Dynamic Composite Load Model Priority Placement Based on Electrical Centrality

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***Abstract*—Dynamic load models are an integral part of transient stability analysis. Due to the non-linearity of realistic demand factors, developing accurate load models is a challenging process. A variety of methods have been developed to reduce the number of parameters to identify and estimate within the models, and methods exist for determining more accurate load models. An alternative to reduce the effort to develop and implement dynamic load models is to reduce the number of models in the system that need to be created and by creating priority placement guidelines of load models in the system. This paper develops preliminary guidelines for priority placement of the composite load model based on electrical centrality. Using a 2383-bus version of the Poland Test Case, we group buses and their loads into quartile levels based on their magnitude of electrical centrality. A statistically significant trend is identified highlighting priority placement of developing composite load models in certain quartile levels. These findings are useful to utilities and balancing authorities that need to prioritize their efforts to develop dynamic load models.**

***Index Terms*—Dynamic Load Modeling, Power System Dynamics, the WECC Composite Load Model, Sensitivity, Electrical Centrality**

I. INTRODUCTION

Transient stability studies are key for ensuring electrical grid reliability, and are used for planning and operation purposes [1]. Dynamic load models are important aspects of transient stability studies in order to create accurate and useful results. However, developing dynamic load models is challenging, as they attempt to represent uncertain and changing physical systems in an aggregate model.

There are several commonly used load models: constant impedance, constant current and constant power model (ZIP), ZIP with induction motor model (IM), exponential model, exponential model with IM, and composite load model (CLM) [2]. The CLM consists of the ZIP model, four induction motor models, and accounts for power electronics [3]. The CLM is currently the most advanced and detailed load model and widely accepted by industry [4]. A consequence of the high dimensionality and intended accuracy of the CLM is high non-linearity.

The non-linear nature of the CLM has created challenges for determining the best fit parameters of the load model. There exist several studies that develop methods to best determine load model parameters based on power systems measurement data, for example synchrophasor measurements [4–7]. There also exist methods to reduce the number of parameters to identify and estimate based on parameter sensitivities [4], [6], [8], [9]. The adoption of these methods rely on reducing the methods' necessary computation and implementation efforts required.

Another method to reduce the effort to develop and implement dynamic load models is to reduce the number of models in the system that need to be created. The North American Electric Reliability Corporation (NERC) standard TPL 001-4 states that "dynamic load modeling only needs to be applied to loads that are expected to affect the simulation results" [10]. In [11], the reduction of a network is studied to determine a region of influence of a disturbance. It is proposed that dynamic load models only need to be placed inside of the region of influence. However, this is dependent on a location of a disturbance, and disturbances can occur anywhere in a power system. To the best of our knowledge, [11] is the only study proposing guidelines for placement of dynamic load models. This identifies an overall lack of guidelines for placement of dynamic load models, especially for global placement throughout a power system not based on disturbance location.

This study develops preliminary guidelines for dynamic load model placement in a power system network. Electrical centrality is used to categorize buses and their corresponding loads and group them into quartile levels. The CLM is implemented in each quartile and evaluated against the benchmark to identify sensitivity trends. The use of electrical centrality allows these guidelines to be applied to any power systems model, and is indifferent to disturbance location.

II. BACKGROUND

A. Composite Load Model

The CLM is the dynamic load model that we use in this study. The CLM consists of 131 parameters outlining machine characteristics such as stator winding resistance of motor, stator leakage reactance of motor, or constant torque coefficient[7]. The diagram of the composite load model is seen in Figure 1.

B. Electrical Distance and Centrality

Electrical centrality is based on the electrical distance of a bus in reference to all buses in the system[13]. The electrical distance, a power system homologous to node degree, is calculated from sensitivities between power injections and

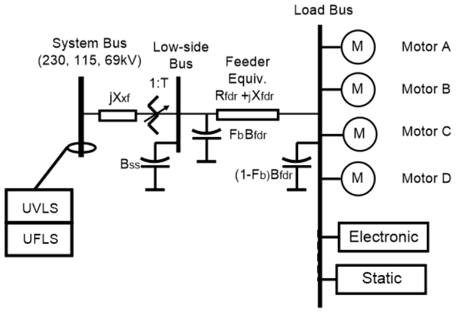

Fig. 1. Composite Load Model [12]

phase angles between buses [13]. The equation for electrical distance based on active power is seen in Equation 1 [14]. The electrical distance from Bus a to Bus b is denoted by $e_{a,b}$. The average electrical distance e_a, comes from electrical distance between two buses, which is obtained from the power flow Jacobian matrices as described in [13] seen in Equation 2. The electrical centrality, denoted by c_a, is found by Equation 3.

$$e_{a,b} = (J^{+}_{P\theta})_{a,a} - (J^{+}_{P\theta})_{a,b} - (J^{+}_{P\theta})_{b,a} + (J^{+}_{P\theta})_{b,b} \tag{1}$$

$$< e_a >= \sum_{b=1}^{n} \frac{e_{ab}}{n-1} \tag{2}$$

$$c_a = \frac{1}{< e_a >} \tag{3}$$

The centrality of the bus is similar to node degree of a network in that it captures properties of node centrality [15].

III. SENSITIVITY APPROACH ON POLAND ELECTRICAL GRID

The sensitivity approach determines if placing CLMs on buses in only certain levels of centrality magnitude results in greater response accuracy. Ideally this method would be tested in a system with historical or online data, and that data would be the benchmark responses. The load models tested in this system would be developed using measurement based methods as mentioned in [4–7]. These developed models would be implemented in the system model to create a benchmark system. Due to the lack of available data, a benchmark is approximated by creating the highest specified system possible by placing a CLM on 50% of the load in the system, evenly dispersed between quartile levels. The CLMs implemented are four pre-defined models of varying motor fractions. A test data set is created from placing CLMs on every load in a certain level of centrality. These data sets are tested for response accuracy in comparison to the benchmark. The approach set up and its constituents are described in this section.

A. Poland Electrical Grid Electrical Centrality

The 2383-bus version of the Poland Test Case, as developed in [16], is used for evaluation of this approach. The test case's large size makes it comparable to a real physical power system. The electrical centrality of each bus in the system was calculated, and the buses were separated into quartile levels of centrality magnitude. Table I highlights the electrical centrality magnitudes contained in each quartile level.

TABLE I. ELECTRICAL CENTRALITY QUARTILES

first	second	third	fourth
1.35-4.61	4.62-5.79	5.8-6.62	6.63-9.58

The distribution of the centrality magnitude and corresponding quartile levels are seen in Figure 2.

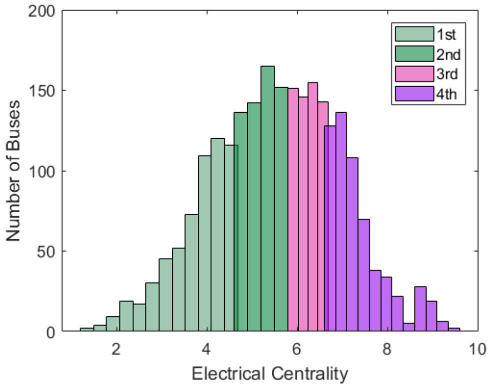

Fig. 2. Electrical Centrality of Buses in Poland Electrical Grid Highlighted in Their Respective Quartile Levels

The distribution of the centrality shows the centrality magnitude of all the buses follows a Gaussian distribution and the quartile levels each contain 25% of the buses. A visualization of the Poland electrical grid as a network model is seen in Figure 3. This figure highlights the quartile locations and corresponding centrality magnitudes of each bus. The purple nodes correspond to the fourth quartile of highest electrical centrality, pink correspond to the third quartile, green correspond to the second quartile, and light green correspond to first quartile. The size of the nodes are proportional to the electrical centrality magnitude of the bus. The network model is only a two-dimensional representation of the Poland network and does not represent the topology of the system. This approach does not consider geographical location as a factor. However, it can been seen from the figure that the quartile levels are not isolated from each other, rather they are intermixed.

B. Dynamic Modeling Method

The benchmark and test data are created by simulating a generator outage in the system. All bus voltage magnitudes are recorded in every simulation and compared. The simulation is repeated on eighty generators in the system. Of the generators tested, they are evenly distributed throughout the quartile levels to assure the sensitivity to location of the disturbances is reduced. The steps of this approach are outlined in Figure 4.

C. Validation of Method

The method is first validated by proving the greater number of CLMs in the network, the greater the response accuracy. The

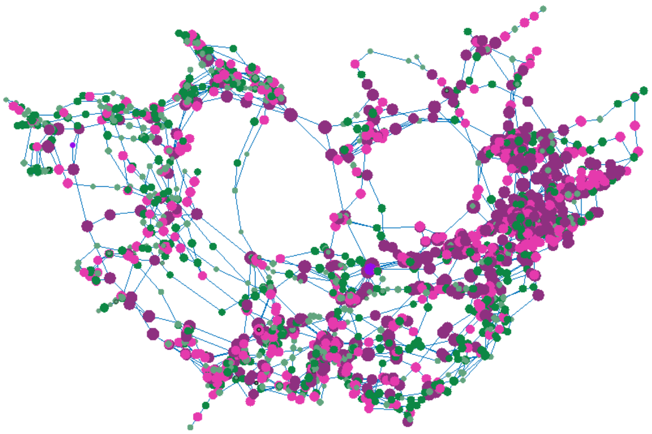

Fig. 3. Poland Electrical Grid Network: electrical centrality magnitude is proportional to size of node, and quartile level is denoted by color.

response accuracy is defined by how close the test response matches the benchmark response by the distance between them. In this system, where the benchmark system is simulated data from the system containing CLMs on 50% of the loads in the system, it can be assumed that the greater number of CLMs included in the system the closer the system response will be to the benchmark. The test systems have a combination of ZIP load models and CLMs, where the CLMs are placed according to quartile. This was evaluated by simulating a generator outage at Bus 45 on four dynamic test systems: no CLM in the system (None), 12.5% of loads with CLM, 25% of loads with CLM, and 37.5% of loads with CLM. The first 12.5% of loads with CLM were the loads located in the first quartile. The 25% of loads chosen were located in the first and second quartiles. The 37.5% of loads chosen were located in the first through third quartiles. Figure 5 shows a comparison of the voltage magnitude at Bus 44 for the benchmark system and all the test systems.

In Figure 5, the response of the system to a generator outage at Bus 45 is seen, with the outage occurring at 0.1 second. The blue line demonstrates the response of the benchmark system. All the test system responses are shifted below the benchmark response. This shift is due to the non-uniform pre-disturbance voltage magnitudes. The pre-disturbance oscillations are due to the large amount of CLMs in the system, as each CLM contains four machine models. The oscillations present before the disturbance can account for the time shifting occurring between the oscillations of the responses. To account for the non-uniform pre-disturbance conditions two types of distance measures were tested for calculating response accuracy, short time series (STS) distance and dynamic time warping (DTW) distance.

STS distance is invariant to amplitude shifting, which is what is found in the test system responses seen in Figure 5. STS distance is based on the numerical first derivative of two signals as seen in equation 4 [17].

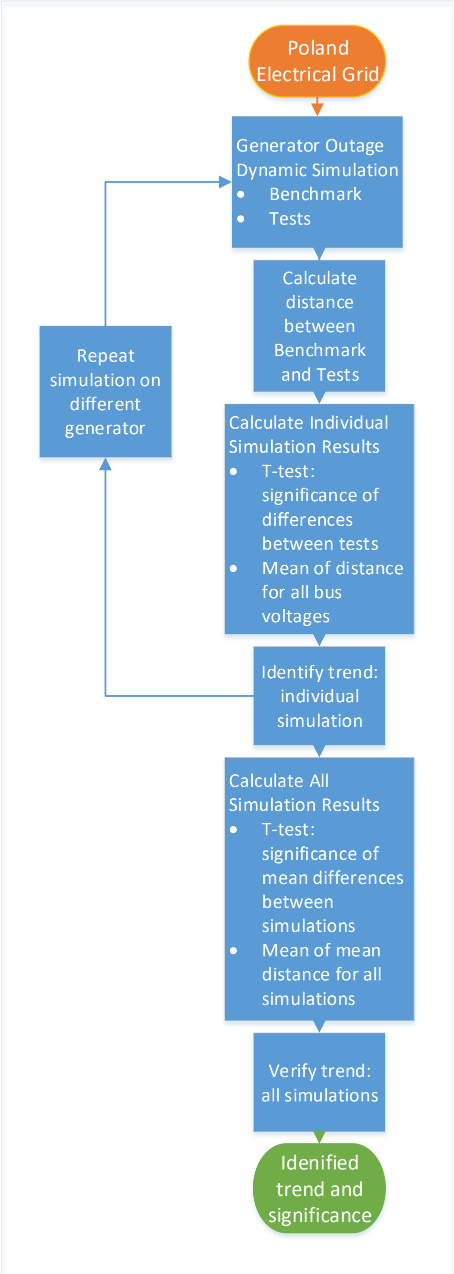

Fig. 4. Electrical Centrality CLM Placement Sensitivity Method

$$d_{STS} = \sqrt{\sum_{t=1}^{T-1} \left(\frac{x[t+1]-x[t]}{\Delta t} - \frac{y[t+1]-y[t]}{\Delta t} \right)^2} \qquad (4)$$

The variable x denotes the benchmark time series, y denotes the test system time series, t denotes the time being evaluated in the time series, and T denotes the total time of the times series.

DTW is tested as a distance measure because it compensates for time shifting and stretching, including local shifting and stretching and it outperforms the commonly used euclidean

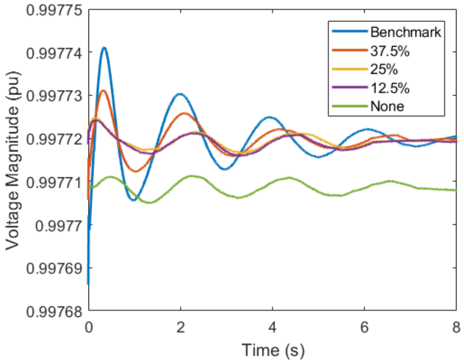

Fig. 5. Times Series Comparison of Percentage of Loads with CLMs in System

distance [17]. Time shifting and stretching is due to different/unknown initialization times and oscillations at different frequencies respectively [17]. DTW is calculated as seen in equation 5, where k specifies the index of the time evaluated, and K is the length of the DTW path.

$$d_{DTW}(x,y) = \min_{p=(t_x,t_y)} \frac{\sum_{k=1}^{K}(x[t_x(k)] - y[t_y(k)])^2}{K} \tag{5}$$

When applied to the system responses, the distance found by STS was too small for comparison. In contrast, DTW performs well in detecting significant differences between responses. Due to DTW's outperformance of euclidean distance and STS's inability to detect significant differences in this study, DTW was used as the chosen distance measure.

The DTW distance was calculated for each bus voltage of the benchmark system to the test systems. The DTW distance from all bus responses for each of the comparisons are shown in the boxplot in Figure 6. Higher response accuracy corresponds with a smaller distance between the benchmark and the test systems.

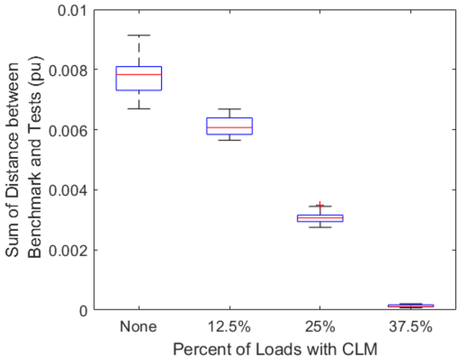

Fig. 6. DTW Distance Comparison between Benchmark and Test Systems based on Percent of Loads with CLMs in the System

A t-test was performed on the mean of the distances for each comparison. The null hypothesis being the mean of the differences of the comparisons of percentage of CLMs in the system are not significant. Significance between all comparisons was proved between all percentage amounts. The corresponding p-values for the t-tests are reported in Table II. This verifies that the more CLM in the system the greater the response accuracy. Assuming the system response accuracy increases with the number of CLMs in the system, the verification of this trend validates the approach.

TABLE II. T-TEST P-VALUES FOR DIFFERENCES BETWEEN PERCENTAGE OF CLMS IN THE SYSTEM

System	12.5%	25%	37.%
None	$1.89{\cdot}10^{-54}$	$1.17{\cdot}10^{-77}$	$1.54{\cdot}10^{-80}$
12.5%	-	$3.69{\cdot}10^{-88}$	$2.12{\cdot}10^{-89}$
25%	-	-	$8.37{\cdot}10^{-59}$

IV. SENSITIVITY RESULTS

The sensitivity to electrical centrality was evaluated by separate dynamic simulations of generator outages on eighty generators in the system. An example simulation result for one generator outage dynamic simulation can be seen in Figure 7.

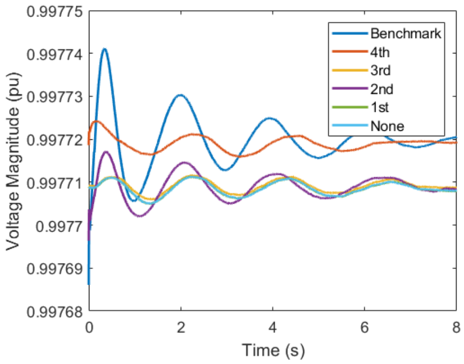

Fig. 7. Times Series Comparison of Centrality Quartile location of CLMs in System

In Figure 7, the response of Bus 44 to a generator outage at Bus 45 is shown, with the outage occurring at 0.1 second. The figure illustrates how all the test system responses are shifted below the benchmark response in the same manner as seen in Figure 5. Again, DTW distance is used as a distance measure to reduce the sensitivity to the non-uniform pre-disturbance responses. Future work will evaluate additional distance measures to further isolate the sensitivity of response to the electrical centrality.

A t-test was performed on the mean of the distances for each comparison for all generator outage simulations. The null hypothesis being the mean of the differences of the comparisons of composite load model quartile level placement are not significant. Significance between all comparisons was proved between all quartile levels. The corresponding p-values for the t-tests are reported in Table III. This result suggests the placement of CLMs in the 2nd quartile results in the best response accuracy. The results from all simulations are summarized in Figure 8.

A trend between sensitivity of placement of CLM between electrical centrality quartiles is found. Since the t-tests reveal that the difference in means of the comparisons are significant, the trend seen in Figure 8 is thereby also significant.

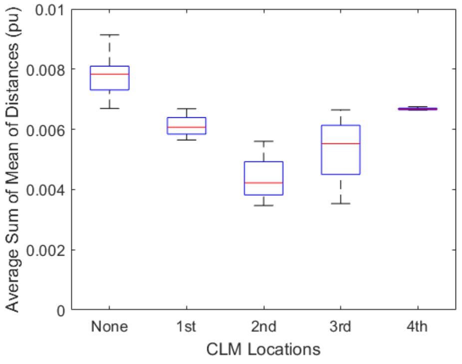

Fig. 8. DTW Distance Comparison between Benchmark and Test Systems based on Centrality Quartile location of CLMs over 80 Simulations

TABLE III. T-TEST P-VALUES FOR DIFFERENCES BETWEEN QUARTILE CLM PLACEMENTS

System	1st	2nd	3rd	4th
None	$1.89{\cdot}10^{-54}$	$2.98{\cdot}10^{-78}$	$2.49{\cdot}10^{-22}$	$2.20{\cdot}10^{-24}$
1st	-	$6.47{\cdot}10^{-54}$	$6.89{\cdot}10^{-7}$	$1.25{\cdot}10^{-21}$
2nd	-	-	$3.44{\cdot}10^{-6}$	$4.38{\cdot}10^{-41}$
3rd	-	-	-	$4.47{\cdot}10^{-20}$

The trend identifies the second quartile as the optimal location to place CLM. This is followed by the third, then first, then fourth quartiles. The lowest reponse accuracy is found when there are no CLMs in the system.

Guidelines for prioritization of development of dynamic load models are derived from these findings and identified trend. Utilities and balancing authorities who need to prioritize their efforts can use these guidelines. When developing load models the electrical centrality of the system should be assessed and buses should be categorized by their electrical centrality magnitude. Buses with loads in the second quartile of electrical centrality should be prioritized for dynamic load model development first. This is followed by developing models for the third, then second, then first quartiles.

V. CONCLUSION AND FUTURE WORK

This paper investigates the sensitivity of dynamic load model placement to electrical centrality of the bus. The CLM was chosen as the tested dynamic load model, and was implemented on 50% of the loads in the system to create the benchmark system. Test systems were created with CLMs located within quartile levels of electrical centrality magnitude. The response of the test systems were compared to the benchmark response in the event of generator outages on eighty generators in the system. The responses were compared with DTW distance to reduce sensitivity to pre-disturbance differences resulting in oscillation time shifting. A statistically significant trend was identified, showing greatest response accuracy resulting from CLMs placed in the second quartile of electrical centrality magnitude. These findings are valuable to utilities and balancing authorities that need to prioritize where in their system to develop load models due to the amount of effort in computation and training data necessary to develop these high complexity models.

Future work will include increasing the number of the electrical centrality levels to increase the granularity of sensitivity. The amount of sensitivity between the different factors such as number of CLMs in the system and the electrical centrality of the bus will be compared to evaluate the prioritization importance of certain factors over others.

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