Synthesis of Load Parameters Using Point on Wave Measurements – Project S-80

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PSERC

PSERC Webinar

March 15, 2022

Presentation Outline

- **Introduction**
  - **Background**
  - **Motivation**
  - **Objectives**
- **Load Synthesis Procedure**
- **Conclusions**
- **Future Work**

Background: Load Modeling

- Previously the primary emphasis in power system modeling was largely focused on power system generation and transmission components.
- Over the years, the importance of load modeling has grown due to their 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.

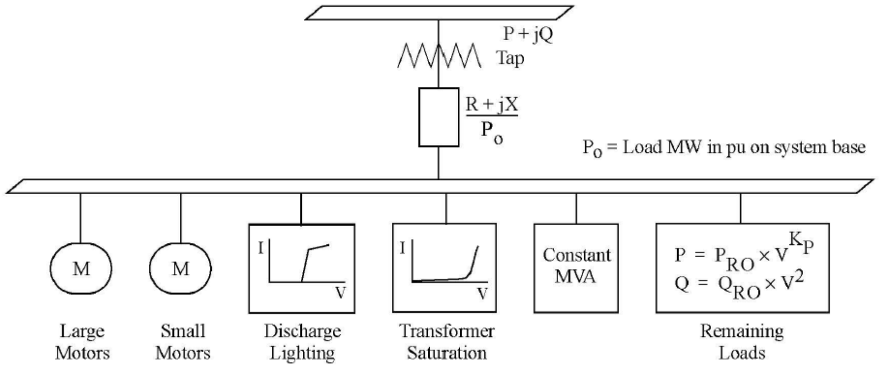
Background: Load Models

- Different types of load models have been utilized over the years –

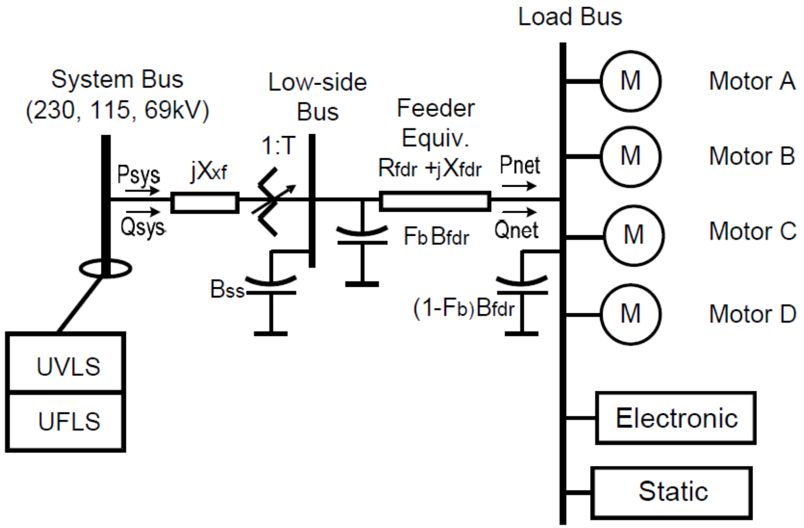
Constant I
(to represent P)

Constant Z
(to represent Q)

Used until 1980s



CLOD type model [1] used until late 2000s



CMPLDW model [2] being used since early 2010s

[1] Siming Guo and T. J. Overbye, "Parameter estimation of a complex load model using phasor measurements," 2012 IEEE Power and Energy Conference at Illinois, Champaign, IL, 2012, pp. 1-6.
[2] GE-PSLF 18.01 user manual, General Electric Intl. Ltd, Schenectady, USA, 2021.

Background: Why EMT Load Models?

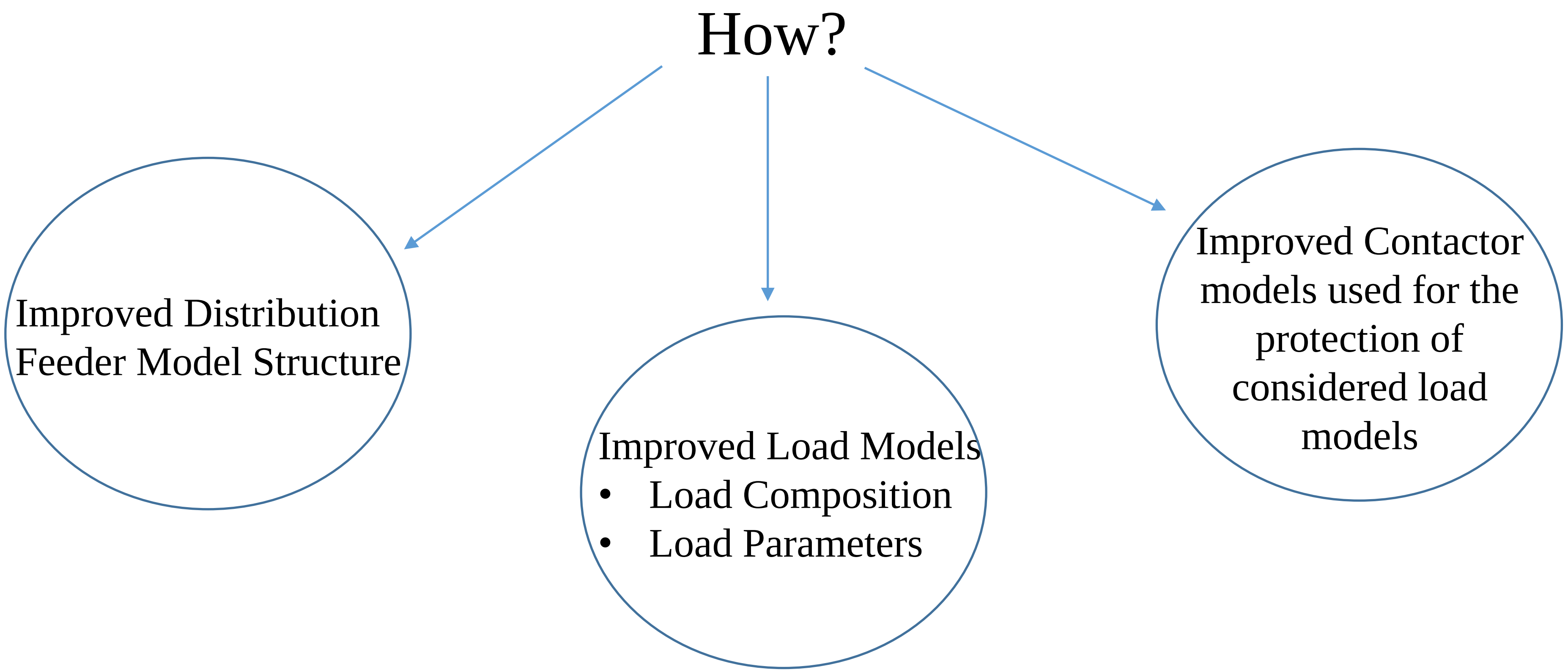
- Conventional RMS based load models are less accurate compared to corresponding EMT load models.

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

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

Motivation:

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

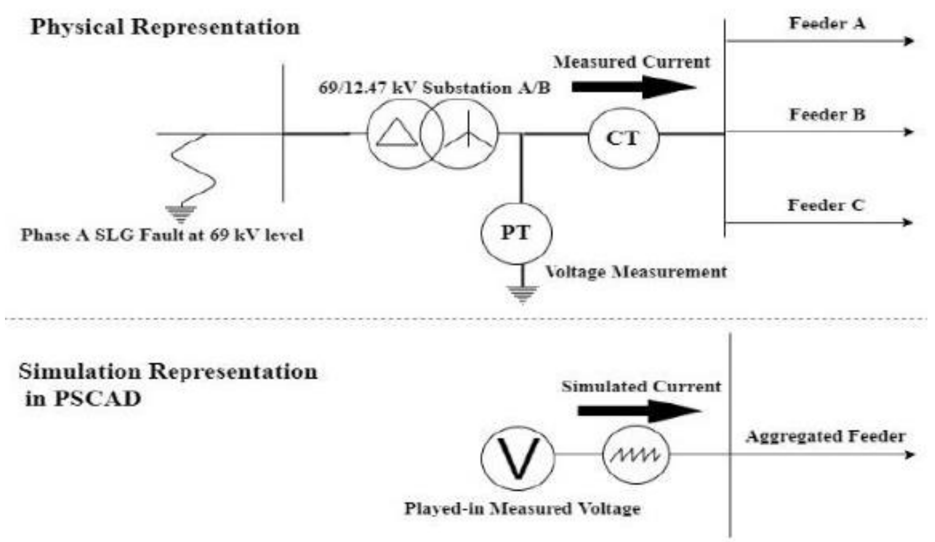


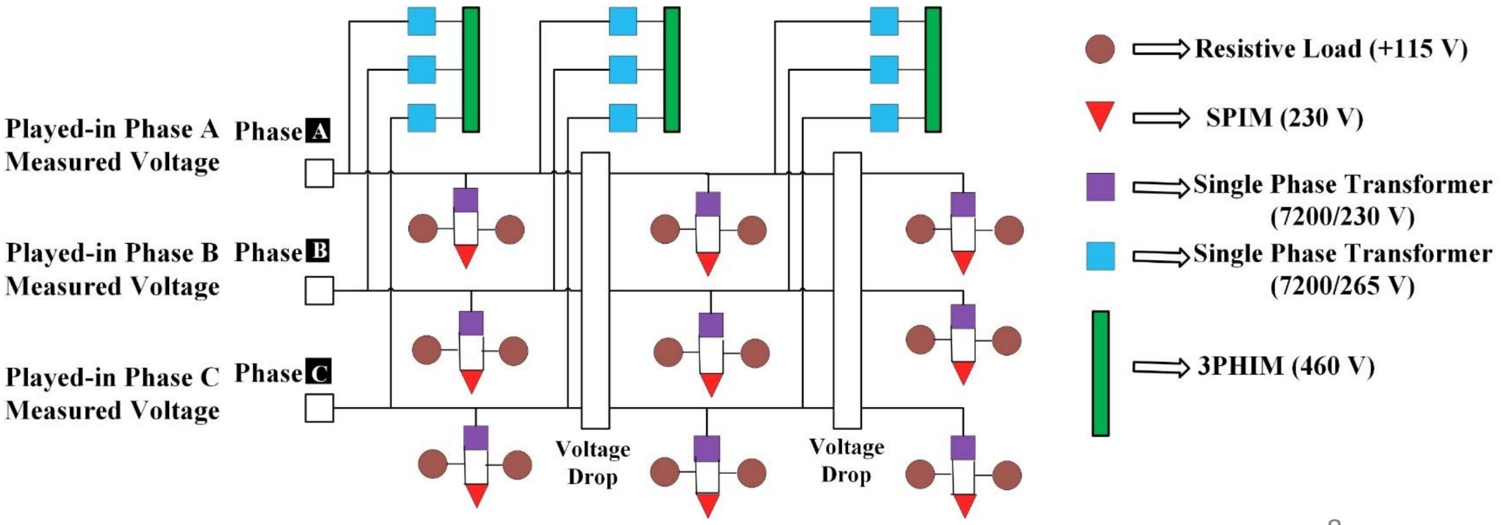
Objectives:

- Develop an algorithm to estimate **load composition** and the **load parameters** in the proposed EMT feeder model.
- Utilize point on wave measurements at the head of the feeder to estimate parameters
- Measurements obtained in response to disturbances on the feeder and on the sub transmission and transmission systems

Load Synthesis Procedure: Overall Approach

- A novel three-segment three-phase feeder model has been used in PSCAD to conduct the simulations.
- Three-phase measured voltages are played-in to this feeder model.
- The three-phase simulated currents at the head of the feeder model are matched with their corresponding measured currents.





Load Synthesis Procedure: Overall Approach [1]

- The voltage and current measurements used in this work are obtained from a local utility for events such as 69 kV and 230 kV level SLG fault events.

- The measurements are obtained on the low voltage side (12.47 kV) of the local city substations.

- The sampling frequency of the measurement data is 1921 Hz and obtained using Schneider ION 7650 and Schneider ION 8650 A meters.

- The simulations are conducted in PSCAD with a sampling frequency of 200 kHz.

[1] S. Nekkalapu, V. Vittal, J. Undrill, B. Keel, B. Gong and K. Brown, "Synthesis of Load and Feeder Models Using Point on Wave Measurement Data," in *IEEE Open Access Journal of Power and Energy*, vol. 8, pp. 198-210, 2021, doi: 10.1109/OAJPE.2021.3079724.

Load Synthesis Procedure: Overall Approach

- The voltage and current measurements used in this work are obtained from a local utility for events such as 69 kV and 230 kV level SLG fault events.
- The measurements are obtained on the low voltage side (12.47 kV) of the local city substations.
- Four test cases have been used to synthesize feeder and load models at two locations (residential and industrial/commercial) using an optimization approach for both summer and winter loading conditions.
- Four new test cases are used to validate the developed feeder and load models at the same locations and for both summer and winter loading conditions.

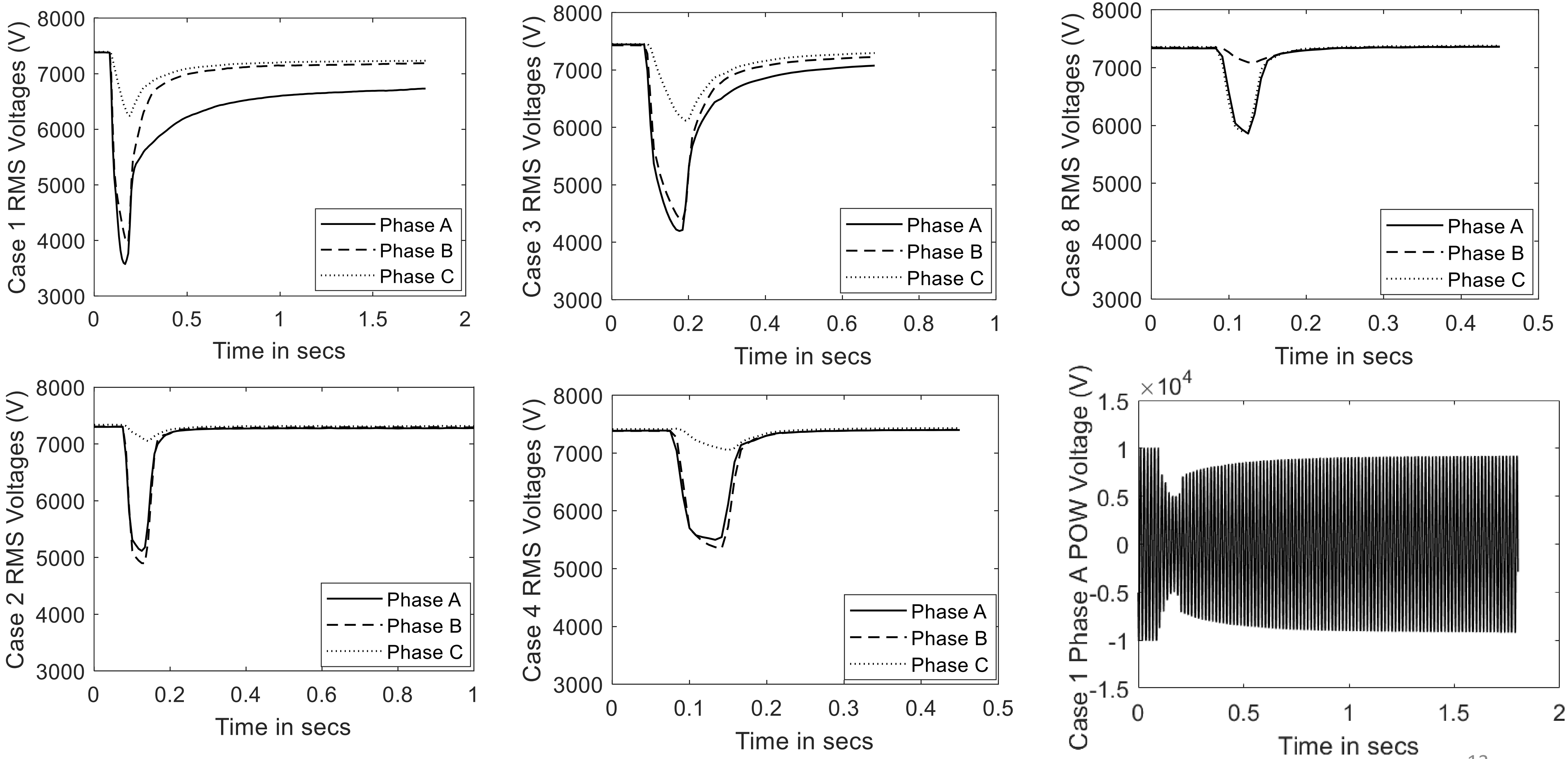
Load Synthesis Procedure: Main Test Cases

	Case 1	Case 2	Case 3	Case 4
Event Type	**Phase-A SLG fault on Substation K Circuit Breaker**	**Phase-A SLG fault on Substation A 69 kV line**	**Phase-A SLG fault on Substation K Circuit Breaker**	**Phase-A SLG Fault on Substation A 69 kV line**
Event Voltage level	69 kV	69 kV	69 kV	69 kV
Time of Event	10:33 AM	5:36 PM	10:33 AM	5:36 PM
Date of Occurrence	8th Aug, 2016	11th Nov, 2016	8th Aug, 2016	11th Nov, 2016
Measurements Location	Substation A	Substation A	Substation B	Substation B
Measurements kV level	12.47 kV	12.47 kV	12.47 kV	12.47 kV
Total Feeder MVA loading	18.33	7.23	23.07	13.59
Voltage Dip % in the Faulted Phase	51%	30%	43%	26%

Load Synthesis Procedure: Validation Test Cases

	Case 5	Case 6	Case 7	Case 8
Event Type	**Phase-A SLG fault on Substation S Circuit Breaker**	**Phase-C SLG fault on Substation K 230 kV line**	**Phase-A SLG fault on Substation S Circuit Breaker**	**Phase-C SLG Fault on Substation K 230 kV line**
Event Voltage level	230 kV	230 kV	230 kV	230 kV
Time of Event	5:52 AM	10:34 PM	5:52 AM	10:34 PM
Date of Occurrence	17th Jun, 2016	19th Oct, 2015	17th Jun, 2016	19th Oct, 2015
Measurements Location	Substation A	Substation A	Substation B	Substation B
Measurements kV level	12.47 kV	12.47 kV	12.47 kV	12.47 kV
Total Feeder MVA loading	13.71	6.84	19	10.77
Voltage Dip % in the Faulted Phase	18%	21%	18%	21%

Load Synthesis Procedure: Played-in Voltage Profiles



Load Synthesis Procedure: Optimization Algorithm

- Gauss-Newton non-linear least squares algorithm has been used to estimate the load composition and the motor load parameters.
- The error between the measured currents and their corresponding simulated currents at the head of the feeder has been minimized by adjusting the estimated parameters in each iteration.
- The proposed algorithm has been used initially to estimate the load composition and then later the motor load parameters.
- The algorithm has been applied on one parameter at a time based on their sensitivity to the considered events.
- The step size for the proposed algorithm has been determined for each iteration using, a line search technique, cubic interpolation method.

Load Synthesis Procedure: Optimization Algorithm

$$\arg\min_{\mu} E(\mu) = \left[\left(I_m - I(\mu)\right)^t \left(I_m - I(\mu)\right) \right]$$ → Objective function

$$\Delta\mu_0 = \left(J^t * J\right)^{-1} * J^t * \left(I_m - I(\mu_0)\right)$$ → Parameter increment

$$\mu_{\text{final}} = \mu_{\text{prev}} + \alpha\Delta\mu_0$$ → Updated parameter at the end of each iteration

Cubic interpolation process:

$$E(\mu_k + \alpha\mu_0) \le E(\mu_k) + C_1 \alpha E'(\mu_k)$$

$$\alpha = \alpha_1 = E'(\mu_k) / 2\left[E(\mu_k + \Delta\mu_0) - E(\mu_k) - E'(\mu_k)\right]$$

$$\alpha = \alpha_2 = -b + \sqrt{b^2 - 3\alpha E'(x_k)} / 3\alpha$$

$$\begin{pmatrix} a \\ b \end{pmatrix} = \frac{1}{\alpha_0^2 \alpha_1^2 (\alpha_1 - \alpha_0)} \begin{pmatrix} \alpha_0^2 & -\alpha_1^2 \\ -\alpha_1^2 & \alpha_0^2 \end{pmatrix} \begin{pmatrix} E(x_k + \alpha_1 \Delta\mu_0) - E(x_k) - \alpha_1 E'(x_k) \\ E(x_k + \alpha_0 \Delta\mu_0) - E(x_k) - \alpha_0 E'(x_k) \end{pmatrix}$$

Load balance constraint ←

$$Scale_1 S_1 + Scale_2 S_2 + \sum_{n=1}^{3} \frac{V_{seg,n}^2}{2 * 3 * R_{seg,n}} = F_S$$

Load Synthesis Procedure: Optimization Algorithm

- Appropriate realistic bounds are considered for the motor parameters and load composition ‘*scale*’ parameter.
- Logit transformation has been used to implement the bounds.

$$\Omega_0 = \log\left(\frac{\mu_0 - \mu_{0,\text{ lower bound}}}{\mu_{0,\text{ upper bound}} - \mu_0}\right)$$

- The optimization problem is solved in terms of the new transformed variable.

Convergence criteria

$$\Omega_k - \Omega_{k-1} < 10^{-2} \longrightarrow \text{For Parameter}$$

$$RMSE_{Current} / Max\ Peak\ Value\ of\ \ Measured\ \ Current \leq \rho \longrightarrow \text{For Case}$$

Load Synthesis Procedure: Optimization Algorithm

- Bounds for the SPHIM parameters are determined using the following criterion:
  - Efficiency of SPHIM is assumed to be between 90-95%
  - Total motor losses at the rated conditions are calculated for the assumed efficiency range.
  - Copper losses are assumed to be 60% of the total losses (25% stator copper losses and 35% copper rotor losses).
  - Combination of stator reactance and rotor reactance is assumed to be equal to the sub-transient reactance (5% - 15%) of the SPHIM.
- Bounds for the 3PHIM parameters are obtained from the literature [3].

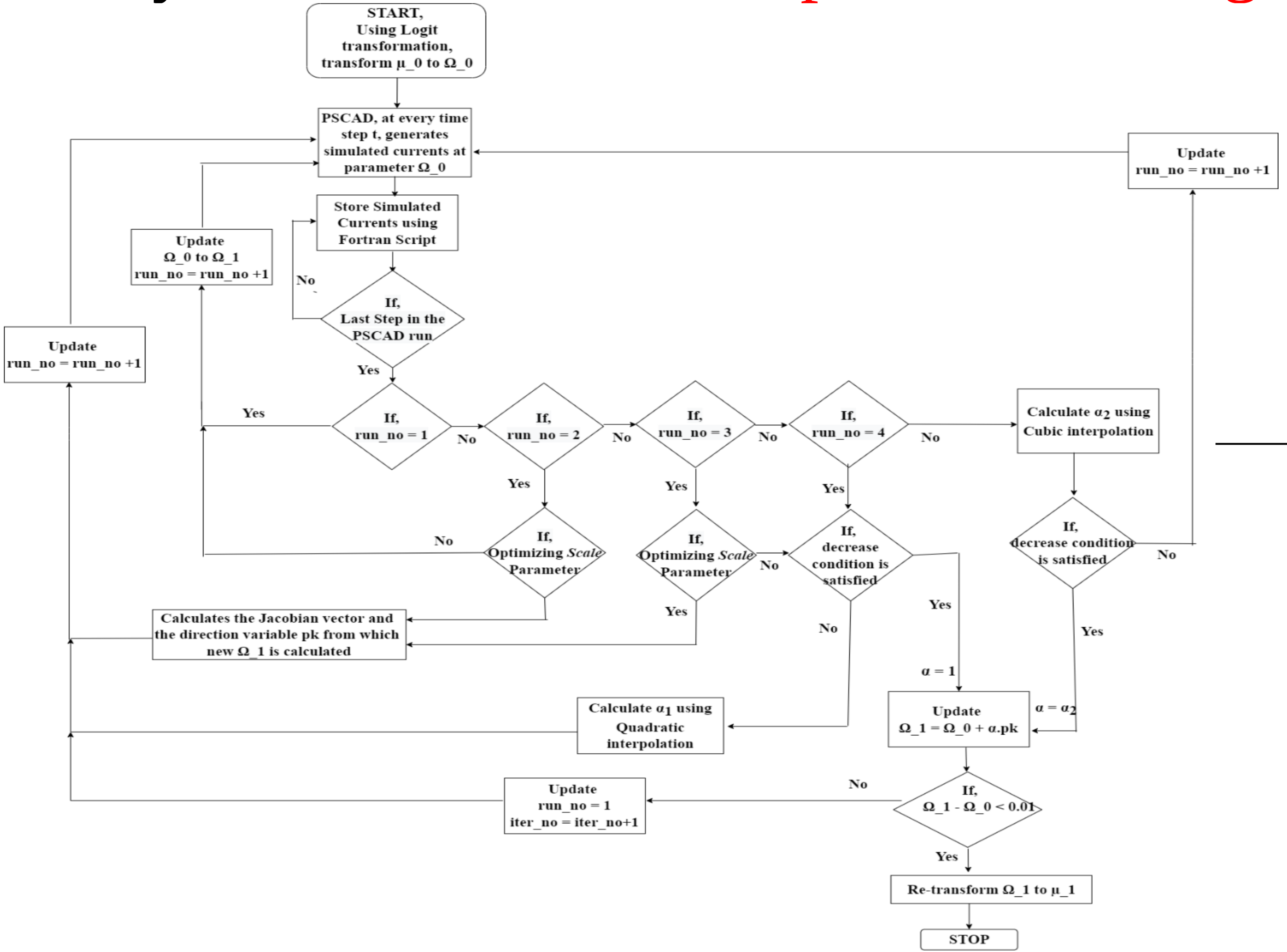
SPHIM Parameters	Lower Bound	Upper Bound	Initial Value
Rotor Resistance	0.026 pu	0.051 pu	0.034 pu
Inertia Constant	0.031 s	0.1 s	0.043 s
Stator Resistance	0.017 pu	0.034 pu	0.026 pu
Rotor Reactance	0.026 pu	0.06 pu	0.034 pu
Stator Reactance	0.026 pu	0.06 pu	0.043 pu

3PHIM Parameters	Lower Bound	Upper Bound	Initial Value
Inner Rotor Resistance	0.002 pu	0.02 pu	0.009 pu
Outer Rotor Resistance	0.1 pu	0.2 pu	0.15 pu
Inertia Constant	0.1 s	0.35 s	0.15 s
Stator Resistance	0.002 pu	0.05 pu	0.013 pu
Inner Rotor Reactance	0.05 pu	0.2 pu	0.17 pu
Outer Rotor Reactance	0.05 pu	0.25 pu	0.225 pu
Stator Reactance	0.05 pu	0.15 pu	0.067 pu

Load Composition	SPHIM Load	3PHIM Load	Impedance Load
Bounds for Case 1 and Case 2	(35%,60%)	(15%,35%)	(5%, 50%)
Bounds for Case 3 and Case 4	(15%,35%)	(35%,60%)	(5%, 50%)
Initial Condition for Case 1 and Case 2	45%	30%	25%
Initial Condition for Case 3 and Case 4	30%	45%	25%

[3] E. A. Yahaya. (2015). Advantage of Double Cage Rotor over Single Cage Rotor Induction Motor. IISTE Journals. [Online]. Vol.6, No.12.

Load Synthesis Procedure: Optimization Algorithm



Interactive process between PSCAD and user written Fortran script containing the optimization algorithm

Load Synthesis Procedure: Estimated Load Composition

- SPHIM load composition obtained during the summer conditions (Case 1 and Case 3) in both types of feeders is higher compared to the SPHIM composition observed during the winter conditions.
- Whereas, for the 3PHIM load, although the % level in the total load varies from summer to winter conditions significantly, the amount (MVA drawn) of 3PHIM load on the feeder between summer and winter conditions is similar for both feeders.

Load Composition	**SPHIM Load (%, MVA)**	**3PHIM Load (%, MVA)**	**Impedance Load (%, MW)**
Case 1	51%, 9.34 MVA	16%, 2.93 MVA	33%, 6.04 MW
Case 2	35%, 2.53 MVA	34%, 2.45 MVA	31%, 2.24 MW
Case 3	23%, 5.3 MVA	38%, 8.76 MVA	39%, 8.99 MW
Case 4	15%, 2.04 MVA	56%, 7.61 MVA	29%, 3.94 MW

Load Synthesis Procedure: Estimated Motor Parameters

- It was observed that the load parameters of SPHIMs and 3PHIMs obtained in (Case 1 and Case 2) and (Case 3 and Case 4) are relatively close to each other.

SPHIM Parameters	Case 1	Case 2	Case 3	Case 4	Initial Val
Rotor R pu	0.033	0.051	0.028	0.035	0.034
Inertia s	0.0568	0.0511	0.0769	0.0442	0.043
Stator R pu	0.0256	0.0297	0.034	0.0316	0.026
Rotor X pu	0.035	0.045	0.0595	0.0576	0.034
Stator X pu	0.0575	0.054	0.0595	0.0561	0.043

3PHIM Parameters	Case 1	Case 2	Case 3	Case 4	Initial Val
Inner Rotor R pu	0.013	0.019	0.02	0.02	0.009
Outer Rotor R pu	0.2	0.2	0.2	0.2	0.15
Inertia s	0.12	0.16	0.25	0.35	0.15
Stator R pu	0.0468	0.0423	0.047	0.05	0.013
Inner Rotor X pu	0.194	0.2	0.2	0.2	0.17
Outer Rotor X pu	0.2396	0.226	0.226	0.229	0.225
Stator X pu	0.139	0.0889	0.069	0.0885	0.067

Load Synthesis Procedure: Quantitative Results

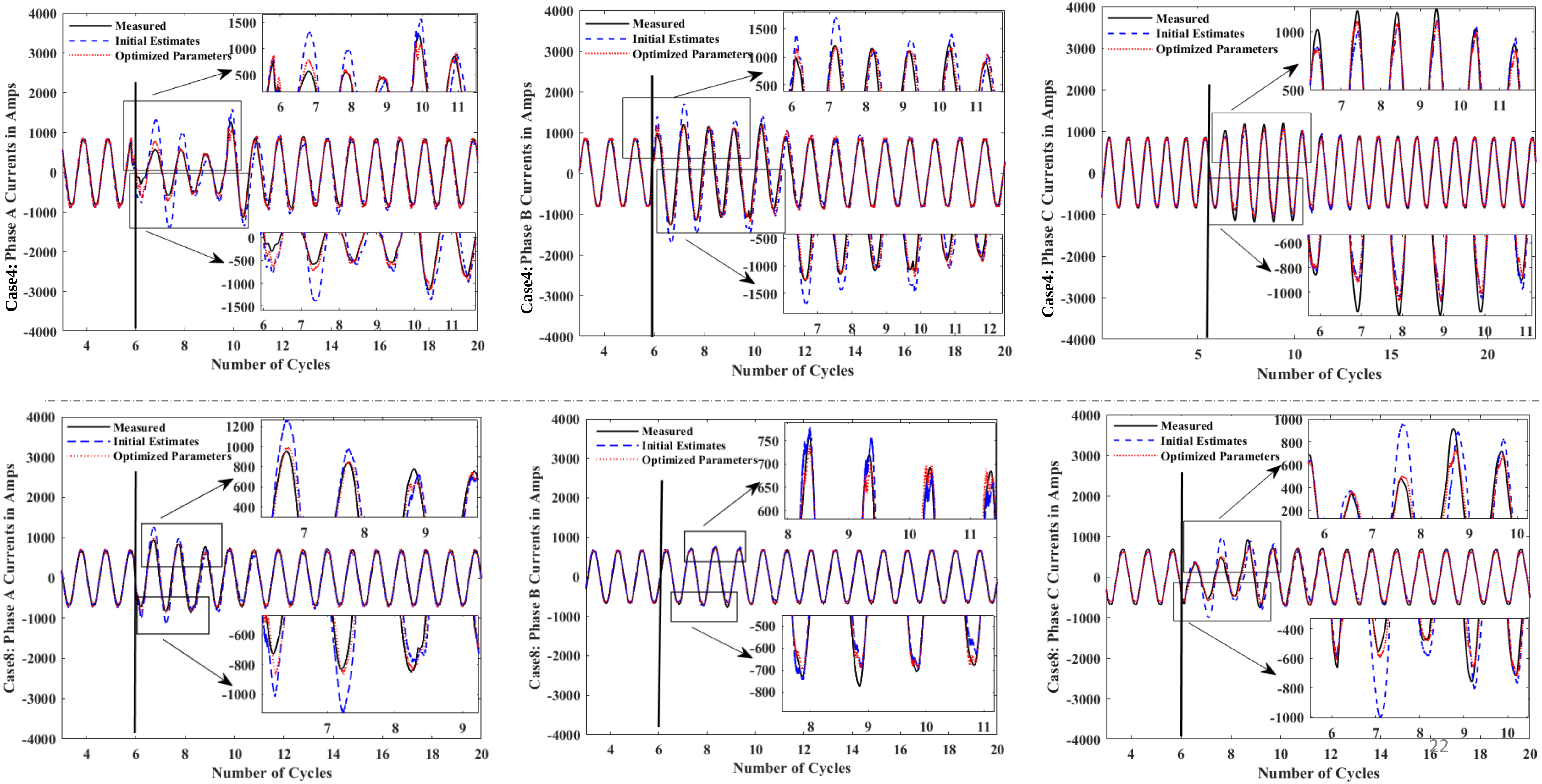
Cases 1-4 (Demonstration of the effectiveness of the algorithm)

Case/ Phase	RMSE per sample in Amps (initial parameter estimates)	RMSE per sample in Amps (Optimized parameters)	RMSE Improvement (%)	Max Error per Time Step in Amps (with initial estimates, after optimizing parameters)
1/A	215.92	150.44	+30%	1026.5, 459.45
1/B	130.93	84.05	+36%	854.6, 371.52
1/C	99.42	90.16	+10%	331.99, 321.75
2/A	228.4	54.25	+76%	1006.1, 200.52
2/B	155.41	52.72	+66%	710.65, 213.21
2/C	49.3	45.28	+8%	181.02, 140.48
3/A	232.53	132.54	+43%	164.62, 98.1
3/B	245.51	148.53	+40%	787.94, 468.7
3/C	160.86	130.48	+19%	185.23, 146.36
4/A	204.45	93.56	+54%	874.29, 461.86
4/B	196.38	99.74	+49%	689.53, 389.74
4/C	77	71.28	+8%	275.93, 256.85

Cases 5-8 (Demonstration of the validation of the algorithm)

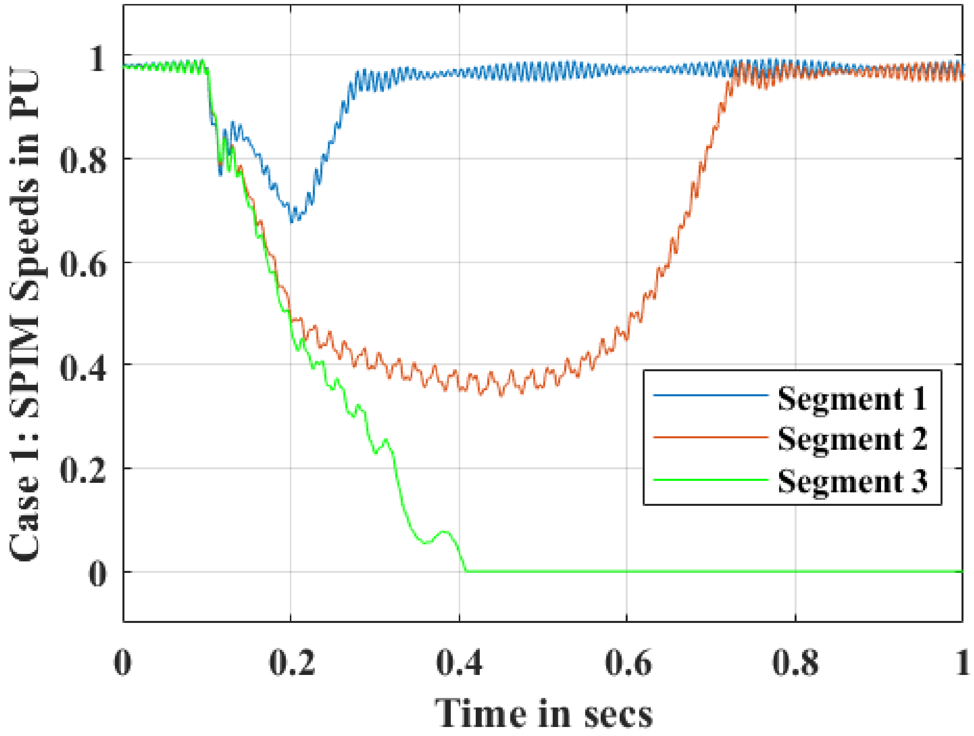
Case/ Phase	RMSE per sample in Amps (initial parameter estimates)	RMSE per sample in Amps (Optimized parameters)	RMSE Improvement (%)	Max Error per Time Step in Amps (with initial estimates, after optimizing parameters)
5/A	113.36	105.34	+7%	632.84, 620.99
5/B	108.47	106.14	+2%	558.28, 433.15
5/C	125.39	98.92	+26%	290.19, 289.2
6/A	88.25	73.22	+17%	486.27, 331.47
6/B	54.1	59.37	-9%	113.73, 110.96
6/C	76.94	67.97	+12%	445.92, 313.63
7/A	161.01	84.54	+48%	673.73, 275.6
7/B	200.35	158.44	+26%	499.74, 478.11
7/C	81.66	62.54	+24%	236.06, 209.49
8/A	92.82	57.99	+37%	402.09, 233.57
8/B	49.22	45.05	+9%	159.44, 128.92
8/C	126.52	53.81	+57%	520.76, 287.49

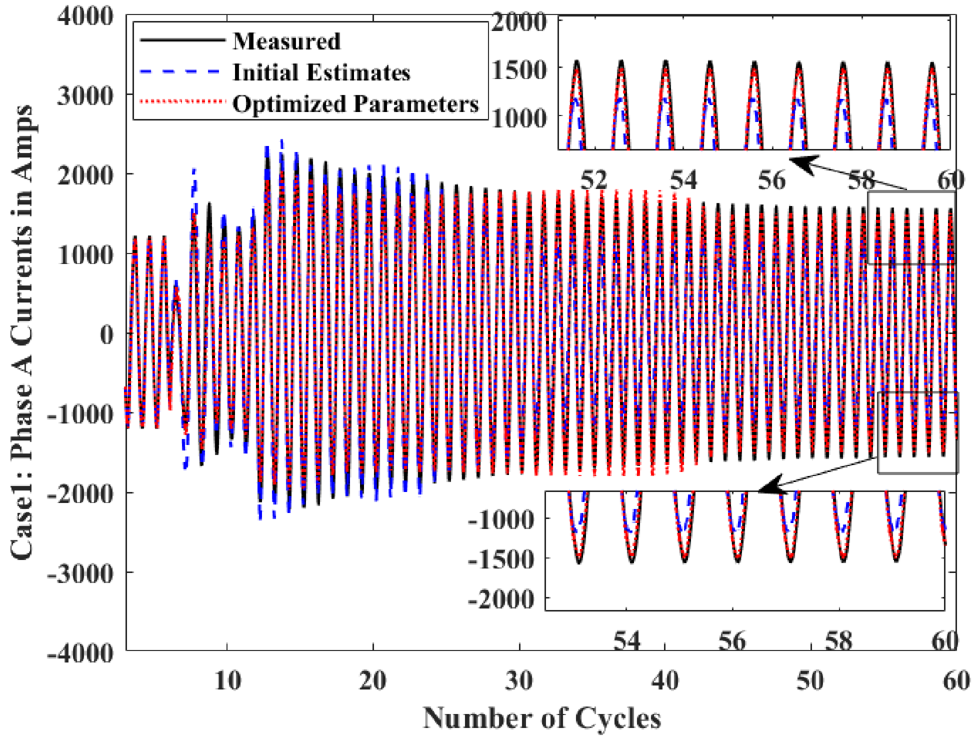
Load Synthesis Procedure: Qualitative Results



Load Synthesis Procedure: Capturing FIDVR

- It was observed that the proposed algorithm captures the FIDVR phenomenon in Case 1 really well.
- It was also observed that the proposed algorithm performance is similar for a different set of initial conditions.





Conclusions (Synthesizing Feeder and Load Model)

- The proposed optimization algorithm effectively obtains both the load composition and load parameters and is able to capture FIDVR type events that cause severe voltage stability issues in the system.
- It was also observed that the loading conditions (summer or winter conditions) do not significantly impact the parameters obtained for the motor loads for a particular feeder.
- The parameters and load composition obtained for the considered feeder models at the same locations are found to be consistent and validated for both summer and winter conditions using four new test cases that represent different faults occurring at different times during the year.

Current Efforts Based on this Work

- We have developed and integrated a 24 V EMT contactor into the synthesized feeder model to trip the SPHIM loads under low voltage conditions [4] .
- We have developed a methodology to incorporate the developed EMT contactor behavioral characteristics (trip and reconnection settings) into positive sequence simulators to trip positive sequence SPHIM loads accurately. This is based on DNN and the use of PSCAD simulations to generate data.

[4] S. Nekkalapu, V. Vittal, "EMTP Contactor Modeling for Load Modeling Studies," Paper # 22PESGM1462, IEEE PES GM2022 – Denver, CO

Future Work

- Currently, efforts are directed towards developing another DNN model to estimate the SPHIM stalling phenomenon using PSCAD test case data.
- The robustness of the proposed methodology to trip the ‘motorc’ model, in PSLF, would be tested on varied loading conditions (high load level, moderate load level, low load level in both summer and winter conditions).
- The proposed methodology, to trip the ‘motorc’ model, would be tested on a more detailed structured feeder model whose topological details would be obtained from the local utility.

Questions?

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