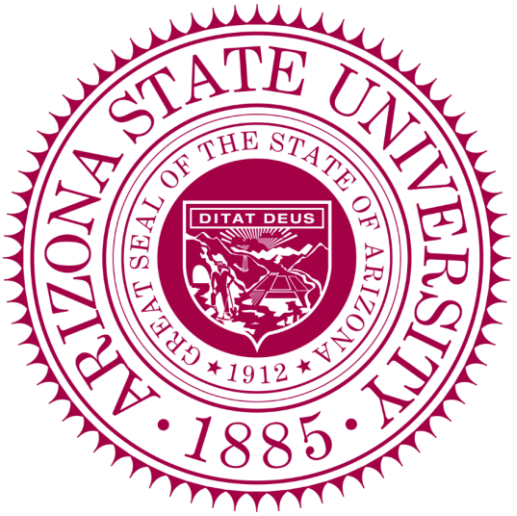


# An Improved Positive Sequence Contactor Model Development Using Deep Neural Networks

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# Outline of Talk

- Introduction
  - ❑Background
  - ❑Motivation
- EMT Contactor Model Development
- Positive Sequence Contactor Implementation
- Conclusions
- Future Work

# Background: Load Modeling

- Previously power system modeling has largely focused on the representation of power system generation and transmission components.
- Over the years, the importance of load modeling grew due to its impact on the dynamic performance. The presence of DERs in the distribution system has further enhanced this interest.
- Having an accurate load model plays an important role in transmission planning studies.
- To properly model the load, it is critical to have a good understanding of the load composition and an accurate set of load parameters.

# Background: Why EMT Load Models?

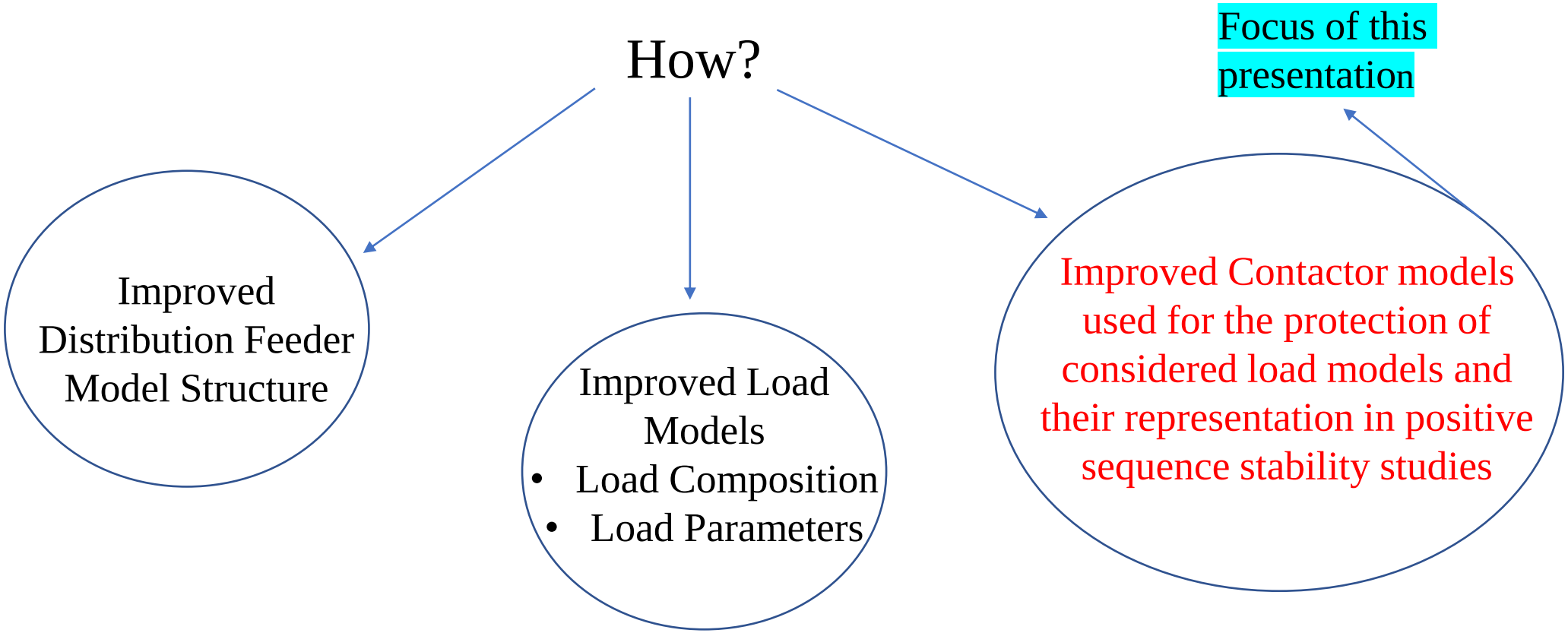
- Conventional RMS based load models are less accurate compared to corresponding EMT load models.

- Aggregated representation of RMS based composite load model is not useful to capture FIDVR events accurately.
  - ❑ All the load in composite model is placed at the end of the feeder.
  - ❑ Performance based ‘Motor D’ model, for air-conditioners, cannot capture POW phenomenon.
  - ❑ Asymmetrical faults impact on the air conditioners response cannot be captured accurately in positive sequence transient simulators.

- Many countries started using EMT based offline large scale system studies due to increasing penetration levels of IBRs.

# Motivation:

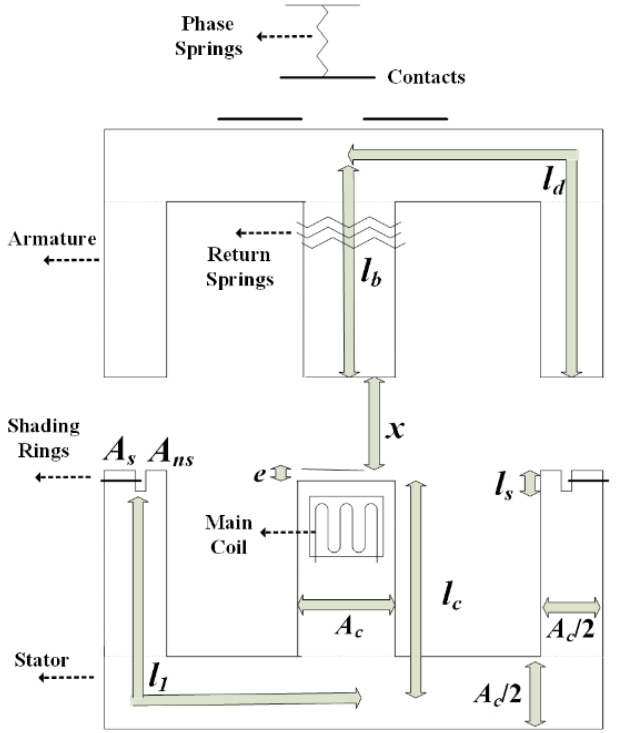
- Develop methodologies to obtain more accurate feeder and load model to represent the distribution system compared to the existing distribution feeder models in the literature



# EMT Contactor Development - Motivation

- In addition to synthesizing an accurate EMT feeder and load model comprising of loads, it is also important to include a realistic EMT contactor model for the protection of SPHIMs.
- This is to investigate their impact on the system response to FIDVR type events.
- A 24 V EMT contactor model has been developed to trip the 230 V EMT SPHIM model under low voltage conditions.

Schematic of the proposed contactor →



# EMT Contactor Development - Choosing Parameters

- The parameters of the developed contactor has been adjusted to ensure that the contactor performance satisfies the following criteria [1]:

| **Voltage Sag Level at Contactor Terminals** | | **Contactor Status** | |
|---|---|---|---|
| > 65% | | Remain unaffected | |
| 50% - 65% | | Chatters | |
| < 50% | | Trips Completely | |
| **Parameters** | | **Corresponding Parameter Values** | |
| **Geometrical** | **Electrical, Mechanical and Magnetic** | | |
| $l_c$ | $R_c$ | 23 mm | 4.5 Ω |
| $l_1$ | $R_s$ | 79 mm | 4 mΩ |
| $l_s$ | $n_1$ | 1.62 mm | 520 |
| $l_a$ | $n_2$ | 104 mm | 1 |
| $e$ | $c_1$ | 0.04 mm | 20 |
| $A_c$ | $c_2$ | 240 $mm^2$ | 6 |
| $A_s$ | $\mu_r$ | 60 $mm^2$ | 450 |
| $A_{ns}$ | $\mu_0$ | 20 $mm^2$ | $4\pi*10^{-7}$ $N/A^2$ |
| $x_{max}$ | $M$ | 5.6 mm | 0.75 kg |
| $x_c$ | $g$ | 2 mm | 9.81 $m/s^2$ |

→ Emulating the behavior of laboratory tested residential contactors

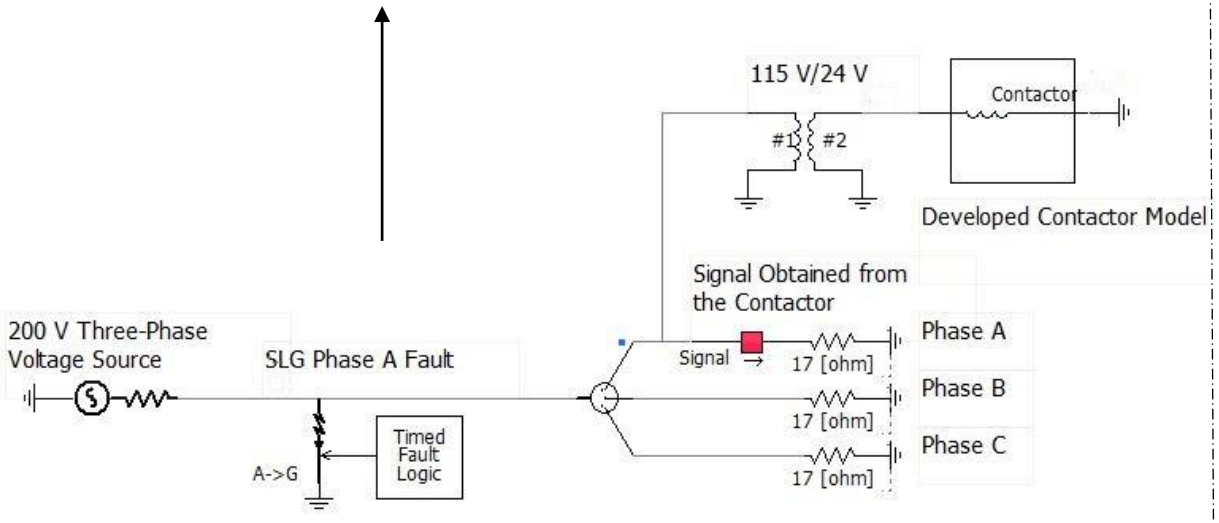
→ Final Contactor Parameters

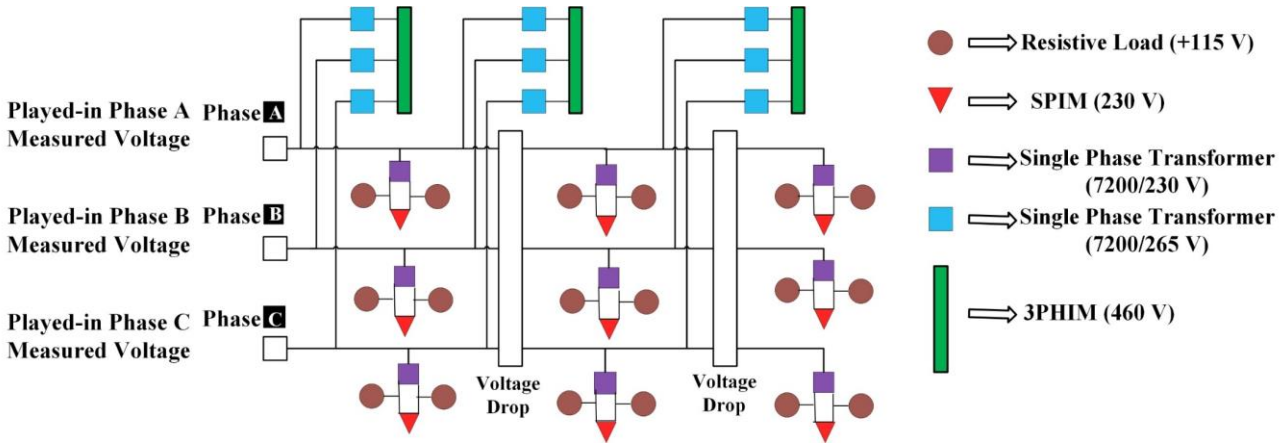
[1] Karady, George G., Saurabh Saksena, Baozhuang Shi, and Nilanjan Senroy. "Effects of voltage sags on loads in a distribution system." Power System Engineering Research Center (2005).

# EMT Contactor Development – Contactor Integration into Feeder

- A 24 V EMT contactor has been integrated into the proposed feeder and load model using a 115V/24 V transformer.

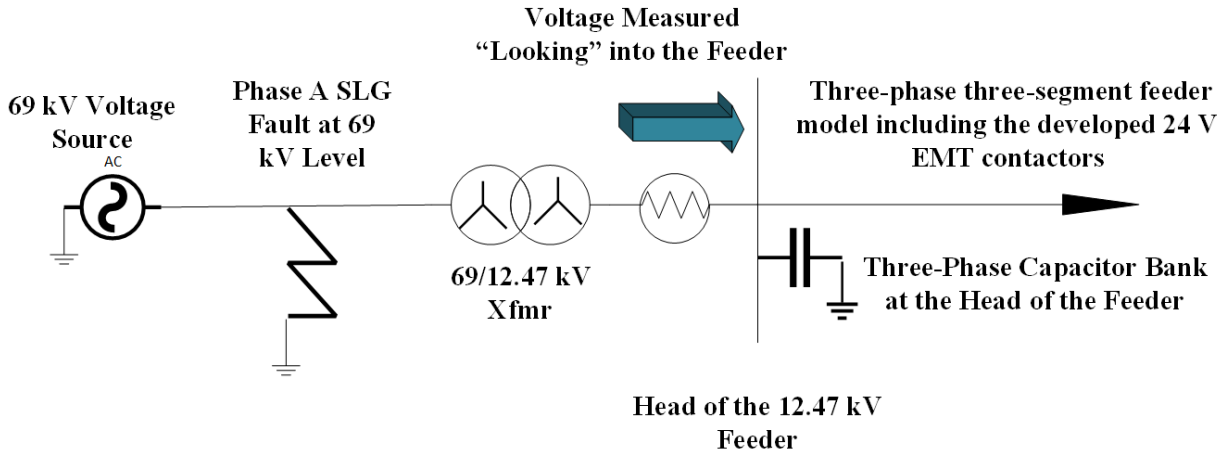
## Individual Contactor Unit Testing in PSCAD



# EMT Contactor vs PS Contactor - Cases Setup [2]

- Three scenarios have been simulated to achieve this objective:
  - ❑ Scenario A: No Contactors (NC) – Any type of contactors are not used.
  - ❑ Scenario B: EMT Contactor Model (EMTC) – Developed EMT contactor integrated into the proposed feeder model.
  - ❑ Scenario C: Contactor Logic Model (CL) – Developed based on the 'Vc1off' and 'Vc2on' parameters of 'Motor D' model in CMPLDW model.

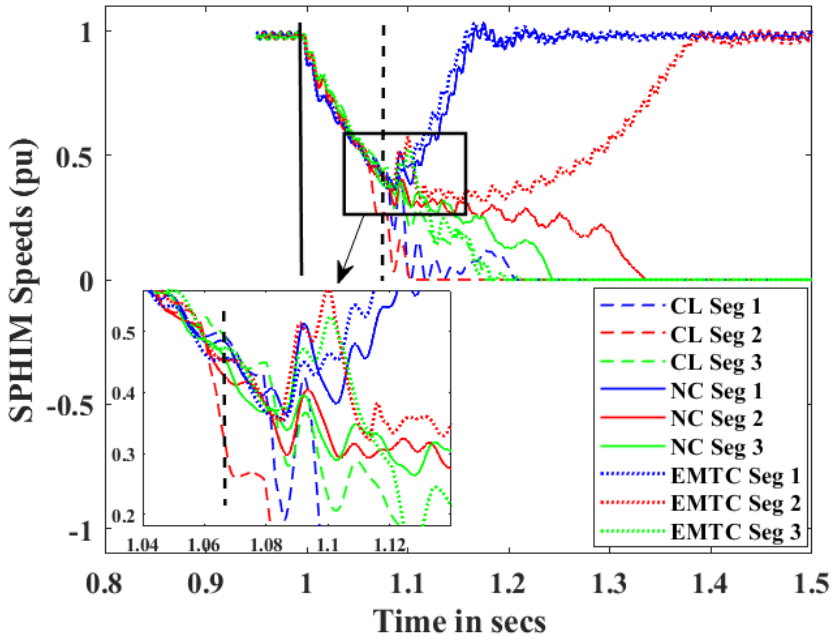


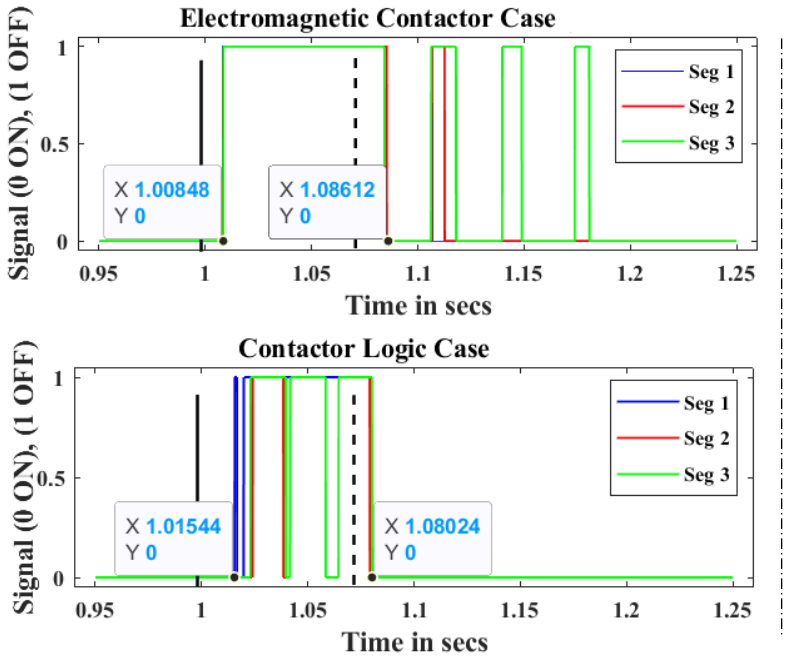

Circuit Schematic used for simulations using a residential summer feeder model

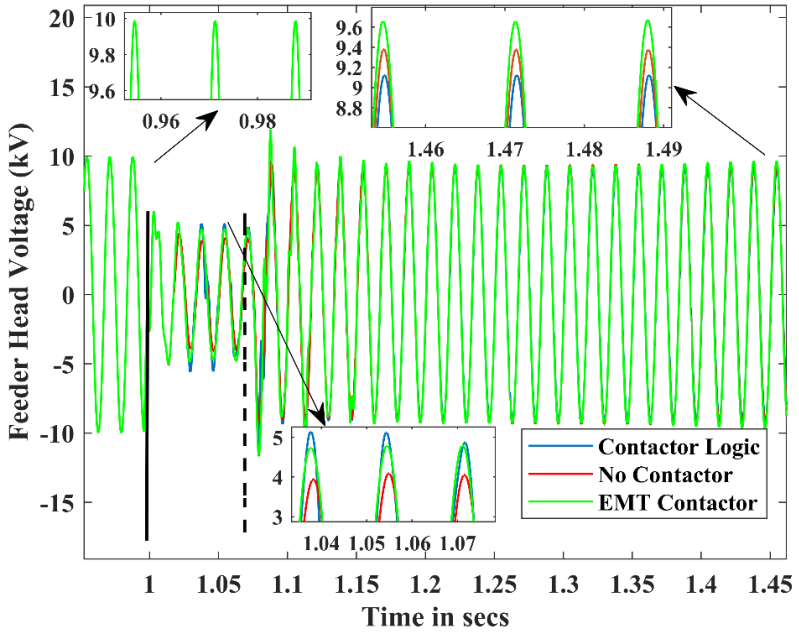
***Overall Observation:*** Performance of EMT contactor and conventional PS contactor is significantly different and has huge impact on system performance.

[2] S. Nekkalapu, V. Vittal, "EMTP Contactor Modeling for Load Modeling Studies", Paper # 22PESGM1462, IEEE PES GM 2022 – Denver, CO

# EMT Contactor vs PS Contactor - Simulation Results




Number of SPHIM segments stalled:
(i) NC Case – 2
(ii) CL Case – 3
(iii) EMTC Case – 1

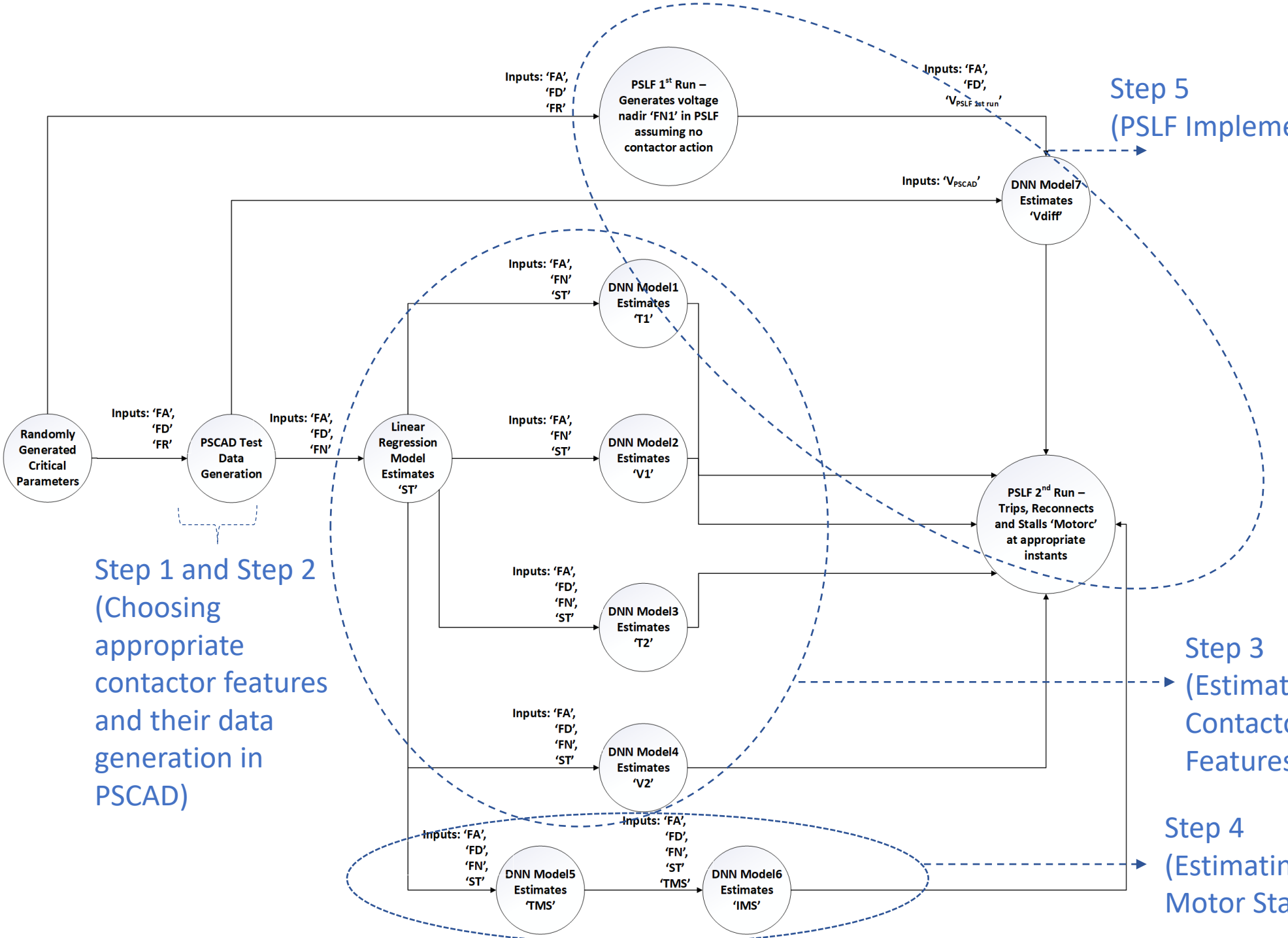
The time instants at which the EMT contactor trips and reconnects is different to the PS contactor

Varied system behavior for different cases

# Steps Followed to Develop a Novel PS Contactor Based on the EMT Contactor Critical Characteristics

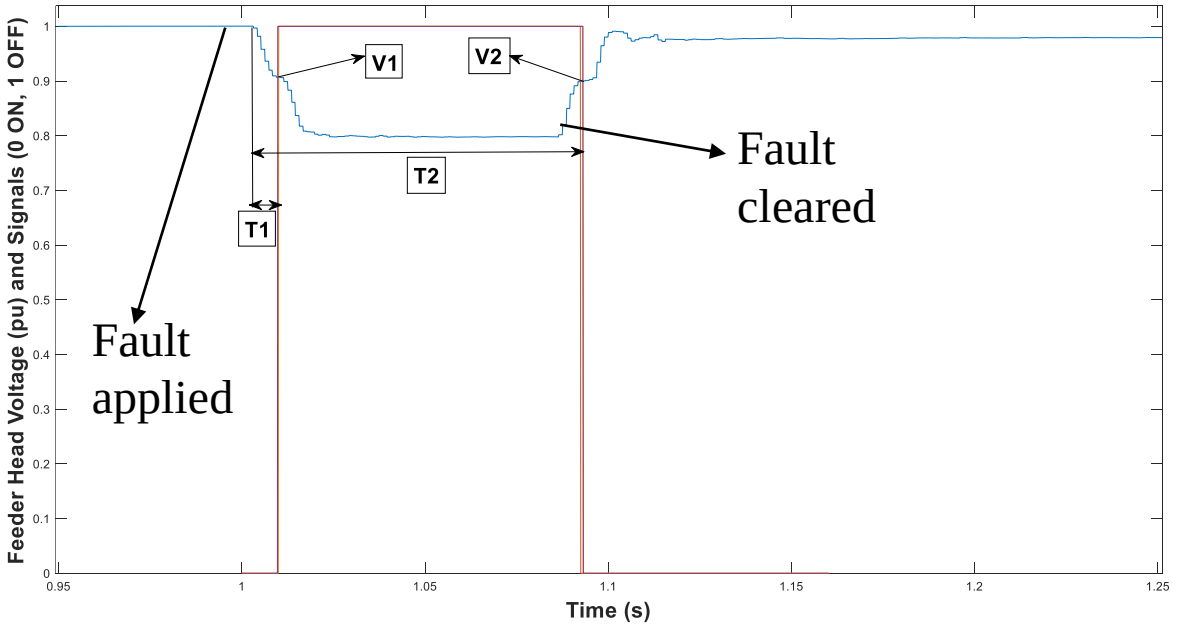
- Step 1: Choosing features of the contactor (status, trip and reconnection settings)
- Step 2: Features generation using PSCAD (generate a large number of test cases)
- Step 3: Development of regression models (linear regression model and deep neural networks) to estimate the contactor features.
- Step 4: Development of regression models (DNNs) to estimate motor stalling behavior in the presence of the developed contactor model.
- Step 5: Implementation of the developed contactor model into PSLF environment.
- Step 6: Comparison between PSLF simulation results vs PSCAD simulation results.

# Overall Implementation of the Proposed Methodology



# Step1:Estimating Contactor Settings -Choosing Features

- Typically, power system engineers have access to voltage measurements at the high voltage and low voltage side of the substation (230 kV, 69 kV and 12.47 kV).
- Therefore, the following characteristics of the EMT contactor performance along the feeder, are desired based on the Positive Seq. **head of the feeder voltage** –
  - ❑ '**ST**': Trip status of the contactors (no trip, chattering or tripping)
  - ❑ '**T1**', '**V1**', **T2**', '**V2**': EMT contactor trip and reconnection settings.



# Step2:Estimating Contactor Settings - Cases Generation

- 300 SLG fault test cases have been generated with the same circuit setup used to conduct contactor performance comparison studies earlier.
- It was observed that for any case, all three contactors (along the three segments) per phase have the same trip status.
- The following critical parameters are randomly generated (from ‘Matlab’), within the bounds, to be used in each test case respectively –
  - ❑ ‘**FR**’: Fault Resistance
    - ✓ Lower Bound: 0 ohm
    - ✓ Upper Bound: 4 ohm
  - ❑ ‘**FD**’: Fault Duration
    - ✓ Lower Bound: 4 cycles
    - ✓ Upper Bound: 6 cycles
  - ❑ ‘**FA**’: Fault Angle
    - ✓ Lower Bound: 0 radians
    - ✓ Upper Bound: 1/240 radians (quarter cycle)

# Step3:Estimating Contactor Settings –Linear Regression

- Using, linear regression, the 'ST' parameter (trip status) has been estimated with 98% accuracy (75% training and 25% testing cases) using the following criterion –
  - ❑ If estimated '$Y_{test}$' < 1 then 'ST' = 0 (no tripping)
  - ❑ If estimated 1 < '$Y_{test}$' < 2 then 'ST' = 1.5 (Chattering)
  - ❑ If estimated '$Y_{test}$'> 2 then 'ST' = 3 (Tripping)
- The following inputs (after normalization) are used for the linear regression –
  - ❑ '*FA*' (fault angle), '*FD*' (fault duration) and '*FN*' (head of the feeder positive sequence voltage nadir)

Linear Regression Model → $Y_{test} = 0.0177 * FA - 0.0316 * FD - 1.1839 * FN + 1.4$

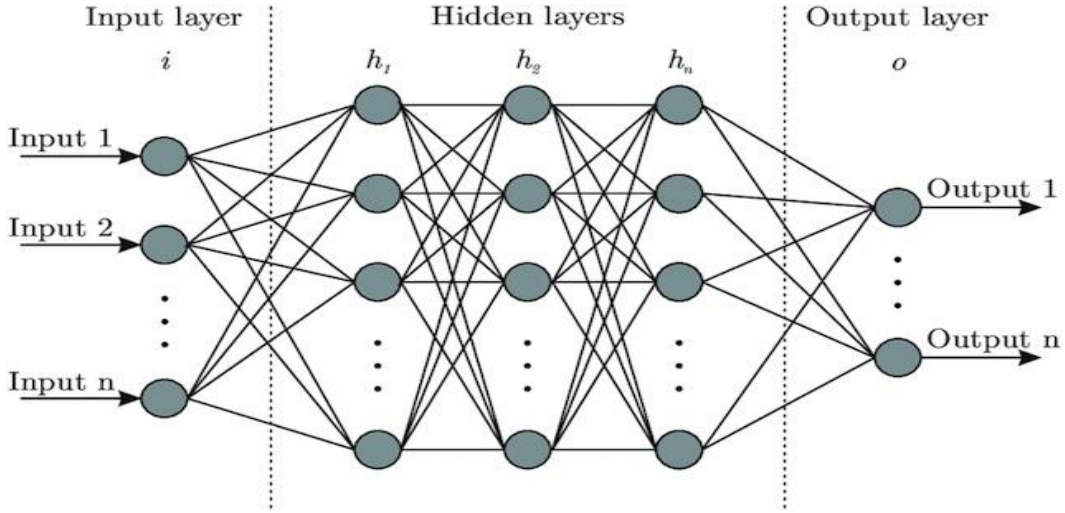
- The trip status of the contactor is primarily dependent on the voltage nadir (at the feeder head) and significantly less correlated to the fault angle and fault duration parameters.

# Step 3: Estimating Contactor Settings - DNN Models

- It was observed that using a simple linear regression approach to estimate the trip settings parameters ‘T1’, ‘V1’, ‘T2’ and ‘V2’ yields results with very poor accuracy.
- Therefore, deep neural networks (DNN) have been employed to estimate the trip setting parameters.
- For estimating the EMT contactor settings, the following inputs after normalization are used:
  - ❑ For DNN models 1 and 2 ‘T1’ and ‘V1’: ‘FA’, ‘FN’ and ‘ST’ (obtained from PSCAD)
  - ❑ For DNN models 3 and 4 ‘T2’ and ‘V2’: ‘FA’, ‘FN’, ‘FD’ and ‘ST’ (obtained from PSCAD)

# Step 3: Estimating Contactor Settings - DNN Details

A General NN Basic Diagram →




- Four different NN models have been developed for estimating each desired output, respectively.

| Model Number | Estimated Output Parameter | Number of Hidden Layers | Number of neurons for each hidden layer respectively | Number of epochs before the training process is terminated |
|---|---|---|---|---|
| DNN Model 1 | 'T1' | 5 | 10, 4, 10, 5 and 2 | 3000 |
| DNN Model 2 | 'V1' | 4 | 6, 6, 5 and 3 | 2100 |
| DNN Model 3 | 'T2' | 4 | 13, 7, 13 and 7 | 900 |
| DNN Model 4 | 'V2' | 4 | 13, 7, 16 and 8 | 1200 |

# Step 3: Estimating Contactor Settings - DNN Results

- 'Adam' optimizer algorithm and 'Relu' activation function have been used to model the DNNs.
- Both 'V1' and 'V2' parameters are estimated within a desirable 5% error bandwidth in the voltages.
- Both 'T1' and 'T2' parameters are estimated with an average RMS error less than or close to 1 time step typically used in PSLF (1/4 cycle).

| **Model** | **Average Training RMS Error** | **Average Testing RMS Error** |
|---|---|---|
| 'T1' DNN model | 2.77 ms | 2.09 ms |
| 'V1' DNN model | 0.0068 pu (0.68 % pu) | 0.0098 pu (0.98 % pu) |
| 'T2' DNN model | 3.62 ms | 4.67 ms |
| 'V2' DNN model | 0.013 pu (1.3 % pu) | 0.021 pu (2.1% pu) |

# Step 4: Estimating Motor Stalling – DNN Models

- TMS DNN 5 Model– Estimates total number of feeder segments in which SPHIMs stalled

- IMS DNN 6 Model– Estimates individual segments in which SPHIMs stalled which uses the estimated ‘TMS’ from TMS DNN model as another input to this model.

# Step 4: Estimating Motor Stalling – DNN Models

- It is important (to capture FIDVR) to estimate accurately if the SPHIMs either stalls or reaccelerates after the fault is cleared and the contactors reconnects based on the PS **head of the feeder voltage**.

- Two DNN models have been developed with the following inputs and outputs:
  - ❑ DNN Model 5 estimates 'TMS' (output) – 'FA', 'FN', 'FD', 'ST' (inputs obtained from PSCAD)
  - ❑ DNN Model 6 estimates 'IMS' (3 outputs) – 'FA', 'FN', 'FD', 'ST' and 'TMS' (inputs obtained from PSCAD)

# Step 4: Estimating Motor Stalling – DNN Models

- Possible values of TMS output – 0, 1, 2, and 3
- Possible values of IMS outputs – (0,1), (0,1), and (0,1)
- The testing accuracy of the TMS DNN and IMS DNN models are observed to be 95% (71 out of 75 cases passed) and 94% (70 out of 75 cases passed) respectively.

| Model Number(s) | Estimated Output Parameter(s) | Number of Hidden Layers | Number of neurons for each hidden layer respectively | Number of epochs before the training process is terminated |
|---|---|---|---|---|
| DNN Model 5/6 | TMS/IMS | 4 | 35,30,30 and 20 | 1500 |

# Step 4: Estimating Motor Stalling – Failed Cases for the IMS DNN Model

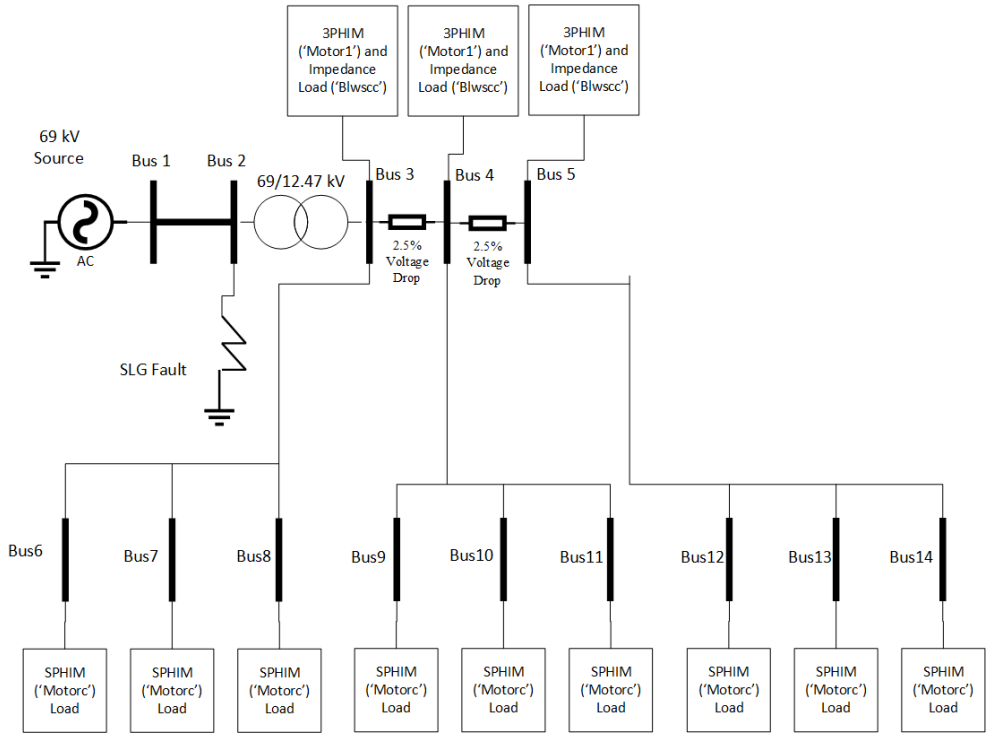
| | Seg 1 True | Seg 2 True | Seg 3 True | Seg 1 Est | Seg 2 Est | Seg 3 Est | Voltage Nadir |
|---|---|---|---|---|---|---|---|
| Case 1 | 0 | 0 | 1 | 0.778948 | 0.046254 | 0.159233 | 0.8644 |
| Case 2 | 0 | 1 | 1 | 0.998342 | 1 | 0.885822 | 0.8353 |
| Case 3 | 0 | 0 | 1 | 0.512823 | 0.553609 | 3.00E-06 | 0.8664 |
| Case 4 | 0 | 1 | 1 | 0.99354 | 1 | 0.999717 | 0.8336 |
| Case 5 | 0 | 1 | 1 | 0.998729 | 1 | 0.456658 | 0.8393 |

0 – Motors did not stall, 1 – Motors did stall

# Step 5: PSLF Implementation - Case setup in PSLF

- The estimated EMT contactor trip and reconnection settings have been used to develop a new positive sequence contactor model to trip ‘motorc’ [2] model in PSLF.
- ‘motorc’ model is a custom-built phasor-based PS SPHIM model, represented as a three-phase balanced SPHIM model in PSLF.

Circuit Schematic used in PSLF simulations comprising of ‘motor1’, ‘motorc’ and ‘blwscc’ loads and three segment feeder




[2] B. Lesieutre, D. Kosterev and J. Undrill, "Phasor modeling approach for single phase A/C motors," 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1-7, doi: 10.1109/PES.2008.4596554.

# Step 5: PSLF Implementation - DNN to estimate PSLF voltage nadir

*How to use 'FN' without using PSCAD for the developed DNNs?*

- PSLF Run1: Firstly, a SLG fault dynamic run in PSLF has been conducted assuming there are no contactors in the PSLF feeder model.
- '$V_{diff}$' = (Voltage nadir obtained from PSCAD) – (Voltage nadir obtained from PSLF 1$^{st}$ run).
- '$V_{diff}$' parameter has been estimated using another DNN model 7 (with four hidden layers: 8, 15, 8 and 5 neurons respectively) whose inputs are:
  - 'FR': Fault resistance (obtained from system parameters)
  - 'FD' : Fault duration (obtained from system parameters)
- It was observed that '$V_{diff}$' has been estimated with very good accuracy (average RMS error of around 0.003 pu).

# Step 5: PSLF Implementation– PSLF Script Generation

- The weights and biases obtained for the trained DNN models (Models 1-7) are fed into the EPCL script via *csv files.

- As the DNN models are already trained via Python Google Colab platform, the time taken to run the DNN models via the EPCL script to obtain the estimated contactor and motor stalling settings, for any case, is ***instantaneous***.

- Equation $\longrightarrow$ $n_{i,j} = Relu\left(b_{i,j} + \sum_{k=1}^{(i-1)_{no\ of\ neurons}} \left(w_{i-1,j} n_{i-1,k}\right)\right)$

  To calculate the estimated parameters from the trained DNNs at the start of 2nd PSLF run

# Step 5: PSLF Implementation - Final Steps

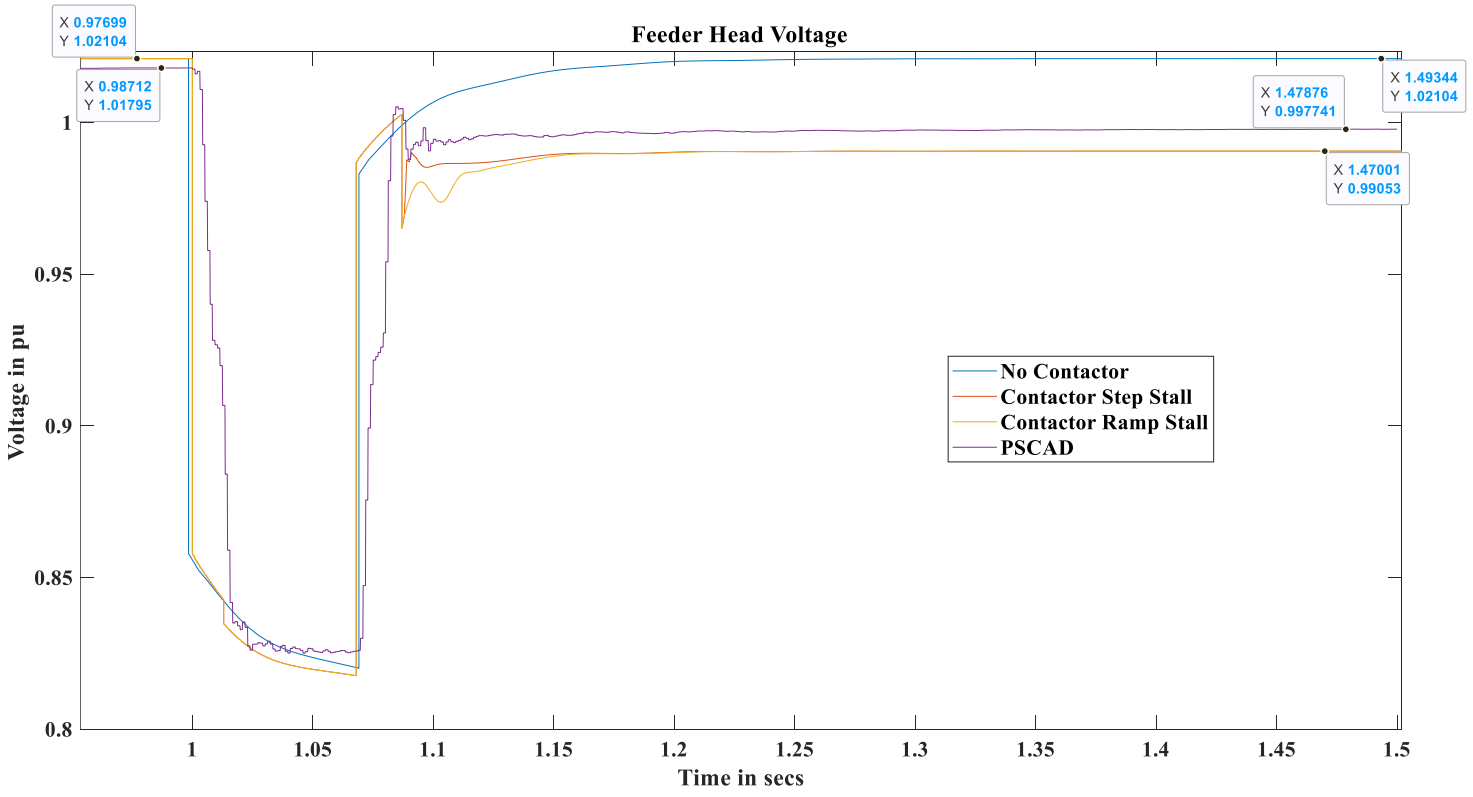
- PSLF Run2: Using estimated '$V_{diff}$', the EMT contactor settings are estimated at the start of this run and are implemented using the following criterion:
  - Tripping: The 'motorc' models are tripped when the head of the feeder voltage goes below *'V1'* for *'T1'* secs after the fault is initiated.
  - Reconnecting: The tripped 'motorc' models are reconnected to the feeder after the fault is cleared when the positive sequence head of the feeder voltage recovers above *'V2'* and after *'T2'* secs from the moment fault is initiated.
  - Stalling: The reconnected 'motorc' models are ***forced*** to stall at appropriate segments based on DNN models 5 and 6 estimated results.

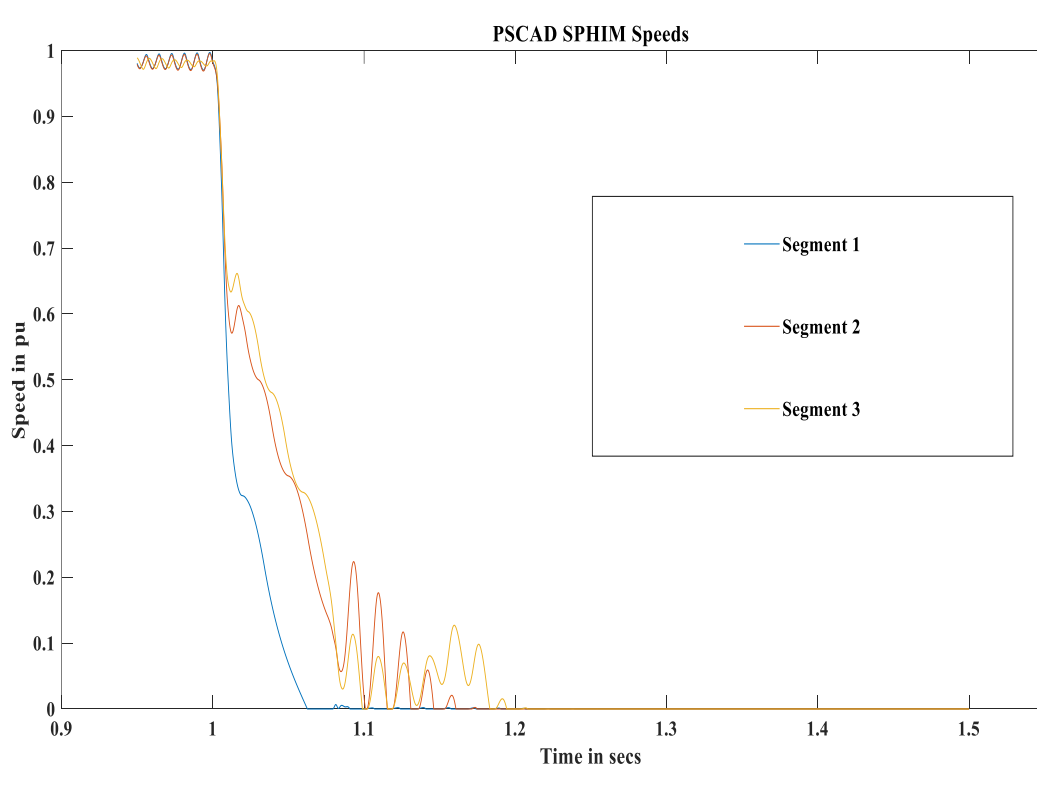
# Step 5: PSLF Implementation– Final Steps

- Therefore, based on the estimated TMS and IMS outputs from DNN 5 and 6 models, the following different cases have been generated in PSLF Run2:
  - **'Contactor No Stall'**: The 'motorc' models are ***not*** forced to stall in PSLF.
  - **'Contactor Step Stall'**: The 'motorc' models are ***forced*** to stall in PSLF after they are reconnected by adding a large load torque (80 pu) as a step response.
  - **'Contactor Ramp Stall'**: The 'motorc' models are ***forced*** to stall in PSLF after they are reconnected by adding large load torques (1.1 pu) incrementally.

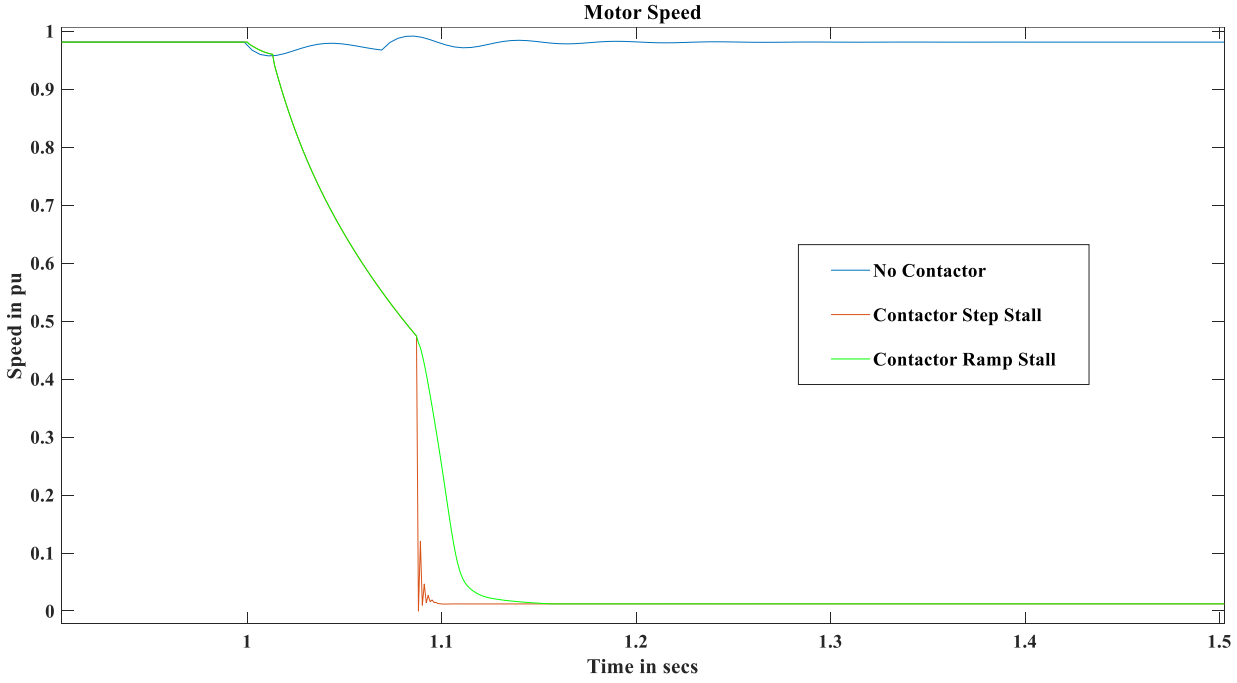
# Step 6: PSLF vs PSCAD Results – Fully Tripped and Fully Stalled Case

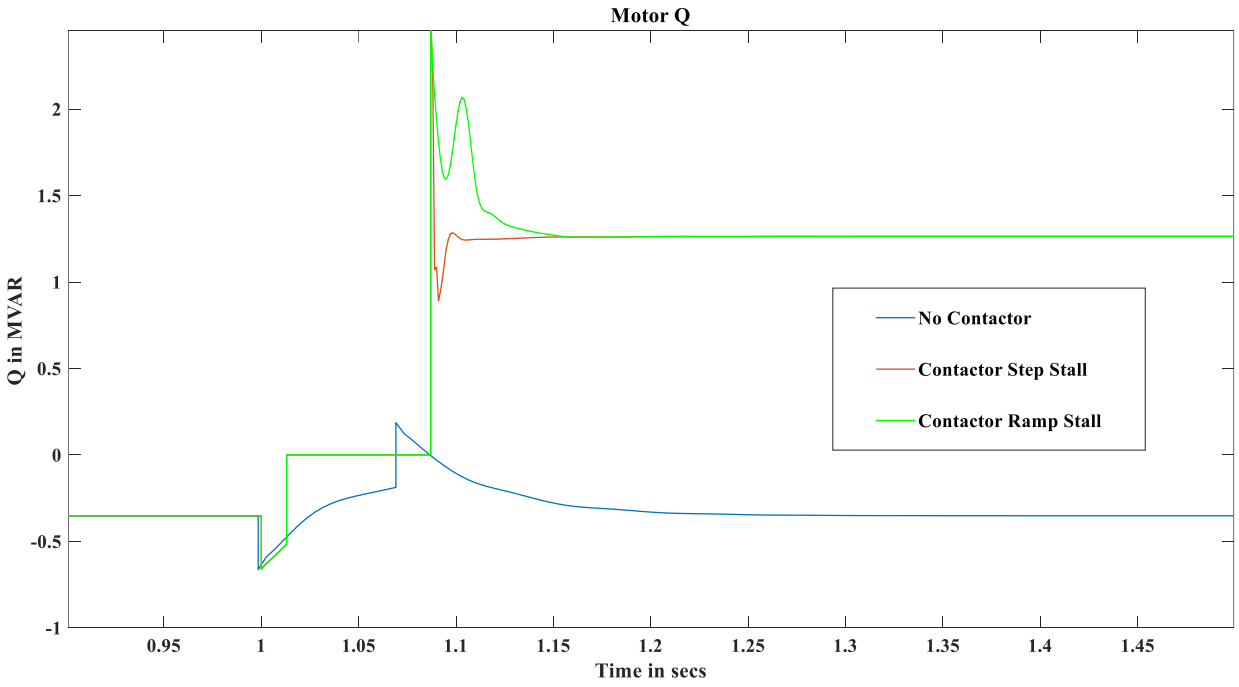
- It was observed that the 'Contactor Step Stall' case response in PSLF closely resembles to its corresponding PSCAD test case system response immediately after the 'motorc' model is reconnected to the feeder.
- The PSCAD simulation and the DNN 5 and 6 models show that the 'motorc' models in all segments have stalled after reconnection.



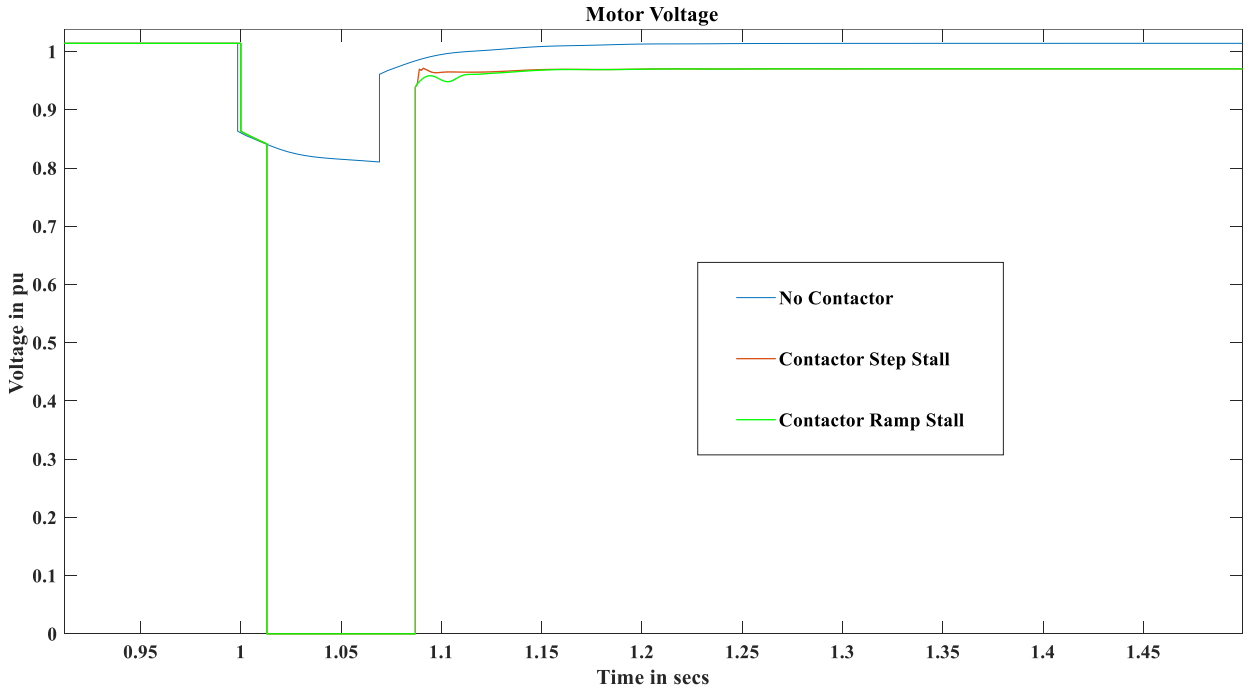



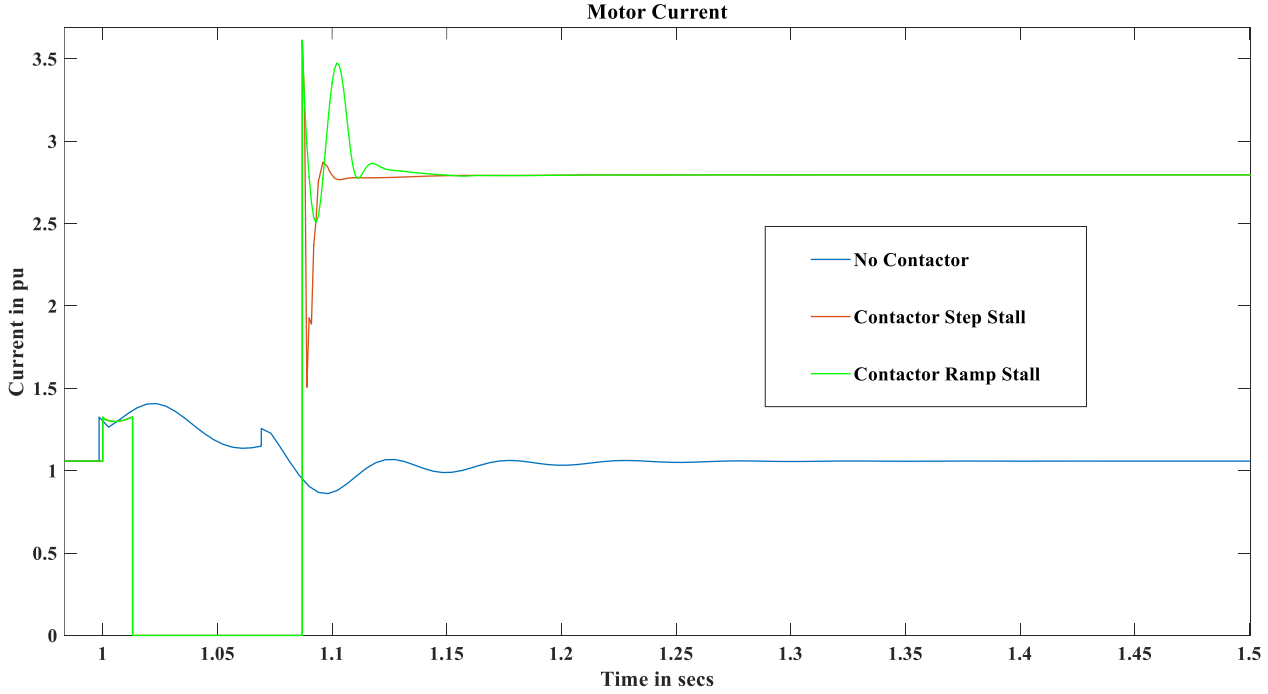
# Step 6: PSLF vs PSCAD Results– Fully Tripped and Fully Stalled Case



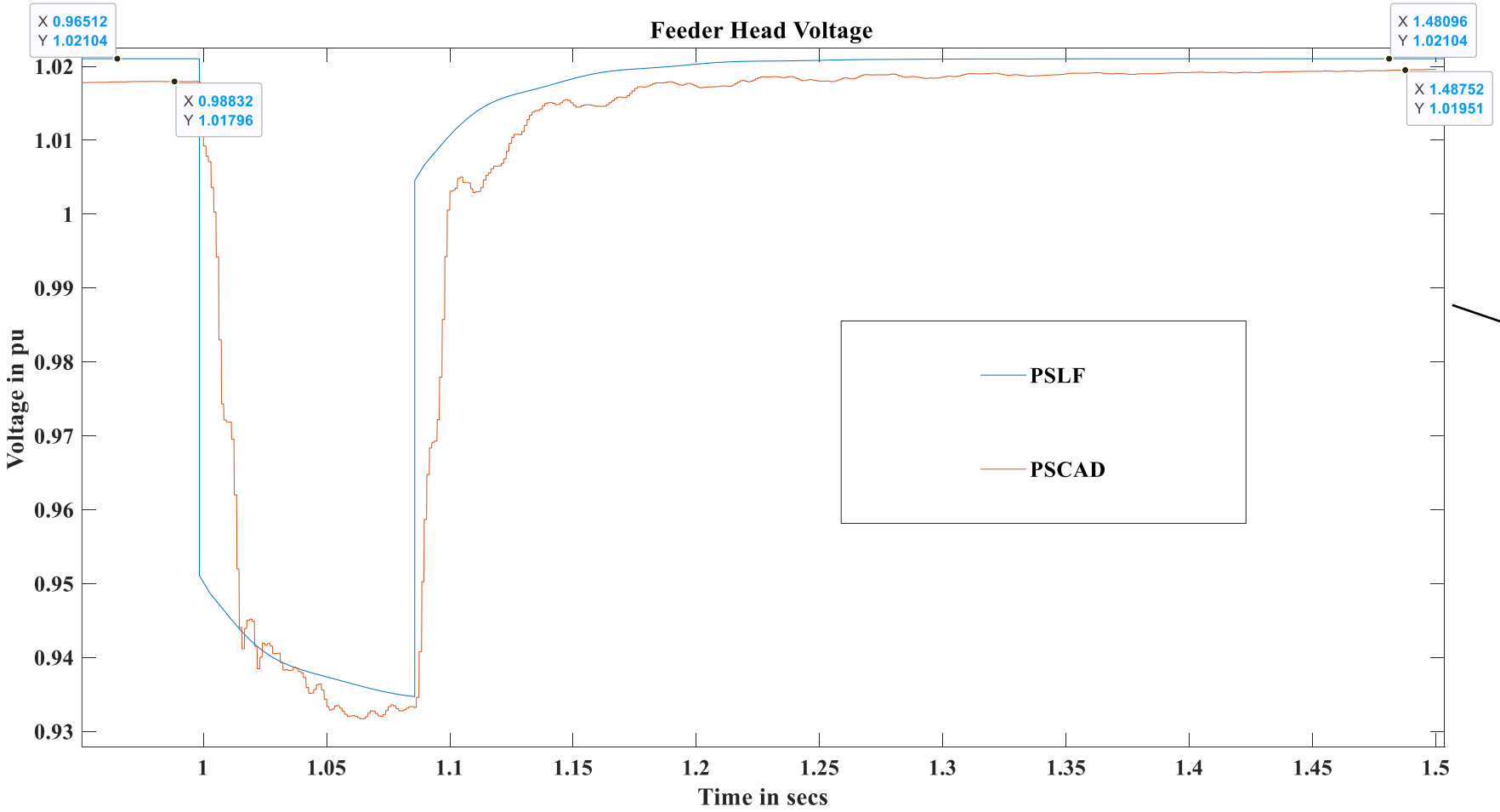



# Step 6: PSLF vs PSCAD Results– Fully Tripped and Fully Stalled Case



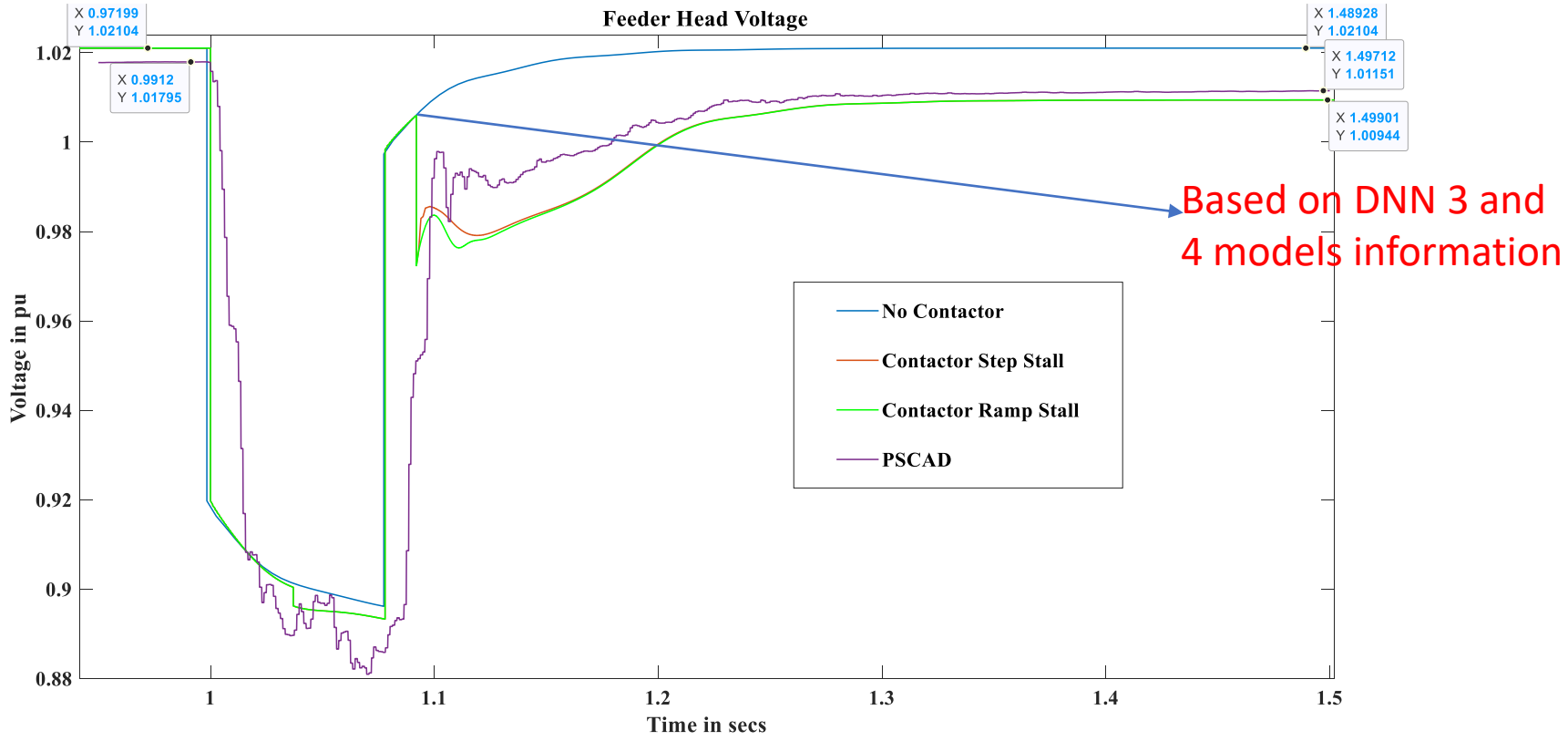
# Step 6: PSLF vs PSCAD Results– No Tripping and No Stalling Case



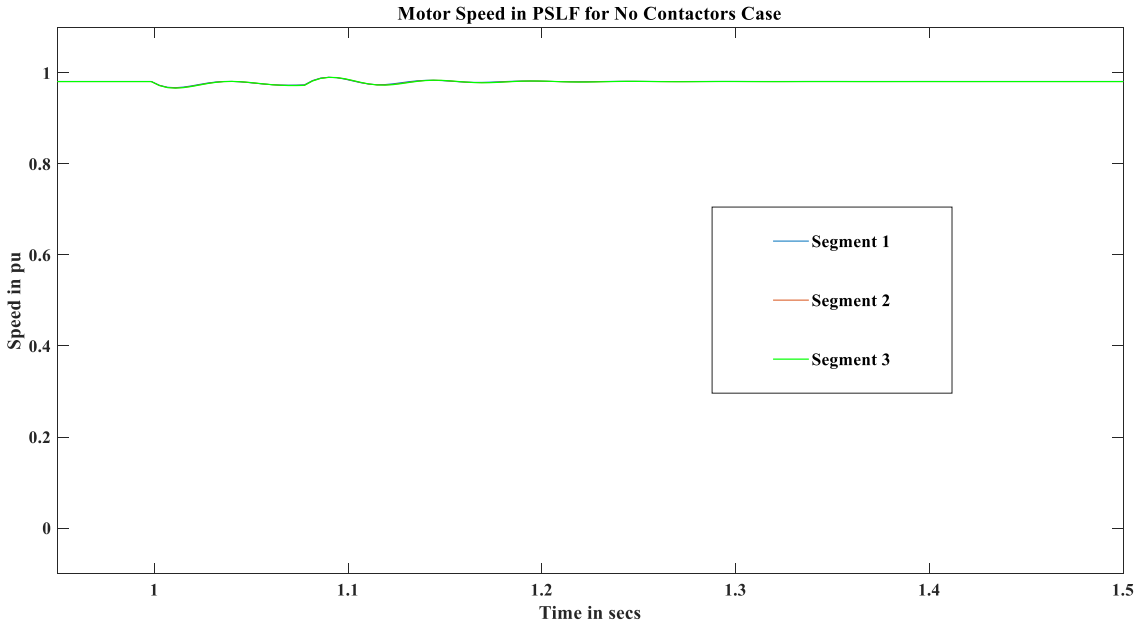

The SPHIM speeds in both PSCAD and PSLF simulations are barely affected for this fault.

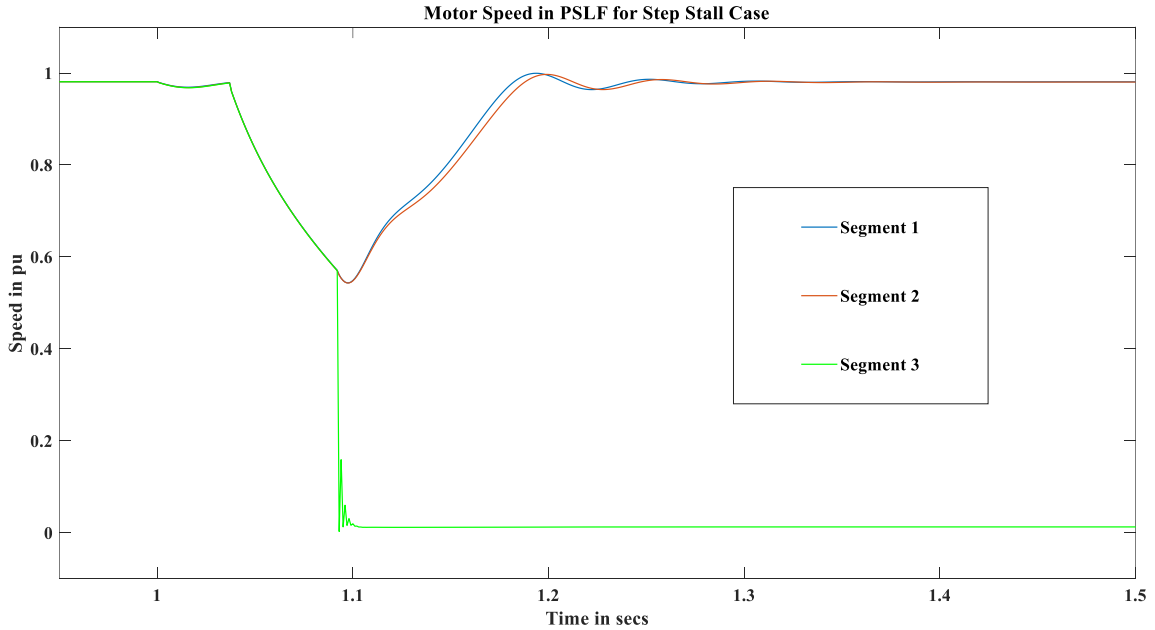
# Step 6: PSLF vs PSCAD Results– Contactor Chattering and Partially Stalled Case

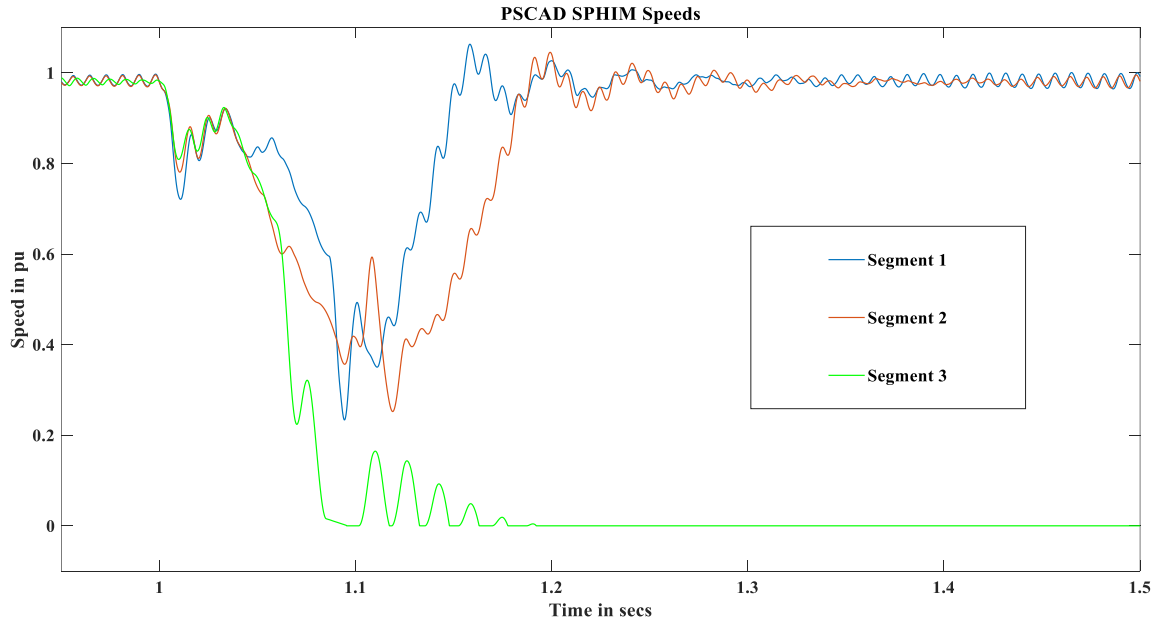
- It was observed that for this case, only the third segment SPHIMs stalled and the SPHIMs in the other segments reaccelerated after they are reconnected.
- This phenomenon is also captured by the developed DNNs.



# Step 6: PSLF vs PSCAD Results–Results: Contactor Chattering and Partially Stalled Case



# Three-Phase Fault Analysis

- After generating new three-phase fault test cases, it is observed that the developed methodology (SLG faults) is not applicable/scalable to three-phase faults.
- This is because the behavior of the SPHIM stalling and contactor behavior along the three phases is different due to the different points along the sine wave at which the fault is seen.
- Currently, efforts are being directed towards developing regression models to capture the contactor and SPHIM behavior for three-phase faults.

# Conclusions (Contactor Modeling)

- System response (without contactors) is significantly different compared to the system response (with contactors).
- EMT contactor response is significantly different to the positive sequence contactor response.
- The regression models (linear and DNNs) developed estimate the desired contactor trip and reconnection settings and motor stalling with a good accuracy.
- A novel pos. seq. contactor model has been developed that captures the critical characteristics of the EMT contactor accurately in PSLF for SLG faults.
- The developed regression models are not sufficient to capture the contactor and motor behavior for three-phase faults.

# Future Work

- The regression models in the proposed methodology would be updated to capture the three-phase faults accurately.

- The proposed methodology, to trip and stall the ‘motorc’ model, would be tested on a more detailed structured feeder model whose topological details would be obtained from the local utility.

# Thank You!

# Questions?