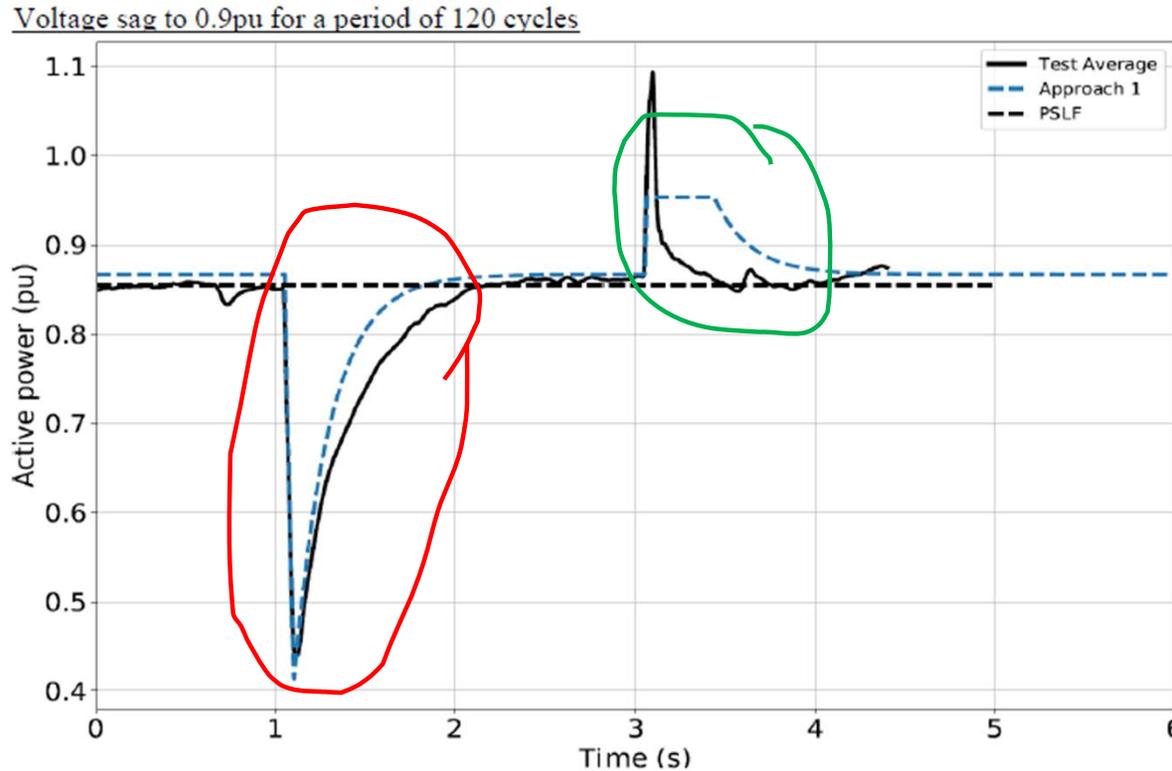


# EPRI Presentation from March 2019 – LDVFD\_A



- 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

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



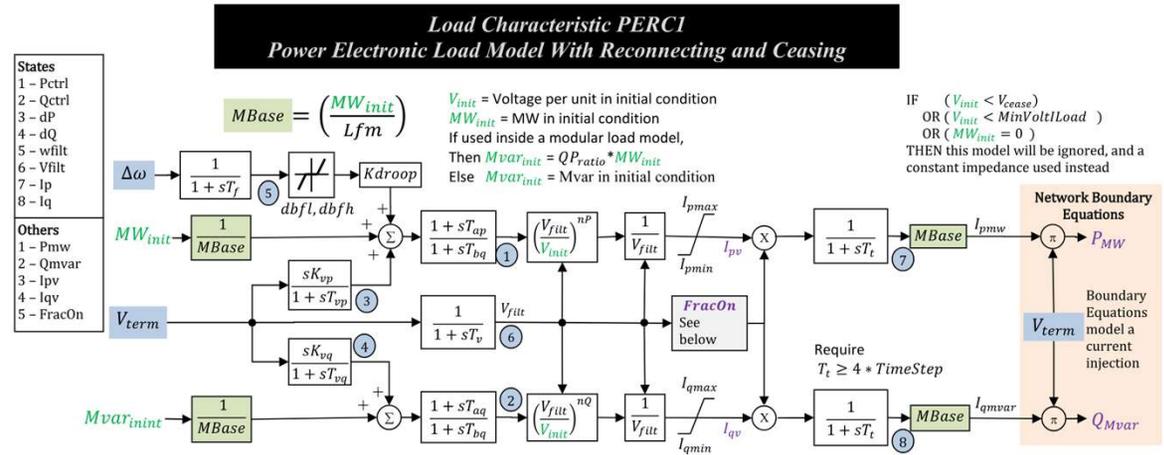
2022

EPRI introduces concept of Electric Vehicle Charger model "EV1"

2025

PERC1 is based on the EV1 model

## Load Characteristic PERC1



## Load Characteristic Model: PERC1

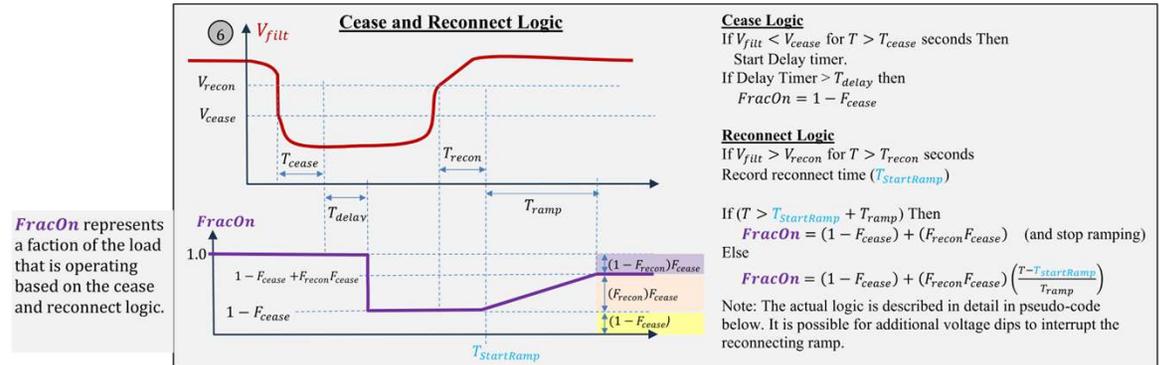
Model is under development, available in October 27, 2025 path of Version 24

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

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- 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

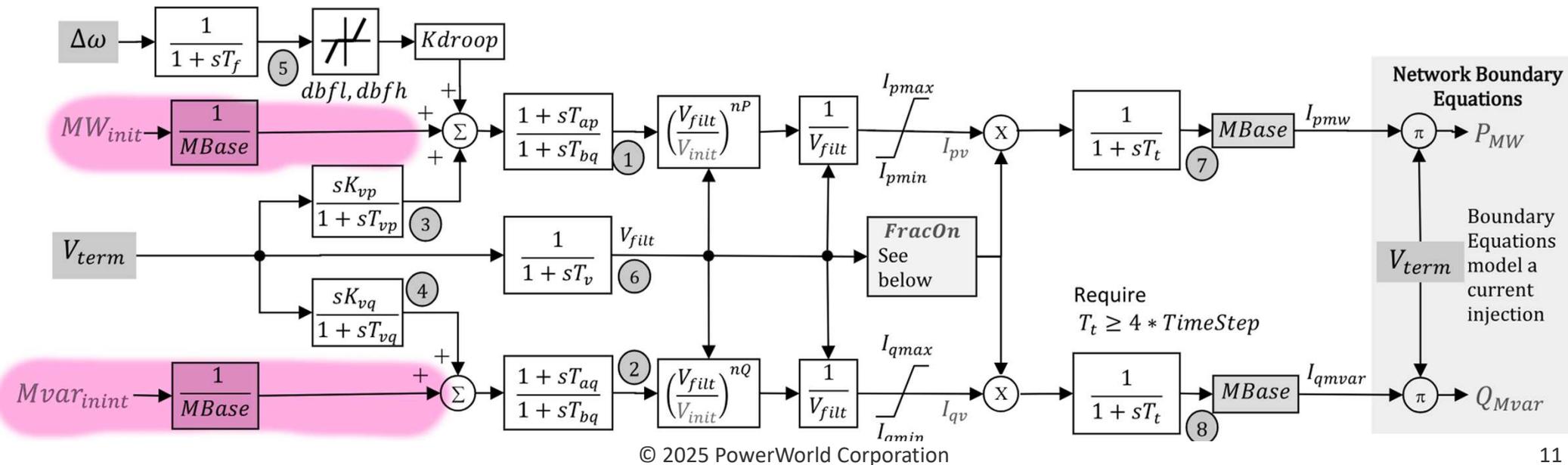
# Initial Condition



- 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



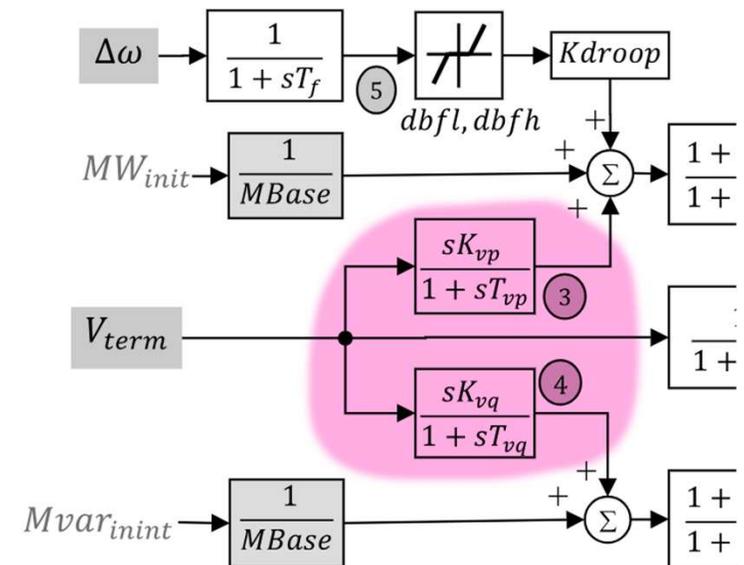
Model brings the MW and Mvar back to the same value as the initial condition



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



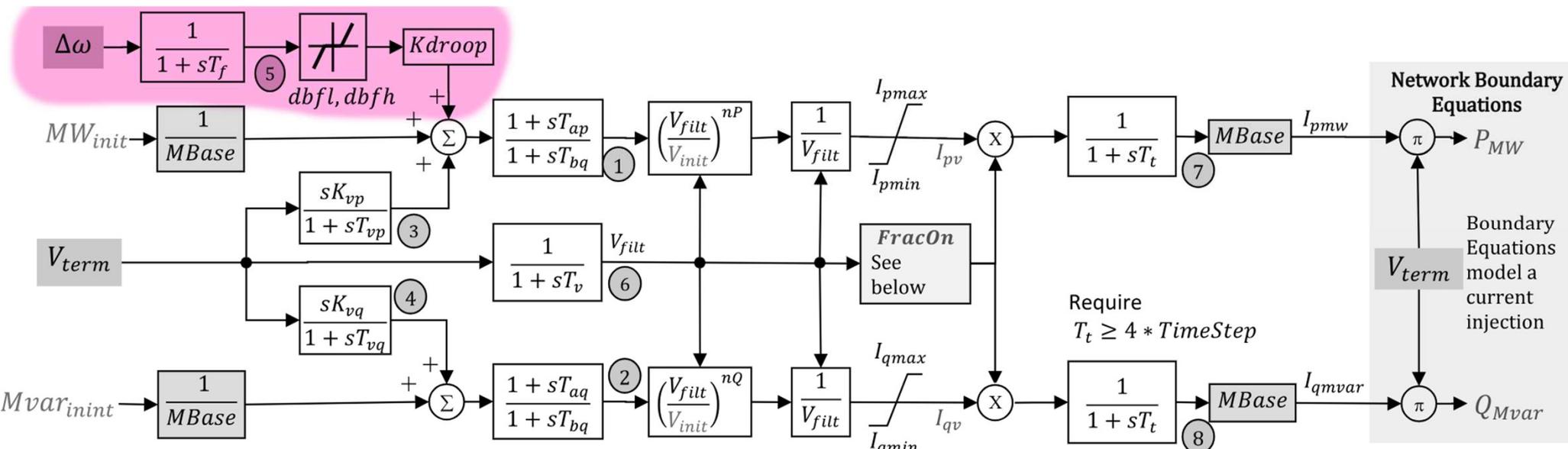
- Derivative blocks come from original work EPRI did with a simple Variable Frequency Drive (VFD) models
  - The mechanical/energy system for VFD reduced power at fault inception, but then recovers some of the energy lost when the voltage recovers
- MW or Mvar vary with the derivative of the terminal voltage
  - Set  $K_{vp}=0$  or  $K_{vq}=0$  to disable this
- At fault inception the voltage drops, so the derivative will be negative,
  - MW and Mvar will reduce temporarily for a voltage drop
- At fault clearing the voltage increases, so the derivative will be positive
  - MW and Mvar will increase temporarily at clearing



# Real Power Frequency Droop



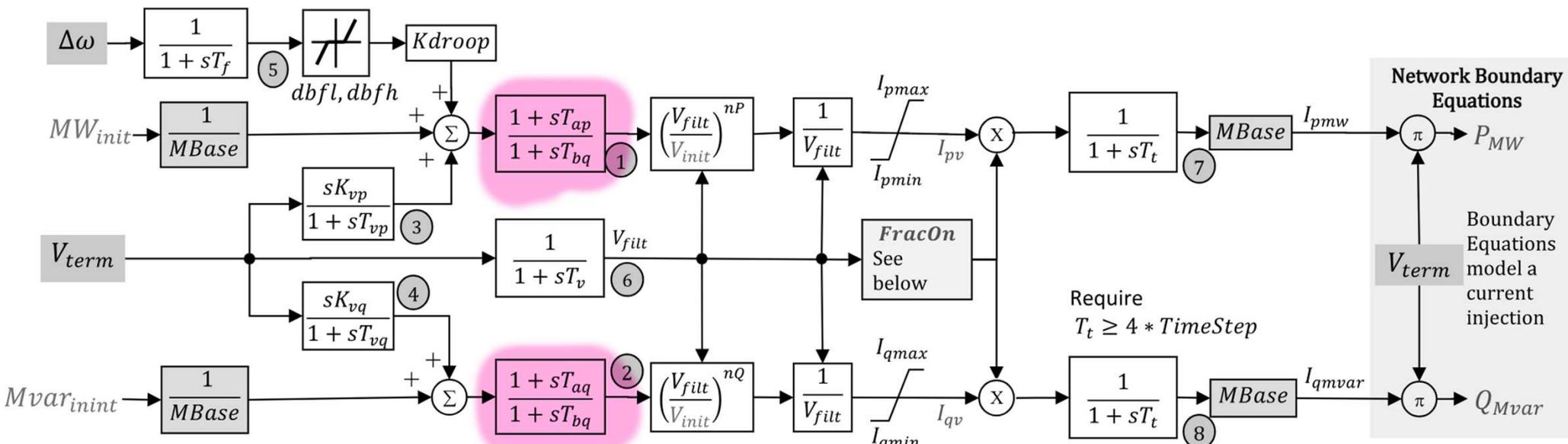
- Real power may respond with a Frequency Droop with deadband characteristic
  - As frequency increases, the load would increase
- Typical input data will not use this feature right now ( $K_{droop} = 0$ )



# Dynamic Response



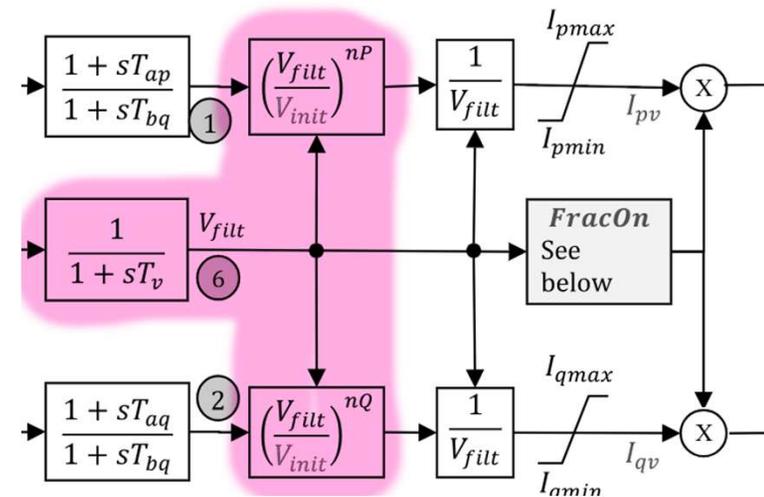
- Lead-Lag blocks added to allow modeling of some dynamic response
  - This is “future-proofing the model”
  - Typical input data will not use this feature right now (Tap=Tbp= 0)



# Steady-State Behavior as a function of voltage



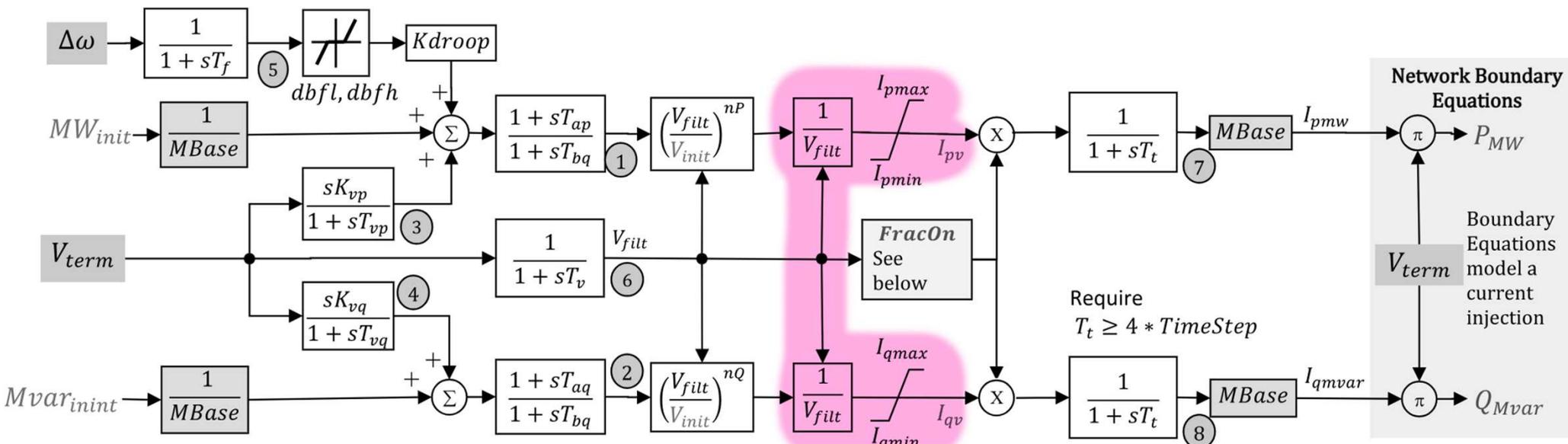
- At the core of this model, it is just an algebraic load model which is a function of voltage
  - nP and nQ exponents as input
    - Modeling the **Power** as voltage raised to an exponential
  - nP=nQ=2 means Constant Impedance
  - nP=nQ=1 means Constant Current
  - nP=nQ=0 means Constant Power



# Convert to a Current Signal and Apply Limits



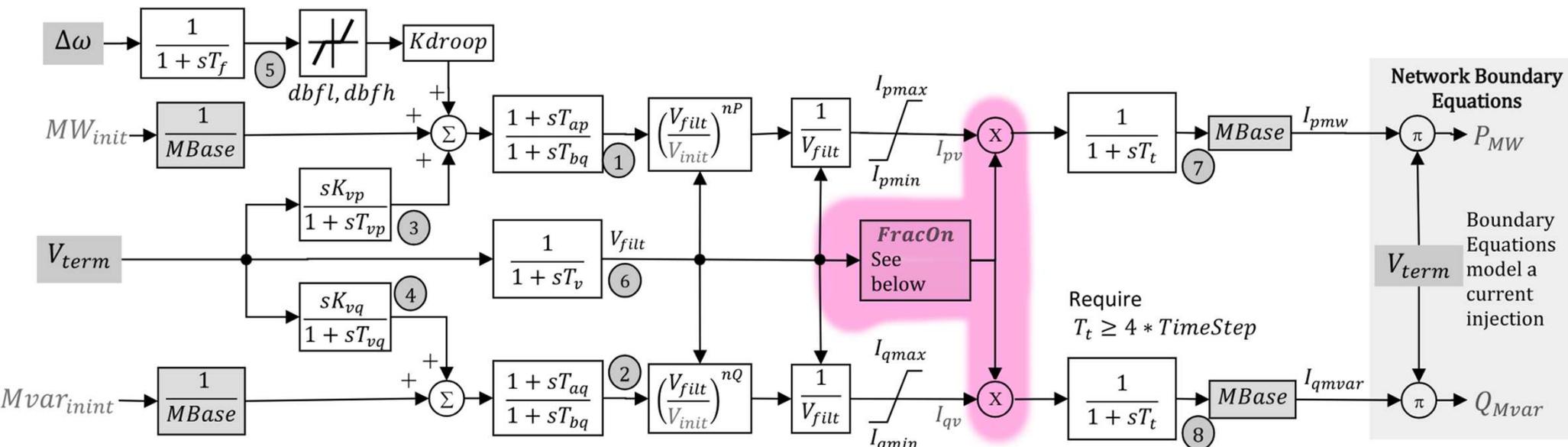
- Convert Power value to a current by dividing by voltage
- Apply  $I_{pmax}/I_{pmin}$  and  $I_{qmax}/I_{qmin}$  current limits



# 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

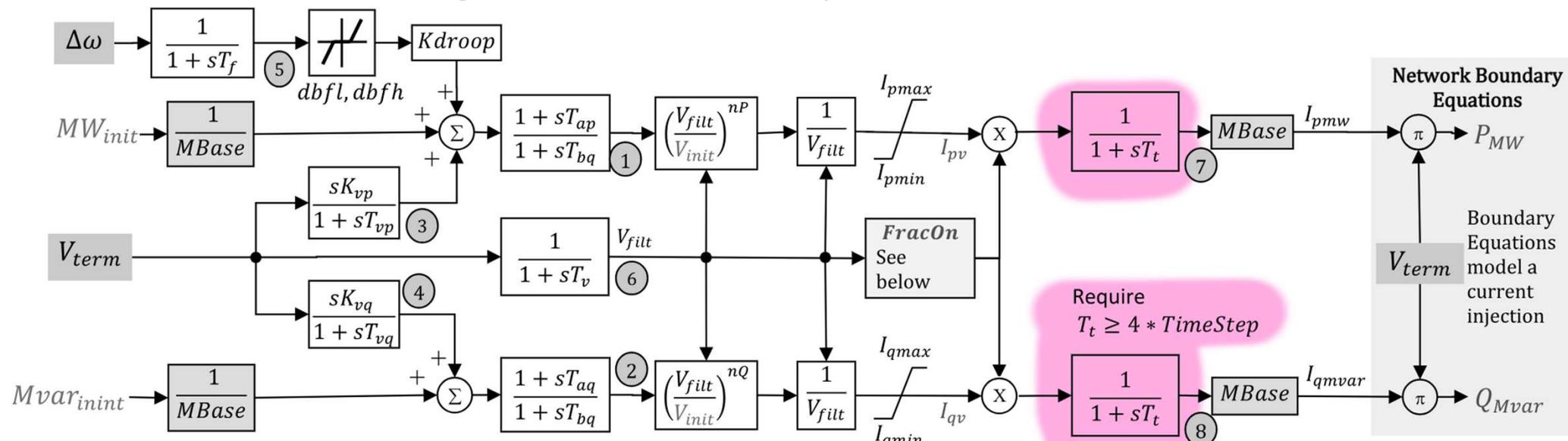


# Short Delays on Output



- Delay Blocks on the output added to help with numerical stability

– Must be set larger than  $4 * \text{TimeStep}$

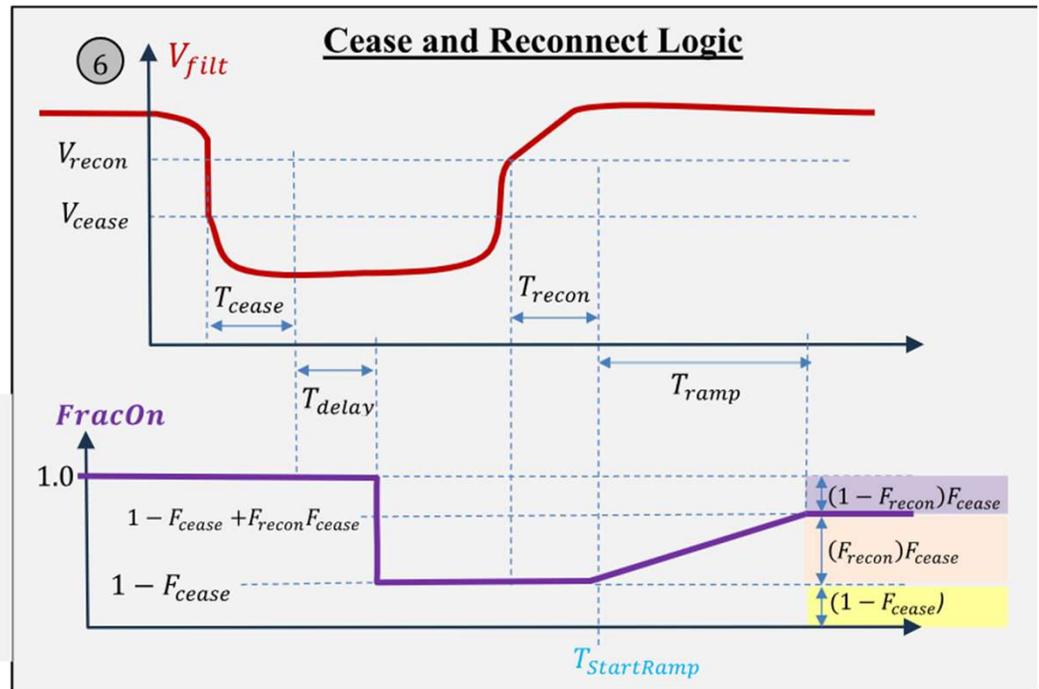


# Reconnecting and Ceasing



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

*FracOn* represents a fraction of the load that is operating based on the cease and reconnect logic.



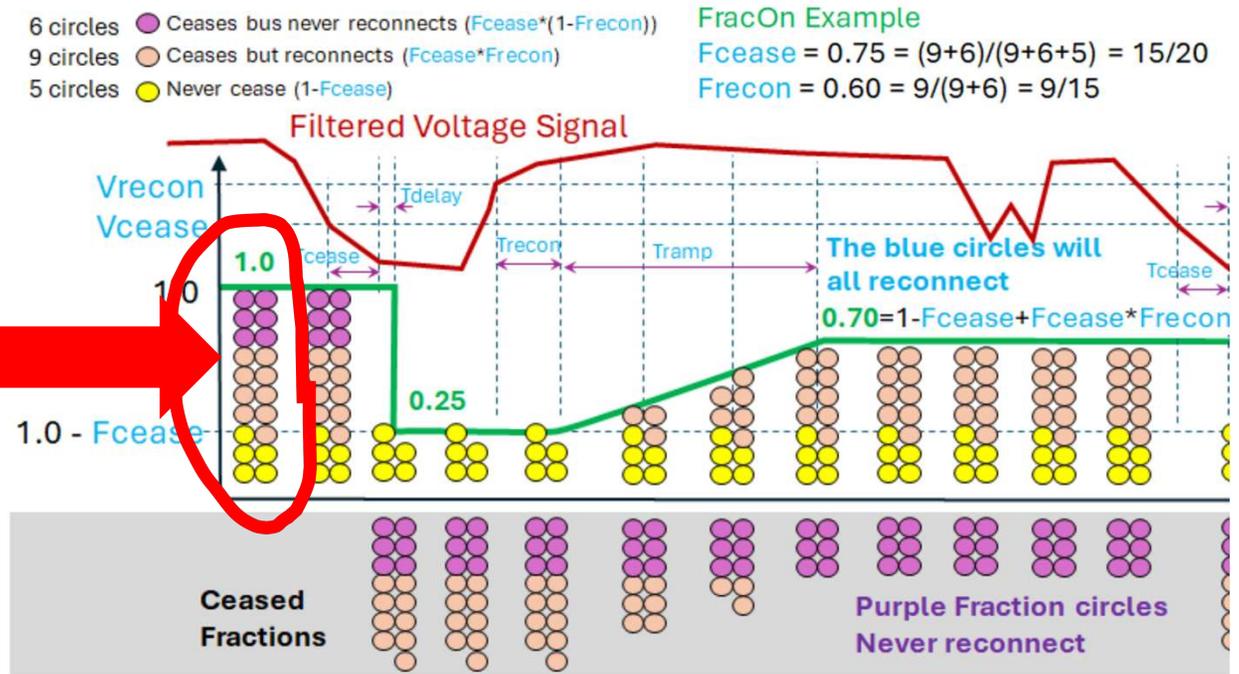


# Visualization of Ceasing and Reconnecting

- 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

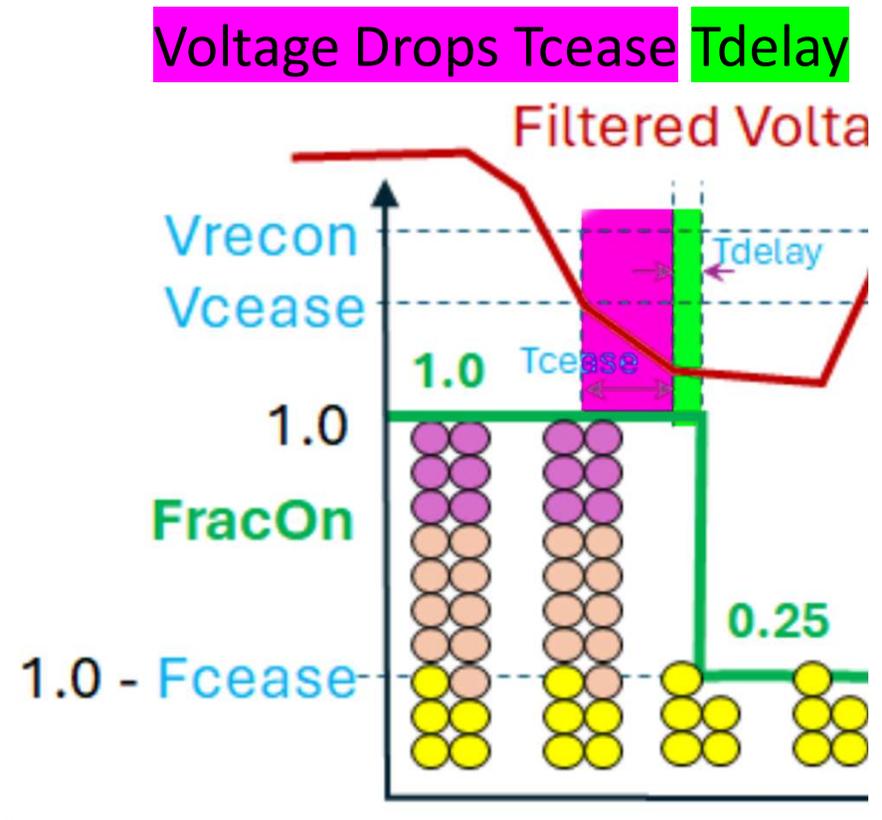
- $F_{cease} = 15/20 = 0.75$
- $F_{recon} = 9/15 = 0.60$



# Vcease/Tcease Timer



- Filtered Voltage Drops below  $V_{cease}$  for  $T_{cease}$  seconds
- Starts a timer  $T_{delay}$ 
  - $T_{delay}$  represents how long it takes the fractional load to turn itself off (very small)
- After  $T_{delay}$  expired  $FracOn$  multiplier drops to  $FracOn = (1 - F_{cease})$



# Vrecon/Trecon



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

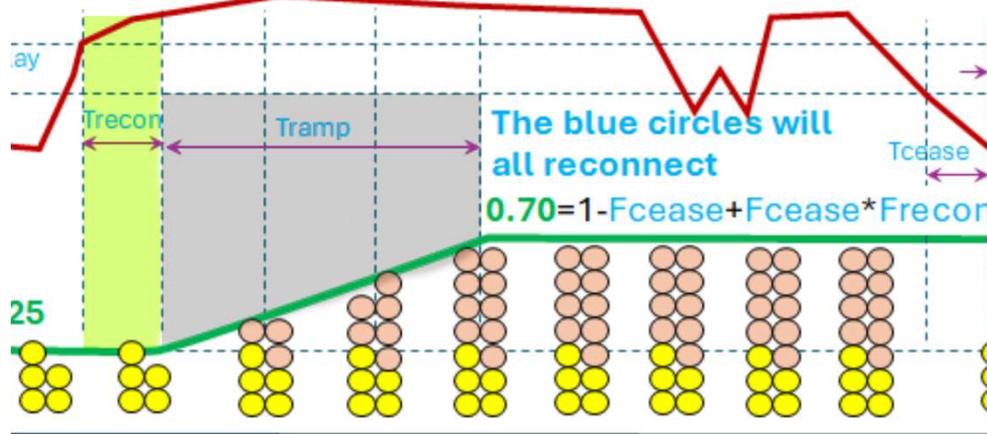
Voltage above for Trecon

Tramp

Purple Circles never come back

Orange Circles Fractionally Reconnect

Yellow Circles Never Cease



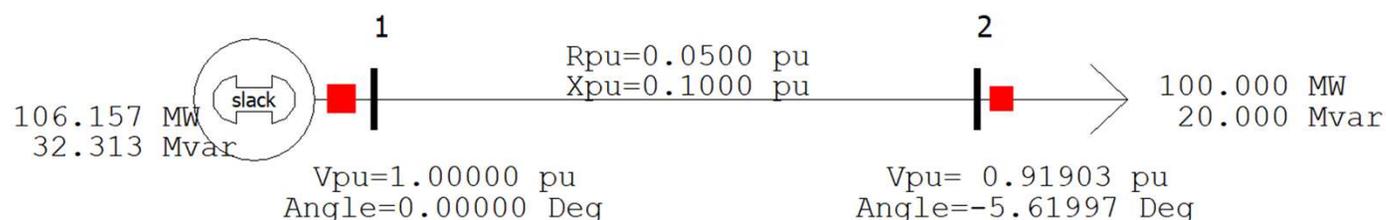
$$\text{FracOn} = (1 - \text{Fcease}) + \text{Frecon} * \text{Fcease} * \left( \frac{\text{PresentTime} - T_{\text{starttramp}}}{T_{\text{tramp}}} \right)$$



# 2-Bus Test System



- 2-bus Test System

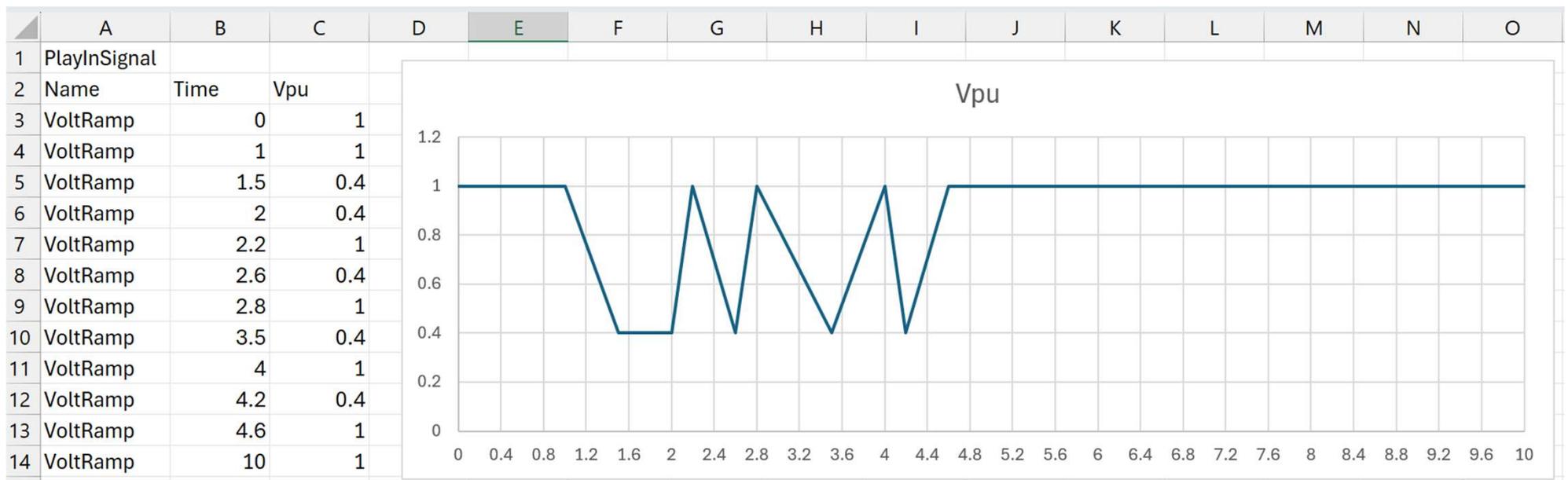


- Generator on the left has a PlayIn Voltage and a flat 60 Hz frequency
- Load model on the right configured with a PERC1 model

# 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!



# PERC1 Input Parameters



Lfm	0.8	nP	2	Fcease	0.9
QPratio	0.2	nQ	1	Vcease	0.5
Dbfl	0	Ipmax	1	Tcease	0.04
Dbfh	0	Ipmin	0	Tdelay	0.05
Kdroop	10	Iqmax	0.66	Vrecon	0.6
Kvp	0.2	Iqmin	-0.66	Trecon	0.05
Tvp	0.05			Tramp	1
Kvq	0.5			Frecon	0.6667
Tvq	0.1			Tt	0.02
Tap	0			Tv	0.05
Tbp	0			Tf	0.02
Taq	0				
Tbq	0				

# Detailed Look at FracOn calculation for Test

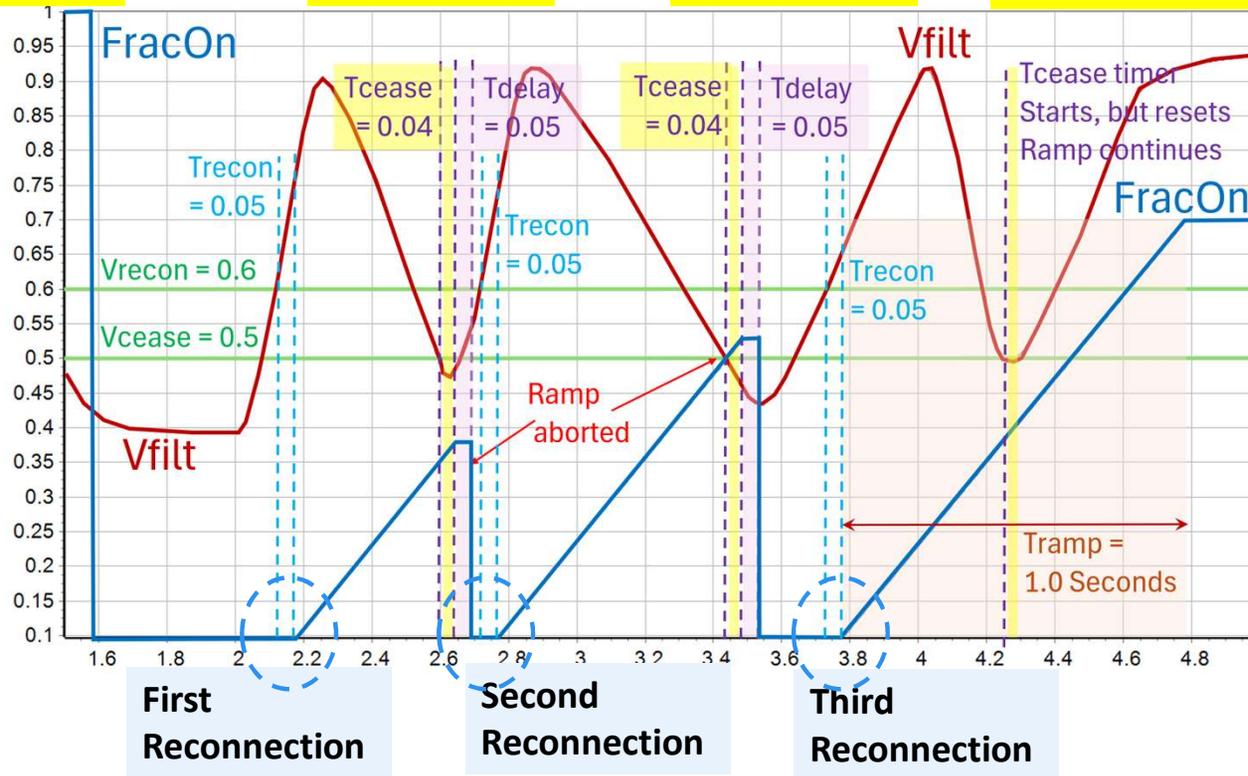


**First  
Cease Occurs**

**Second  
Cease Occurs**

**Third  
Cease Occurs**

**Fourth Cease Timer Starts,  
But Cease does NOT occur**



$$= 1 - F_{cease} + F_{cease} * F_{recon}$$

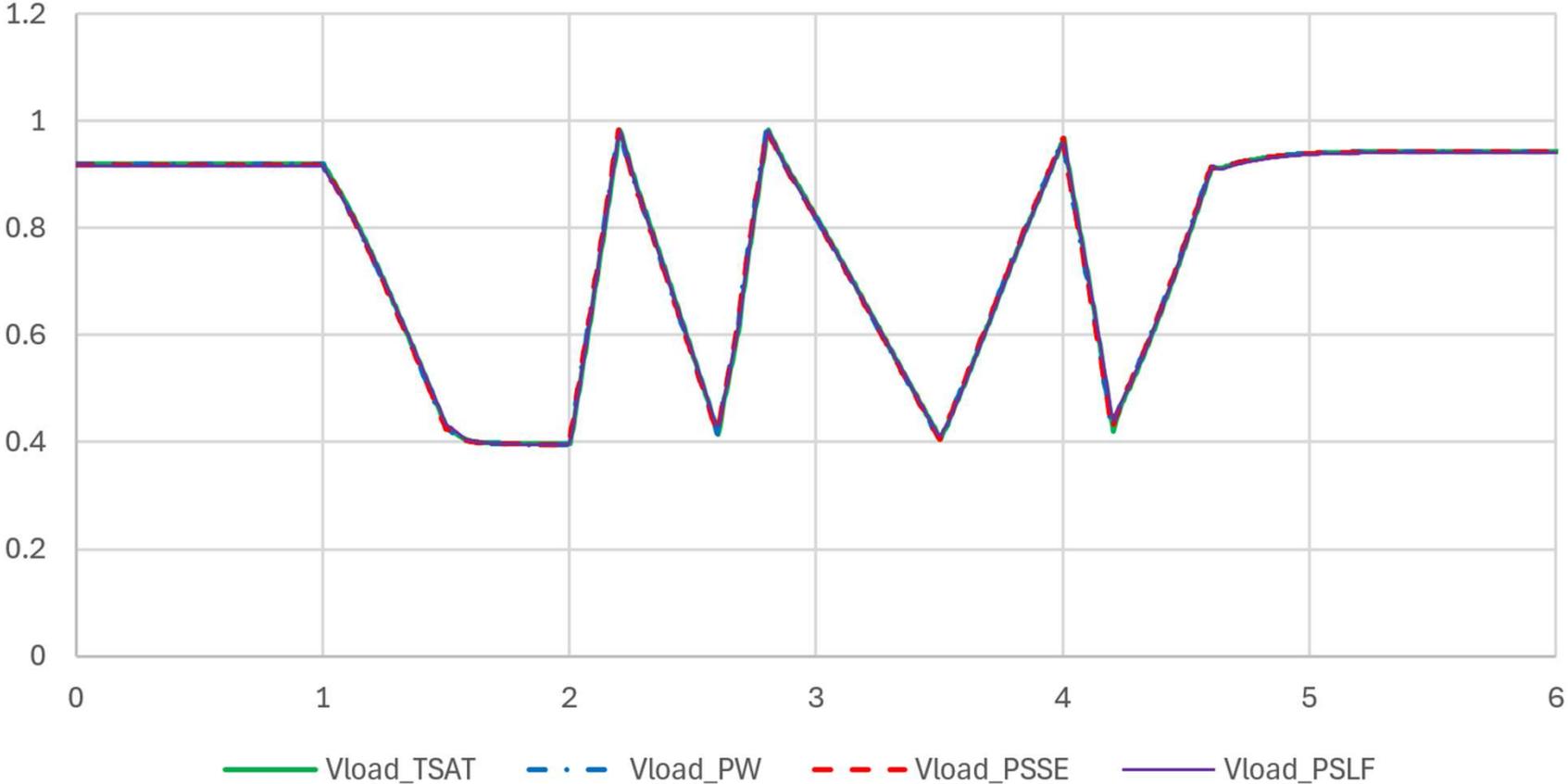
$$= 1 - 0.9 + 0.9 * 0.6667$$

$$= 0.7$$

**Recovers to final  
FracOn = 0.70**

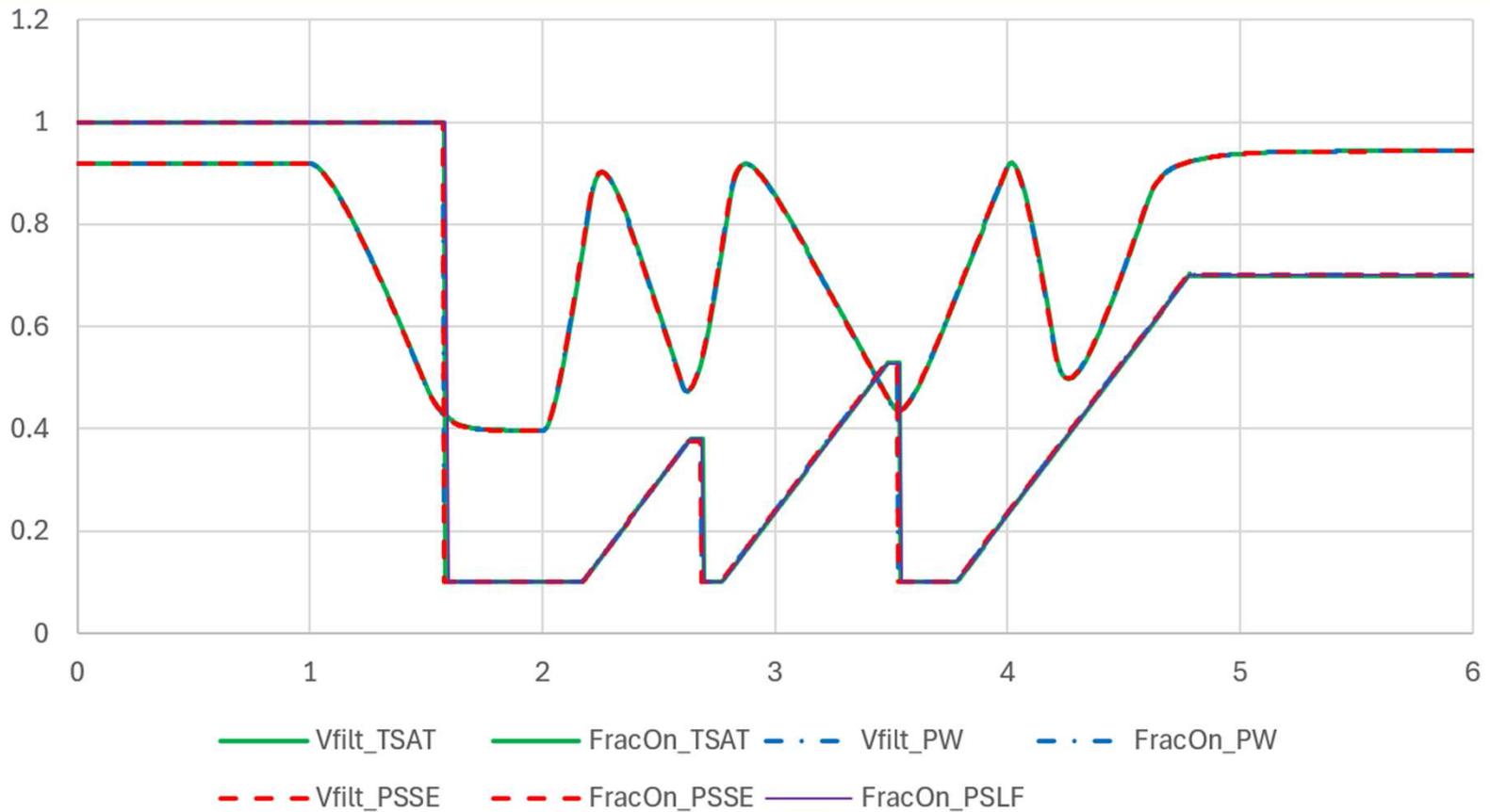
# PowerWorld, TSAT, PSSE, and PSLF Results

## Vpu at Load – Identical



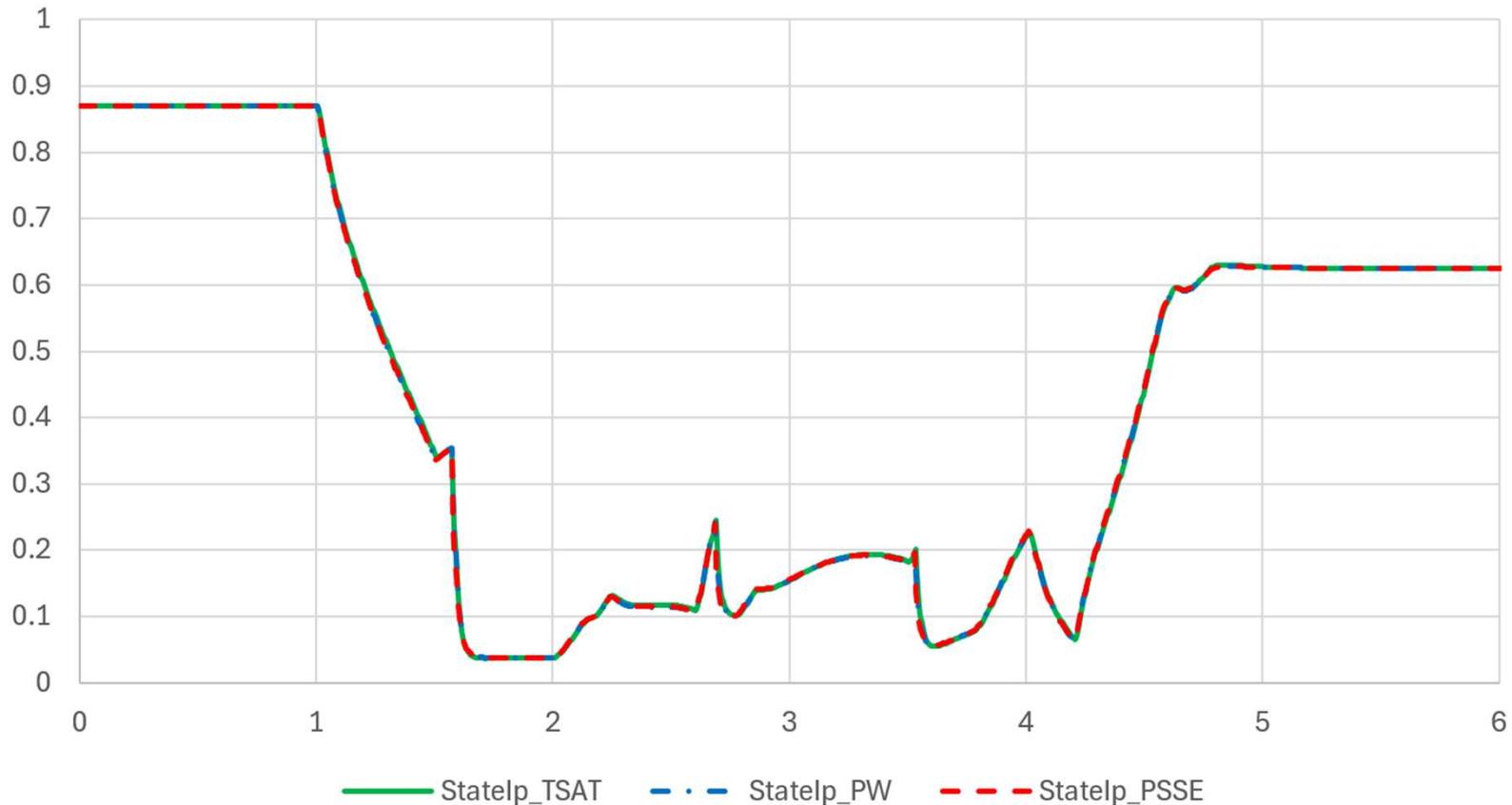
# PowerWorld, TSAT, PSSE, and PSLF Results

## Vfilt and FracOn – Identical



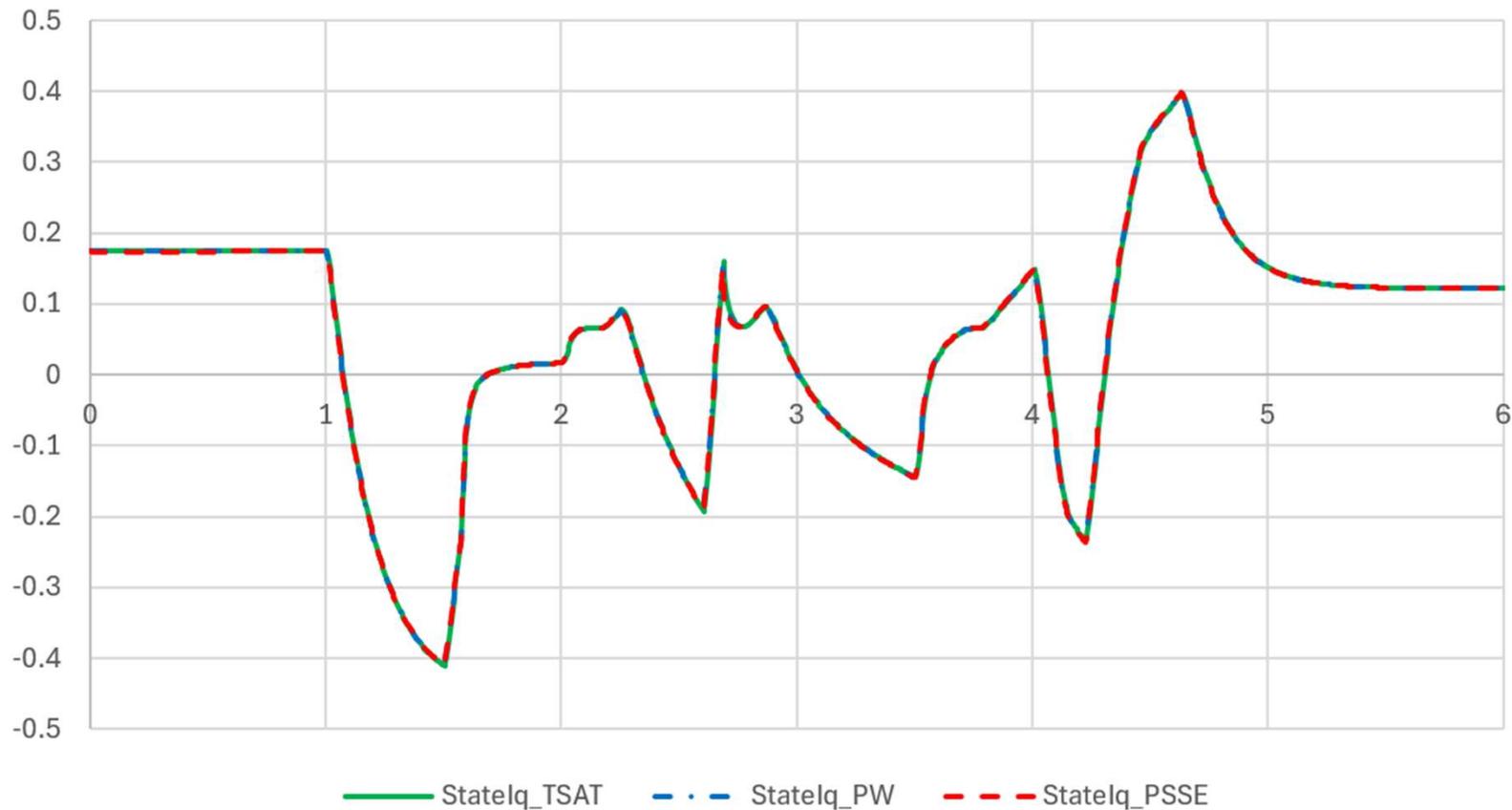
# PowerWorld, TSAT, and PSSE Results

## State Ip output of Dynamic Model – Identical



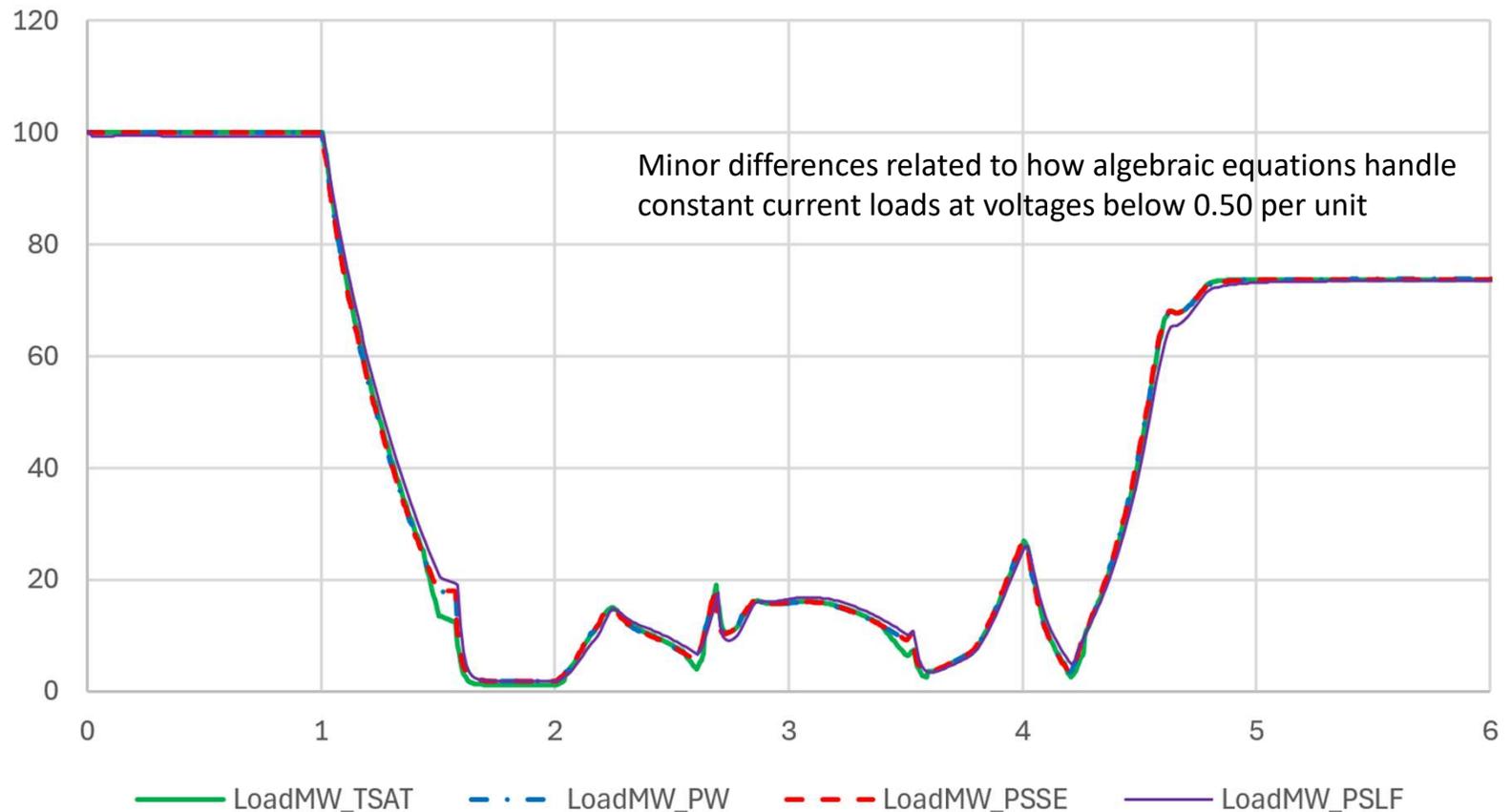
# PowerWorld, TSAT, and PSSE Results

## State Iq output of Dynamic Model – Identical



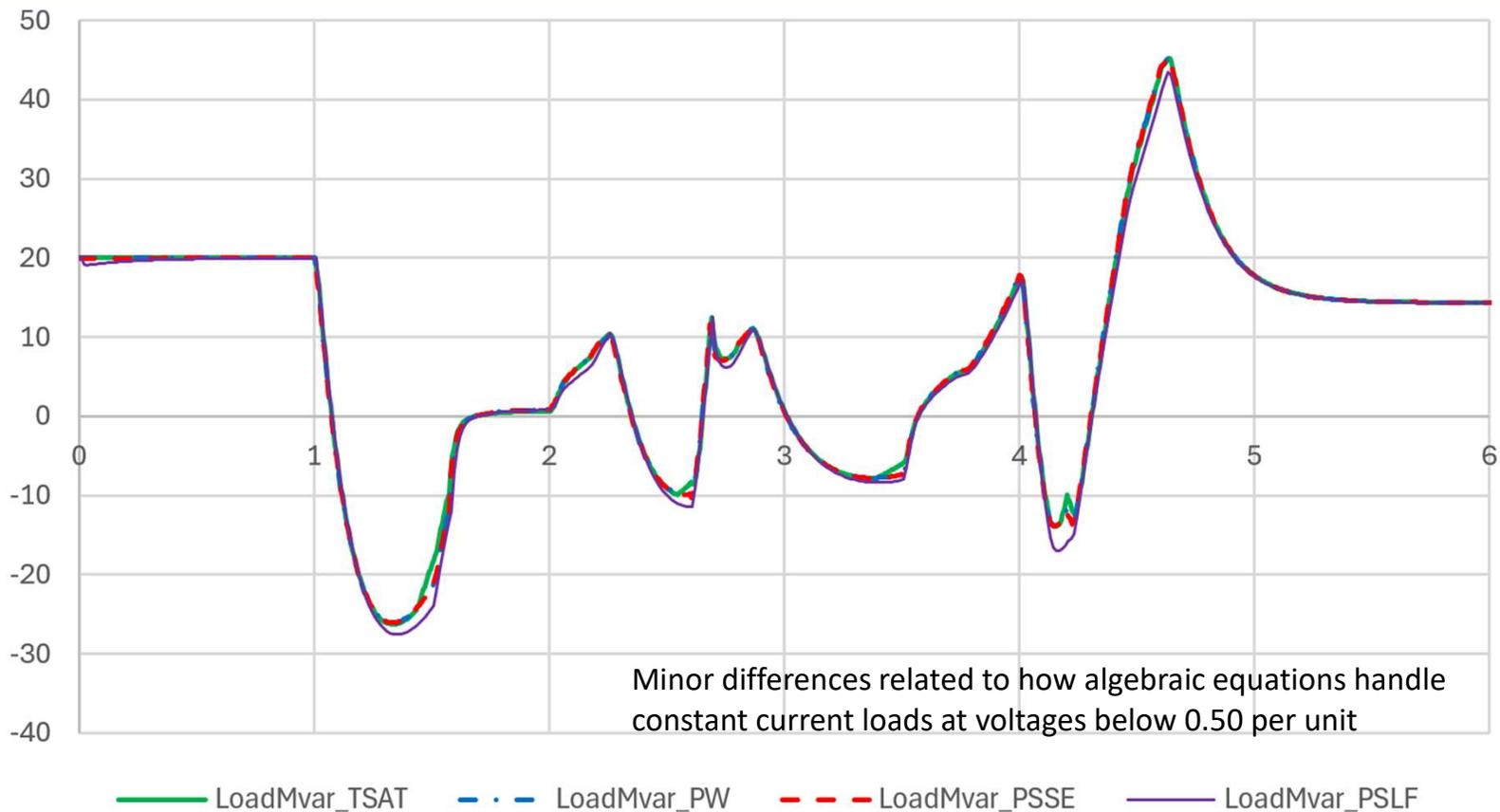
# PowerWorld, TSAT, PSSE, and PSLF Results

## 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

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- 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