Data-Driven and Machine Learning-Based Load Modeling

Final Project Report

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Power Systems Engineering Research Center
Empowering Minds to Engineer the Future Electric Energy System
Data-Driven and Machine Learning-Based Load Modeling

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Executive Summary

Load modeling is of great significance for various power grid studies, such as power system operation optimization, energy reservation, and stability analysis. The overall purpose of this project is to develop and apply cutting-edge data-driven and machine learning-based methods to accurately model power system loads using real utility data.

First, we conducted a comprehensive review of the load models, analyze their advantages and disadvantages, research trends, and industrial applications, which laid a valid foundation for the model selection, parameter reduction, and order reduction. There are a variety of load models available in the power system industry and academia. The commonly used models be classified into static load models, dynamic load models, and composite load models.

- Static load models: They include the constant impedance-current-power (ZIP) model, exponential model, and frequency dependent model. Static models express the active and reactive power at any instant of time as functions of bus voltage magnitudes and frequency, and the dynamics of load are neglected.

- Dynamic load models: They include induction motor (IM) and exponential recovery load model. Dynamic models express the active and reactive powers as a function of voltage and time, and they consider the dynamics of load variations.

- Composite load models: For providing more accurate responses, composite load models are developed by combining static and dynamic load models. Typical composite load models are ZIP+IM composite load model, and Western Electricity Coordinating Council (WECC) model. The WECC model contains a substation transformer, shunt reactance, feeder equivalent, induction motors, single-phase AC motor, ZIP load, electronic load, and distributed energy resources (DER). It can effectively capture the commonly-observed fault-induced delayed voltage recovery (FIDVR) events and has drawn great attention recently.

The WECC composite load model (WECC CMLD) produces accurate responses; nevertheless, the large number of parameters and high model complexity raises new challenges for power system studies. For the parameter identification problem, the large number of parameters brings great difficulties to search for global optimum when performing parameter identification. The reason is twofold: firstly, the large number of parameters results in a large search space that reduces the optimization efficiency; secondly, the insensitive parameters and parameter interdependencies usually result in a large number of local optima, which increases the difficulty of achieving global optimum. Although the parameters have physical meanings, some of them only have marginal impacts on the model response altogether or along certain parameter variation directions. Moreover, considering the full load model parameter set could significantly increase the complexity of power system studies. Therefore, it is imperative to develop a method to screen out the insensitive parameters. Then, only the sensitive parameters are to be determined in the parameter identification problem, while the others can be kept at their respective default values. In this way, the dimension of the search space of load model parameters can be significantly reduced. Thus, lower computational cost (less model runs) and higher accuracy (easier to find the optimum)
can be achieved when conducting power system studies such as parameter identification without compromising the fidelity of the load model.

Second, we developed multiple data-driven and machine learning based methods for dimension reduction in parameter space to address the above-mentioned problems. Specifically, three major methods were proposed and validated, explained as follows.

- **A cutting-edge parameter reduction (PR) approach for WECC CMLD based on the active subspace method (ASM) was proposed, briefly explained as follows.** Firstly, the WECC CMLD is parameterized in a discrete-time manner for the application of the proposed method. Then, parameter sensitivities are calculated by discovering the active subspace, which is a lower-dimensional linear subspace of the parameter space of WECC CMLD in which the dynamic response is most sensitive. The interdependency among parameters can be taken into consideration by our approach. Finally, the numerical experiments validate the effectiveness and advantages of the proposed approach for the WECC CMLD model.

- **A novel approach inspired by the evolutionary deep reinforcement learning (EDRL) with an intelligent exploration mechanism was obtained to perform parameter identification for the composite load model with distributed generation (CMPLDWS).** First, to extract parameters’ contributions to dynamic power, parameter sensitivity analysis is conducted using a data-driven feature-wise kernelized Lasso (FWKL). Then, the EDRL with intelligent exploration, which can handle the natural high nonlinearity and nonconvexity of CMPLDWS, is employed to perform parameter identification. In the parameter identification process, the extracted parameter sensitivity weights are innovatively integrated into the EDRL with intelligent exploration to improve discovery efficiency. Finally, the proposed approach is validated using numerical experiments.

- **A Python-PSSE-combined autonomous parameter identification program was developed.** It enables efficient information change between the optimization method sited in the Python environment and the WECC load module in PSSE software. As the WECC load module is the available most convincing representation of the WECC load module, this approach can eliminate the possible errors brought by the inaccurate representation of the WECC load modeling. As an example of the heuristic optimization methods, the SSA is adopted to optimize the WECC load parameters using real event data provided by AEP. The SSA sends the WECC parameters to the PSSE as its inputs. Based on these WECC parameters provided by SSA, a dynamic simulation is conducted in the PSSE using the PMU frequency measurements and voltage measurements. After the simulation is conducted, an active power curve and a reactive power curve are obtained, and they are provided to the SSA. The SSA then compares the simulated P, Q curves with the real P, Q measurement curves to update the WECC parameters. The obtained results are very promising, and they validate the efficiency and accuracy of our proposed Python-PSSE-combined autonomous parameter identification program.

Third, we developed a large-signal order reduction (LSOR) method using singular perturbation theory to reduce the order of the WECC composite load model. The WECC composite load model is a complex high-order nonlinear system with multi-time-scale property, which poses challenges on power system studies with a heavy computational burden. In order to reduce the model
complexity, an order reduction method was derived based on the singular perturbation theory. In this method, the fast dynamics are integrated into the slow ones to preserve the transient characteristics of the former. Then, accuracy assessment conditions are proposed and embedded into the LSOR to improve and guarantee the accuracy of the reduced-order model. Finally, the reduced-order WECC composite load model is derived by using the proposed algorithm. Simulation results show that the reduced-order large-signal model significantly alleviates the computational burden while maintaining similar dynamic responses as the original composite load model. The derived reduced-order model has guaranteed high accuracy that can replace the original load model in high-order system simulation to perform power system studies. This replacement can significantly reduce the difficulty of stability analysis and computational burden.

The major research outcomes of this project are listed as follows.

- Provided an all-inclusive review of load modeling.
- Developed a general global sensitivity analysis method to reduce the dimension of input space of any nonlinear model with scalar output.
- Proposed a WECC composite load model parameter identification approach using evolutionary deep reinforcement learning.
- Developed an autonomous parameter identification approach by calling PSSE dynamic simulation in python-based optimization algorithms.
- Derived an order reduction technique based on the singular perturbation theory to obtain a reduced load model.

Some next steps to move the research toward applications are discussed as follows.

- Test and validate the proposed methods using more real event data from the industrial partners, and finally make some software packages available to the public.
- Develop novel models with reduced complexity and computational requirements to better represent active distribution networks, distributed generators, and microgrids.
- Research parameter estimation algorithms that are able to process data from existing and emerging measurement devices with different resolutions, such as smart meters, PMUs, and SCADA.

**Project Publications:**


