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On Verification of Load Models for Frequency Response Using PMU Data

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SUMMARY

During frequency excursions, generators are not the only system elements that respond to frequency deviations. Most electric loads are sensitive to large variations in frequency as well, and such deviations lead to changes in their energy consumption. Accurate load modelling is a crucial element in power system simulations to gain a better understanding of load responses during frequency excursion events. The main objective of this paper is to investigate the performance of available load models, used in the industry to represent the frequency response of system load elements during frequency excursion events, in power system simulations.

A dynamic simulation approach is proposed to investigate and evaluate the frequency response of an industrial load simulated with different load models recommended in the industry based on real-life frequency excursions. PMU data collected in Alberta's grid is used for the scope of studies. Load models explored include CLOD, ZIP and exponential load models. Furthermore, the measurement-based load modelling is defined to optimize the load model parameters to improve the accuracy of load response for frequency excursion studies. The performances of these optimized models are compared. The results provide a better understanding of load response and guidelines for choosing load models to be used in frequency excursion studies to make better judgements in power system analysis and planning in terms of power system security and required balancing resources.

KEYWORDS

Dynamic load modelling, Frequency excursion, Load model selection, Load frequency response, Parameter optimization, Evolutionary algorithms.

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1. Introduction

System operators maintain the balance between load and generation and respond to disturbances due to various system conditions and contingencies that could impact the reliability of the power system [1]. A disturbance can cause an imbalance in generation and load, resulting in deviation of the system frequency from the set-point value. During frequency excursions, generators are not the only system elements that respond to frequency deviations. Most electric loads are sensitive to large variations in frequency as well, and such deviations lead to changes in their energy consumption. The load effect increases the damping of frequency dynamics because demand decreases as the frequency drops. Omara [2] concluded that load frequency sensitivity could account for 36% of the post-fault responses in the case of Britain, and that a better understanding of load frequency sensitivity can help with proper operation and spinning reserve planning in case of contingencies. Therefore, the load is a crucial element in power system simulation, and a more in-depth insight of load response in frequency excursion events is required.

Load characteristics have changed in the last few decades with the increased penetration of power electronic-based components, for example, digital electronics and computer controls in homes, offices and factories. Also, with the recent emergence of electric vehicles as charging-discharging loads in the power systems, this changes the load pattern and load responses to the power system [3]. Therefore, a better understanding of the impacts of load characteristics on power system operation and planning is necessary. There are works of literature that investigated the application of frequency-dependent composite load models, for example, in [4] and [5]. The load modelling mentioned in the literature demonstrated that the accuracy of load characteristics was improved using frequency-dependent load models and the optimized parameters. However, the above implementations cannot be effectively adopted by utility companies because these studies were not conducted with commonly used commercial-grade software tools.

This paper investigates how well the available load models used for power system simulations represent the frequency response of system load elements during frequency excursion events when simulating with commercial-grade software tools. Data recorded by Phasor Measurement Units (PMU) is used to evaluate load responses and characteristics during frequency excursion events and to find out if load models can represent the load response in power system simulations. A methodology is proposed to investigate and evaluate the frequency response of an industrial load simulated with different load models recommended in the industry. The optimization of commonly used load models will also be explored to improve the accuracy of their load responses. An optimization process is designed to find the best load models and parameters so that that load response can be more accurately represented in frequency excursion studies.

The remaining parts of this paper are organized as follows. Section 2 describes the methodology used to evaluate the performance of load models used in the industry in the simulation of frequency excursions and compares the measured and simulated results. Section 3 proposes the optimization of load models. Numerical results are presented and analyzed. Finally, Section 4 concludes the paper.

2. Performance of load models used in the industry in the simulation of frequency excursion events

A single machine infinite bus (SMIB) system model was developed for the case of the investigated load in Alberta, as shown in Figure 1. Bus 11 represents the measuring point of the PMU installed one substation away from the investigated load substation. The line between busses 11 and 111 is the transmission line between the substation where the PMU was installed and the target load substation. The load substation consists of a 138kV/ 13.8kV point of delivery transformer and a load connected to the 13.8kV bus. Data for the transmission line and transformer are obtained from AESO's Operations Planning base case. In the dynamic simulation of this work, the play-in model, PLBVFU1 [6], a built-in model in PSS®E, is attached to the generator created at bus 11. The generator represents the rest of the system by playing back the recorded voltage and frequency data. Therefore, the load response is solely affected by the system changes during frequency excursion events represented by the playback PMU data at bus 11.

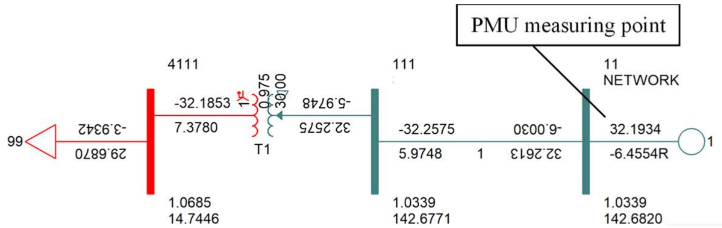

Figure 1. Network diagram of SMIB setup for the target load substation

PMU data consists of voltage phasors (voltage magnitude and voltage phase angle), current phasors (current magnitude and current phase angle) and the frequency. Voltage magnitude and frequency, as shown in Figure 2, are the inputs to the playback generator. On the other hand, all the measurements of the PMU data are used to calculate the instantaneous power, which will then be used as the reference signals for the evaluation of outputs of dynamic simulation using different load models.

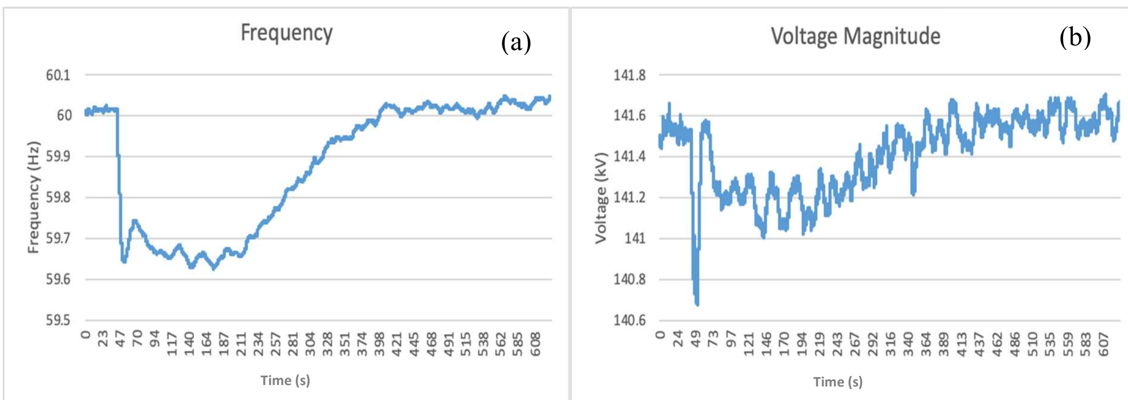

Figure 2. PMU data of a frequency excursion event. (a) is frequency, (b) voltage magnitude

Since single-phase measurements are only available for voltage phasors and current phasors due to current PMU installations in the Alberta system, the following assumptions are made in this paper for conventional instantaneous power calculations, as shown in (1).

- The system is a balanced 3-phase system,
- It is in a steady-state condition and the frequency is constant at each sampling instant

Active power is the real part of the complex power, $S_{3\phi}$ while reactive power is the imaginary part of $S_{3\phi}$ as shown in (1). The calculations agree with the p-q theory that uses the Clarke transformation proposed in Akagi's Instantaneous Power Theory presented in [7] with the above assumptions.

$$P_{3\phi} = Re(S_{3\phi}) = 3V_{LN}I_L\cos(\delta - \beta)\ \text{W} \quad (1)$$
$$Q_{3\phi} = Im(S_{3\phi}) = 3V_{LN}I_L\sin(\delta - \beta)\ \text{Var}$$

Three different load models are evaluated in this study, which includes static and composite load models. Static load models express active and reactive power at any instant of time as functions of voltage magnitude and frequency at a particular time instant [8]. In this paper, static models are represented by the IEEE load model [6] in dynamic simulations in PSS®E. The constant admittance/current/power (ZIP) and exponential load models are two commonly used static load models. Active and reactive power are expressed, as shown in (2) for the ZIP model. NERC assumes the ZIP model in a study, as shown in (3), where active power is independent of frequency, and reactive power is inversely frequency dependent [9]. Active and reactive power of exponential load models are represented in (4). The parameters k_{pv}, k_{qv}, k_{pf} and k_{qf} are expressed in the IEEE model to represent voltage and frequency dependencies, and the recommended parameters are summarized in Table *1*.

$$P = P_0(a_1\bar{V}^2 + a_2\bar{V} + a_3)(1 + K_1\Delta f)$$
$$Q = Q_0(a_4\bar{V}^2 + a_5\bar{V} + a_6)(1 + K_2\Delta f) \quad (2)$$

$$P = P_{load}(0.3v^2 + 0.7v)$$
$$Q = Q_{load}(-0.5v^2 + 1.5v)\,(1 - \Delta f) \quad (3)$$

$$P = P_n\left(\frac{V}{V_n}\right)^{k_{pv}}(1 + k_{pf}\Delta f)$$
$$Q = Q_n\left(\frac{V}{V_n}\right)^{k_{qv}}(1 + k_{qf}\Delta f) \quad (4)$$

Table 1. Recommended exponential load model parameters for industrial and mixed loads

Reference	Load	Season	k_{pv}	k_{qv}	k_{pf}	k_{qf}
[10]	Industrial	Summer	0.84	9.40	0.39	7.47
		Winter	1.17	11.95	0.42	3.09
	Mixed	Summer	0.78	3.29	0.69	-8.89
		Winter	1.21	3.88	0.77	-10.85

The complex load model (CLOD) is a composite load model that is widely used by system operators to simulate the dynamic behaviour of loads. CLOD has separate models for large and small motors, discharge lightning and few other load elements. Details of each element are fixed in this model, and the percentage of these components are the parameters that can be adjusted by the users. K_p is the voltage exponent of the active power of the remaining loads. The CLOD parameters recommended in the industry are summarized in Table 2.

Table 2. Summary of recommended CLOD parameters

Parameters	Large motors (%)	Small motors (%)	Transformer exciting current (%)	Discharge lighting (%)	Constant power (%)	K_p	Branch R (pu)	Branch X (pu)
WECC [11] [12]	10	10	0	0	0	1	0	0.0001
NERC [9]	15	45	0	20	6	1.25	0	0.1
AESO Industrial [13]	40	30	0	0	0	1	0	0.0001

This paper examines the load response focusing on the active power because frequency deviations and changes in load active power response are interdependent [8]. The following are some of the key quantitative measures of load responses evaluated in this paper.

- Power drop – power difference between the pre-contingency power level and the minimum power
- Initial power recovery – the percentage of power recovery relative to the power drop magnitude as shown in (5) between 20-52 seconds [14] to captures mainly the effects of the primary frequency responses and before significance influence of secondary controls
- Mean Absolute Error (MAE)

$$Power\ recovery = \frac{\bar{P}_{recovery} - P_{min}}{P_{power\ drop}} \quad (5)$$

Dynamic simulations were performed with the input voltage and frequency of a frequency excursion event, as shown in Figure 2. Active power results of the industry recommend parameters for CLOD, ZIP and exponential load models are shown in Figure 3. As observed in the figure, the load models do not always represent the load response to the real-life measurements accurately. Comparing the load responses, the static load models have a more significant power drop than CLOD models of various percentages of large motors and small motors. The load parameters of the "mixed loads in winter season" represented by exponential load model (grey) is the closest to the PMU data (brown) by visual inspection.

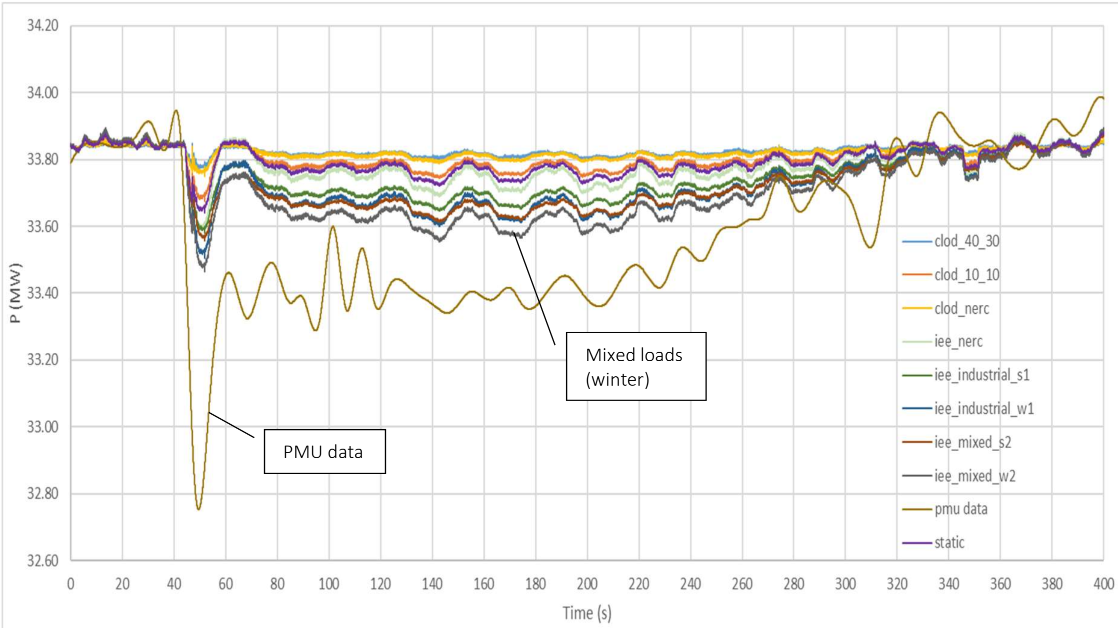

Figure 3. Active power results simulated with different load models compared with PMU data

Table 3. Quantitative comparison of various load models to PMU data

Scenario	Power drop (MW)	Initial power recovery (%)	MAE_p (pu)
PMU	1.103	57.5	-
Exp_mixed_w2	0.385	52.8	3.886e-3
Exp _industrial_w1	0.342	58.3	4.306e-3
Exp _mixed_s2	0.291	47.2	4.333e-3
Exp _industrial_s1	0.266	54.3	4.663e-3
ZIP_NERC	0.258	74.4	5.177e-3
Static	0.201	74.0	5.442e-3
CLOD_10_10	0.165	74.3	5.633e-3
CLOD NERC	0.090	76.5	6.023e-3
CLOD_40_30	0.073	76.2	6.122e-3

Table 3 presents the quantitative comparisons of the simulation results. The power drop magnitude of the mixed load is about 1/3 of the magnitude of the PMU measurements, and it has a comparable power recovery percentage to the PMU data. In addition, MAE of the active power response for the mixed load is 3.886e-3 pu, which is the lowest among the load models evaluated. The MAE results align with the observations in Figure 3, as well as other quantitative comparisons to achieve an informative conclusion.

In this evaluation, the exponential models are better approximations of the real-life load response in comparison to the ZIP and CLOD model in terms of power drop, power recovery and MAE. The CLOD models have smaller active power drop, and they give more conservative approximations of load responses for frequency disturbance studies. When a jurisdiction has a high percentage of conventional large motorized loads in the load profile, this can provide load damping during frequency disturbance to resist frequency drop. Therefore, if frequency sensitivity is modelled to reflect more accurate load responses in real-life frequency disturbances, this can increase the credibility of the studies and pose positive impacts to the required balancing resources required for contingency management.

3. Optimization of load models

The dynamic load modelling problem is generally highly non-linear. Therefore, model-independent optimizations like evolutionary techniques are more suitable choices [15] because they can perform a diverse search in the solution space and do not depend heavily on the initial guess of parameters compared to other conventional optimization algorithms. The optimization problem in this paper is based on Genetic Algorithms (GA).

The optimization procedure proposed, as shown in Figure 4, cooperates with the dynamic simulation procedures discussed in the previous section, to perform dynamic simulation using the play-in model by playing back the input voltage and frequency in Figure 2 with the PSS®E. The objectives of the optimization problem are to find the set of load model parameters to minimize the Mean Absolute Error (MAE) between the simulated active and reactive power results and those from the PMU data. Hence, the fitness function can be written as (6).

The parameters of ZIP and exponential load models correspond to voltage and frequency dependencies in (2) and (4) are optimized. For CLOD, the dependencies of both large and small motors are very significant [16], it increases the risk of the optimization problem getting stuck in a local optimal solution. Therefore, the percentage for large motor and K_p are the optimized parameters. The percentage of small motor is fixed to a generic parameter of 10% because the load is considered as large motor loads in this paper by observing the PMU data for average power consumption.

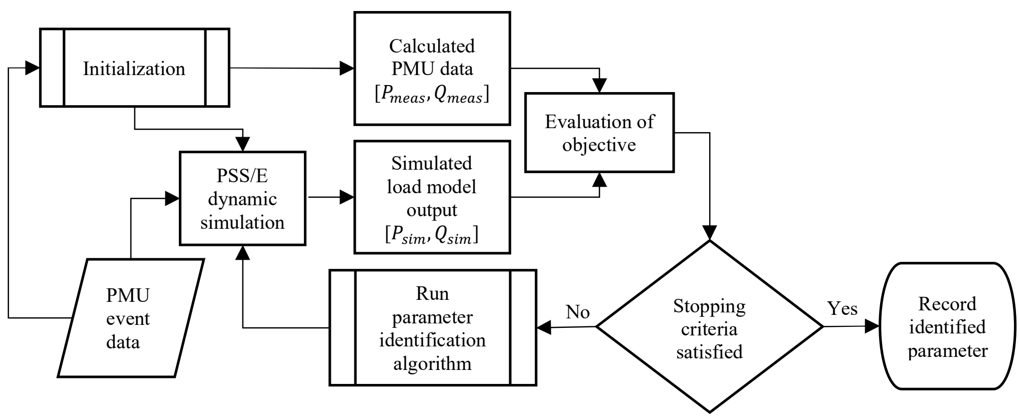

Figure 4. Flowchart diagram for evolutionary-based load model identification

$$f_1(t) = \frac{1}{M}\sum_{t=0}^{M} |P_{sim}(t) - P_{meas}(t)|$$
$$f_2(t) = \frac{1}{M}\sum_{t=0}^{M} |Q_{sim}(t) - Q_{meas}(t)| \quad (6)$$

where *M* accounts for the number of measurement points to be compared at each of these available measurements.

The active power responses simulated with the optimized load models are shown in Figure 5 and the quantitative comparisons are reported in Table 4. The optimized load response shows significant improvement compared to the recommended models presented in the last section. Comparing the optimized load models, CLOD can better predict the power drop in a frequency excursion event, followed by exponential and ZIP models and the magnitude of power drop has significantly improved by 43% with respect to the static load models discussed in the last section. In terms of power recovery, the optimized exponential model and the mixed load model have the closest performance compared to the PMU response. The active power of these two models recovered about halfway from the power drop before ramping back to the pre-contingency level. The optimized ZIP load model has the lowest MAE. However, it cannot completely predict load response accurately in terms of power drop and power recovery compared to CLOD and exponential models. Therefore, MAE, as well as other quantitative comparisons, are required to better understand the difference in the performance of these optimized load models.

The optimized load models are simulated in another frequency excursion event. The active power responses are presented in Figure 6, and the quantitative comparisons are reported in Table 5. Consistent simulation results can be observed in terms of improvements in power drop, power recovery and MAE. However, the improvement of load responses in this scenario is not as prominent. This is because the optimized CLOD, having a high proportion of voltage-dependent static loads, and the static load models express the active power as a function of voltage magnitude and frequency of the first event. System frequency responses, as demonstrated in the two events, usually have similar characteristics for frequency disturbances occur within a jurisdiction. Therefore, as confirmed in this evaluation, the static load models can provide reasonable approximations of the real-life load responses with proper load model optimization and provide insights into the propositions and characteristics of the investigated load.

Table 4. Quantitative comparisons of the optimized load models

Scenario	MAE_p (pu)	Power drop (MW)	Power recovery (%)
PMU	-	1.103	57.5
Mixed load	3.886e-3	0.385	52.8
CLOD	2.999e-3	0.863	73.8
ZIP	2.344e-3	0.506	34.3
Exponential	2.681e-3	0.656	53.0

Table 5. Quantitative comparisons of the optimized load models in event 2

Scenario	MAE_p (pu)	Power drop (MW)	Power recovery (%)
PMU	-	1.524	72.9
Mixed load	3.631e-3	0.420	54.2
CLOD	3.813e-3	0.799	84.3
ZIP	2.956e-3	0.514	36.6
Exponential	2.989e-3	0.638	57.1

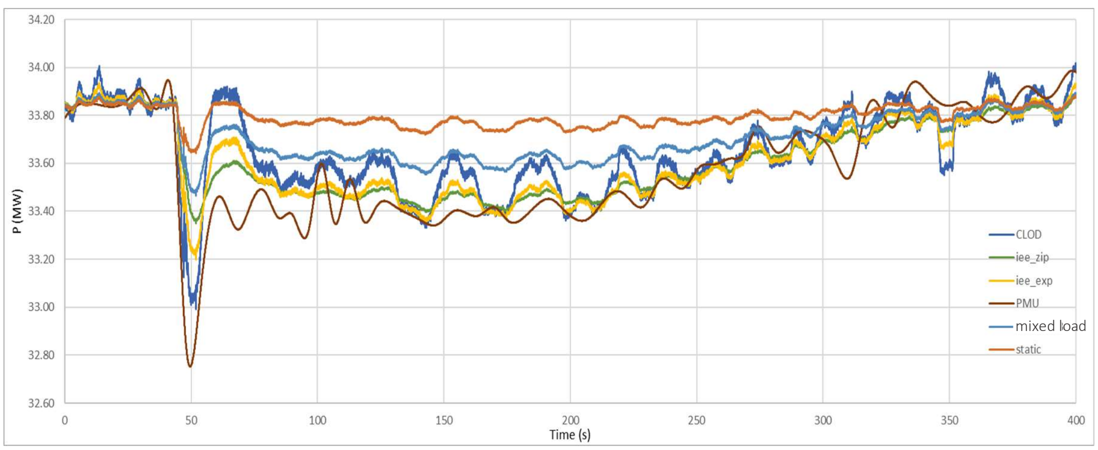

Figure 5. Active power results simulated with optimized CLOD, ZIP and exponential model

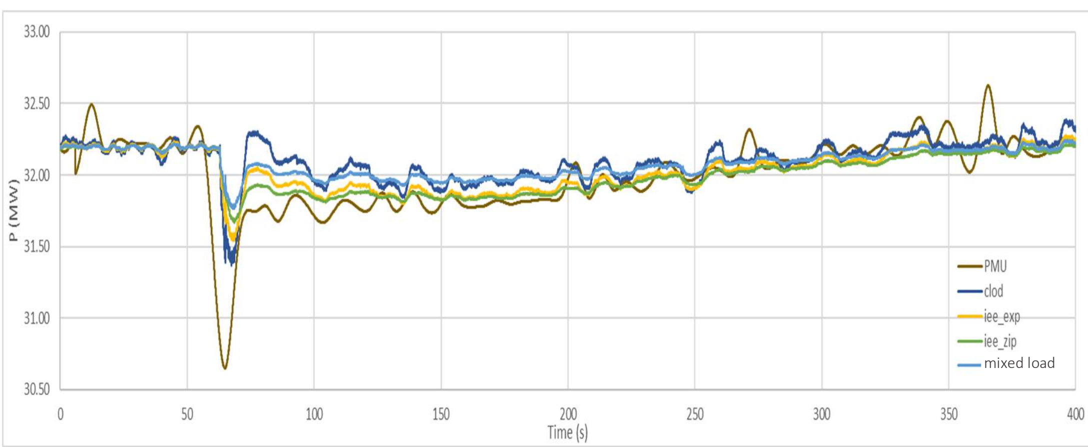

Figure 6. Active power results simulated with optimized CLOD, ZIP and exponential model in event 2

Given the quantitative and qualitative comparisons presented on the investigations in the case of Alberta, significant improvements achieved by using the optimized load models instead of the recommended ones are observed. From the proposed process, power system operators can understand the impact of accurate load models on the load response. This is especially useful in understanding the load impact in frequency disturbance events. The choice of load model and its parameters are highly dependent on the engineer's knowledge on the load customer and on their judgement regarding power system planning and contingency management.

4. Conclusion

A comprehensive investigation of the performance of available load models used in the industry to represent the frequency response of system load elements during frequency excursion events in power system simulations is considered in this paper. Furthermore, this paper demonstrated the improvement of optimized load models and their parameters to better match the real-life measurements for the investigated load in Alberta.

Electrical loads greatly influence the behaviour of the electric system, and accurate load modelling of these devices needs more considerable attention, especially in power system planning and contingency management for frequency excursions. Evaluation of the choice of load model and its parameters is, therefore, a critical step in power system analysis. The selection of load models depends on the study scope and the engineer's knowledge of the loads.

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