Data-Driven Load Diversity and Variability Modeling for Quasi-Static Time-Series Simulation on Distribution Feeders

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Data-Driven Load Diversity and Variability Modeling for Quasi-Static Time-Series Simulation on Distribution Feeders

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***Abstract*—This paper presents a data-driven load modeling methodology for distribution system quasi-static time-series (QSTS) simulation considering both diversity and variability characteristics of distribution loads. Based on our previous work in [1]–[2], a variability library and diversity library have been established based on the realistic high-resolution data collected from actual utility feeders. Given the load profile for the start-of-circuit load of a feeder, the loads on the feeder nodes can be modeled with both diversity and variability instead of being directly scaled from the substation load profile according to the distribution allocation factors. With diversified load models, the load-induced impact on the feeder operation characteristics, such as voltage ramp and regulator operations, can be better considered in QSTS simulation. The proposed modeling methodology has been tested on both the IEEE 123-bus feeder and an actual utility feeder model, and the simulation results have demonstrated the merits of deploying the proposed load modeling methodology.**

Keywords—data-driven; distribution system; diversity; load modeling; quasi-static time series (QSTS); variability;

I. INTRODUCTION

Recently, the high penetrations of distributed energy resources such as photovoltaic and community-/home-owned energy storage is beginning to require grid operators to deploy more accurate system simulations for system planning purposes and to maintain proper distribution system operations. This demands more effective quasi-static time-series (QSTS) simulation [3]–[5]. Therefore, load modeling, especially high-resolution load modeling, has become critical because high-performance QSTS simulation requires realistic load modeling down to the level of the customer transformer.

In current QSTS simulation, every node in a distribution system was populated with the same load shape as the substation but with scaled magnitude differences introduced by distribution factors [6]. In reality, however, the load profiles for the nodes in a distribution system are mostly diversified, with different patterns and temporal variability. Therefore, representing all the nodes in a distribution system with only one load shape cannot effectively capture the operation characteristics of the system over time. Nowadays, benefiting from smart meter installations, some utilities have some measured customer load profiles. But the locations with smart meters are often limited, and the temporal resolution is often low. Furthermore, the use of measured utility data is often restricted due to potential privacy concerns because energy consumption patterns might reveal the living patterns of the customers.

To address these issues of load modeling for QSTS simulation, in our previous work [1]–[2],we developed a discrete wavelet transform (DWT) based load modeling and aggregation method to add variability onto the load profiles at different nodes (i.e., transformer locations) so that the QSTS simulation could capture the operational impact caused by the load variability.

Based on our previous work, we further deploy a k-means clustering method based load diversity modeling approach, to build a diversity library based on the measured high-resolution customer transformer level data, to ensure that different load patterns can be applied to the load profiles at different locations. Then diversified load profiles with various patterns and variabilities for the nodes on a distribution system can be created.

The proposed load modeling methodology has been tested on both the IEEE 123-bus system model and a realistic utility feeder model from California. The performance of the simulation with diversified load profiles has been compared with that of the simulation with the same load shapes at all the nodes (i.e., simply allocated loads). The comparison has effectively demonstrated that the proposed load modeling methodology successfully captured more feeder operation characteristics from various aspects, including voltage ramping and legacy device operations.

This paper is organized as follows: Section II introduces the load modeling methodology, Section III presents the case studies on the IEEE 123-bus feeder model and the realistic feeder model, and Section IV concludes the paper and discusses future work.

II. MODELING METHODOLOGY

In this section, the overall modeling methodology is introduced first, then the approach of building the diversity and variability libraries is discussed.

A. Modeling Overview

The overall modeling approach is summarized in Fig. 1. Basically, the modeled load profile on each node comprises four major parts: 1) the diversity model extracted from the diversity library, 2) the variability model extracted from the variability library, 3) the substation load profile, and 4) the distribution factor for the particular node. Here the variability and diversity libraries contain the second-level variation models and diversified load patterns respectively.

As shown in Table I, the modeling flow is described in three steps: first, the substation load profile is scaled by the distribution factor for the node; second, the extracted diversity model is applied to the scaled substation load profile so that the scaled substation load profile will have the certain load pattern defined by the diversity model; finally, the variability model extracted from the variability library is employed to create the detailed load model for this node.

The detailed and sample models of the diversity and variability libraries are introduced in parts B and C, respectively. Both the diversity library and variability library are constructed from actual high-resolution transformer level data; thus, this approach is data-driven and replicable for all utilities with a limited amount of collected high-resolution customer data.

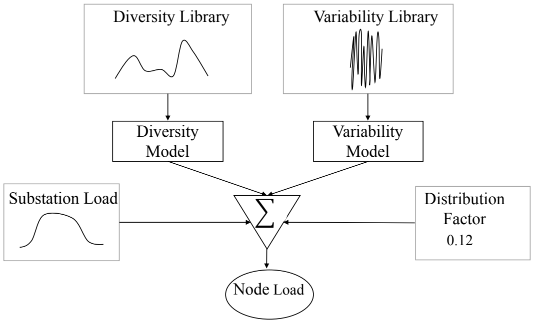


Fig.1. Overview of modeling approach

TABLE I MODELING PROCESS

Step 1	Scale substation load profile by distribution factor
Step 2	Extract diversity model from library and apply to scaled substation load profile
Step 3	Extract variability model from library and apply to the profile with diversity applied

B. Diversity Library

As shown in Fig. 2, the diversity library is built by four steps: first, the elbow method [7] is deployed to determine the number of clusters appropriate for the data set; second, the k-means clustering method [8] is deployed to cluster the data into k groups; third, the center profile of each cluster is extracted; then, finally, the load patterns are formulated from the center profiles, and the diversity library is built from the load patterns.

The k-means clustering is a classic approach commonly used to automatically divide a data set into k different groups. The elbow method is usually used to effectively determine the appropriate number of clusters for this data set. An example of the k-means clustering and elbow method application in this paper along with the diversity library constructing process is discussed as follows.

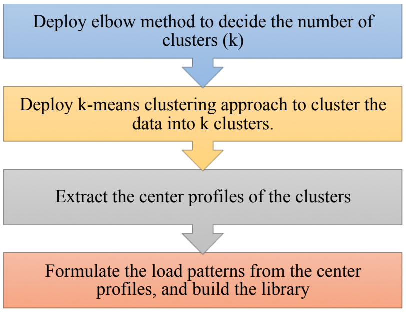


Fig. 2. Load pattern extraction process

The data set in this example has 77 load profiles in total. Fig. 3 shows how the elbow method is deployed to determine the number of clusters for this data set. For Fig. 3(a), the x-axes denotes the number of clusters, and the y-axes denotes the sum of squared errors (SSE). A squared error is the summation of the squared distance between the profiles in a cluster and the cluster center profile. SSE represents the summation of squared errors from all the clusters. Fig. 3(b) shows the gradient for SSE for different numbers of clusters. It is observed that 15 is approximately a turning point.

Ideally, a small number of clusters (k) with a small value of SSE is desired. In this case, k=15 is an appropriate choice because it appears around the elbow in Fig. 3(a) and serves as turning point in Fig. 3(b).

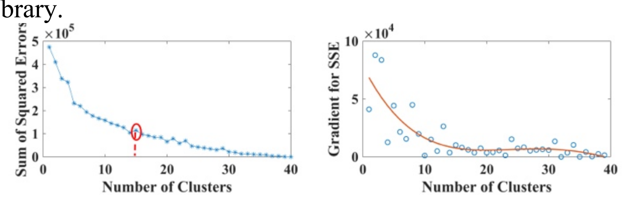
Given the number of clusters as 15, two sample clusters are shown in Fig. 4 after the data are clustered. As shown in Fig. 4 (a), 6 profiles are clustered into this group, with similar characteristics of valley bottom at noon and some sharp peaks in the evening. Fig. 4(b) shows the profiles in another sample cluster: three profiles that all have similar shapes with morning peaks.

After the data are clustered into different groups, the center profile of each cluster is extracted. Then the k-means clustering method is applied to the center profile to cluster the data points in the center profile into several groups for the purpose of extracting load patterns. After the clustering, each time spot will belong to a group, then the load patterns are formulated by matching the mean of each group to every time spot, as shown in the right two figures in Fig. 5 (a) and (b). Finally, the diversity library is built by collecting all the load patterns.

C. Variability Library

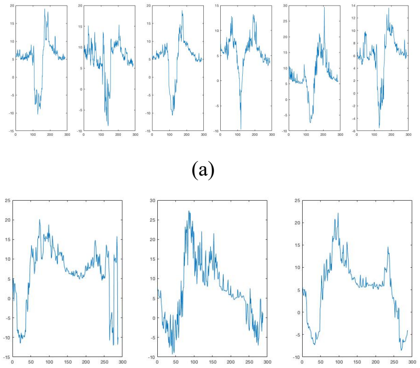
Multi-resolution DWT is used to extract the variability from the realistic high-resolution data. Basically, the high-frequency variabilities of the data are extracted and used to build the variability library. Details of the construction of the variability library are introduced in our previous paper [1].

The general idea of extracting the variability could be described as follows [9-11]: As shown in Fig. 6, input data s will be decomposed into detailed and approximate coefficients. a_1, a_2, and a_3 represent approximate coefficients, which are obtained by a low-pass filter and contain the low-frequency signal. d_1, d_2, and d_3 represent detailed coefficients, which are obtained by a high-pass filter and contain the high-frequency signal. As shown in (1), the summation of all the detailed coefficients and the approximate coefficient from the last level of decomposition will reconstruct the original signal. Basically, the detailed coefficients that contain the high-frequency variability are retained and can be used to build the variability library.



(a) (b)

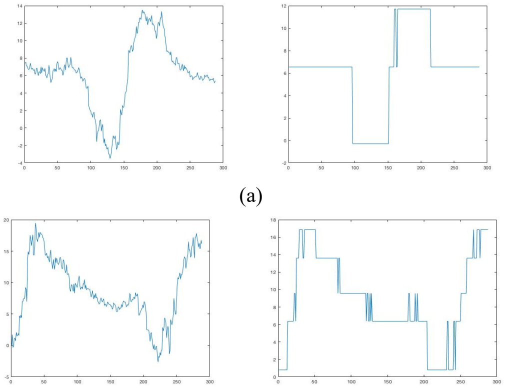
Fig. 3. Selection of k with elbow method



(a)

(b)

Fig. 4. Sample clusters



(a)

(b)

Fig. 5. Load pattern formulation

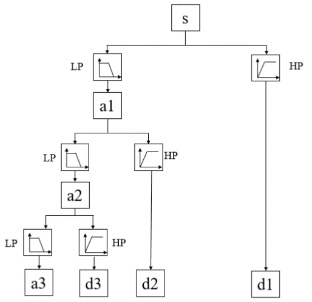


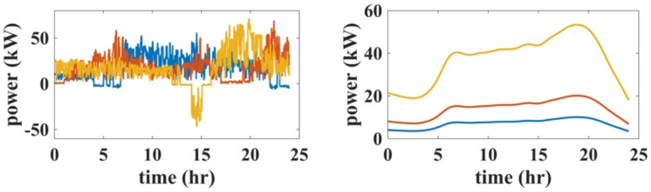
Fig. 6. Wavelet decompostion illustration

$$s = d1 + d2 + d3 + a3 \tag{1}$$

III. CASE STUDY

Case studies have been performed on both the IEEE 123-bus system model and a realistic utility feeder model to test and evaluate the proposed load modeling methodology. For each case study, two sets of tests have been conducted: one with plain loads and one with diversified loads. For the testing with plain loads, the load profile on each node is directly scaled from the substation load profile according to the distribution factor. Therefore, in the case with plain loads, each load node has exactly the same load shape as the substation load profile, with different magnitudes. For the testing with diversified loads, the load profile on each node is constructed by the modeling methodology introduced in Section II, with both diversity and variability built in, and with the shape of the substation load profile as the modeling base. In this case, load shapes among nodes are diversified with different patterns and variabilities.

Fig. 7(a) and (b) show the sample load profiles for the testing with diversified loads and plain loads, respectively. Three node load profiles are shown in each figure. It can be observed that the diversified loads have different patterns and variabilities for different nodes, whereas the plain loads all have the same shape as the substation load with different load levels. In both the diversified load and plain load situations, the summation of all the loads is equal to the substation load profile.



(a) (b)

Fig. 7. Sample load profiles

Day-long OpenDSS simulations with various temporal resolutions ranging from 1 second to 30 minutes are performed for each case study to investigate the impact of the load diversity on the distribution system simulation for different temporal resolutions.

Voltage profile characteristics such as maximum voltage, minimum voltage, and voltage ramp were measured. Voltage regulator operations were also measured to evaluate the modeling methodology.

A. *Case Study on IEEE 123-Bus Feeder*

The first case study is performed on an IEEE 123-bus feeder [12], as shown in Fig. 8 . There are a total of 91 load nodes in the IEEE 123-bus feeder. Four regulators are scattered along the feeder, including two three-phase regulators.

Table II shows the comparison of the voltage characteristics from simulations with different time resolutions. It was observed that the maximum voltages for diversified loads are generally higher than those of the plain loads; vice versa, the minimum voltages for the diversified loads are lower than those of the plain loads. Table II also shows that the maximum voltage ramps at various resolutions of the simulation with diversified loads are all much higher than those of the simulations with plain loads.

Fig. 9 (a-c) demonstrates the voltage ramp distribution of the one-day simulation with various time resolutions. The left three figures represents diversified loads, the right three represents plain loads. To better show the comparison, some of the large ramps in the diversified load simulation results are not plotted in the figures. From Fig. 9, it could be observed that the voltage ramps of the diversified loads for the whole day are mostly much higher than those of the plain loads

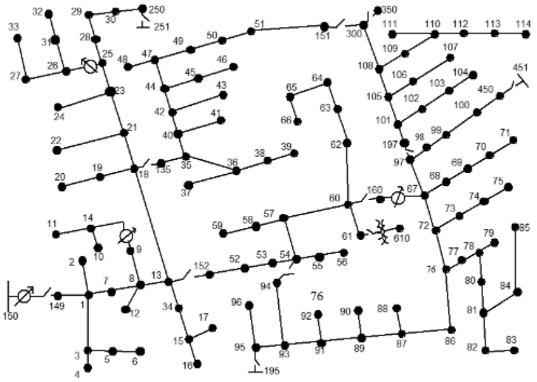


Fig. 8. IEEE 123-bus feeder

TABLE II VOLTAGE RESULTS COMPARISON FOR VARIOUS RESOLUTION (IEEE 123-BUS FEEDER MODEL)

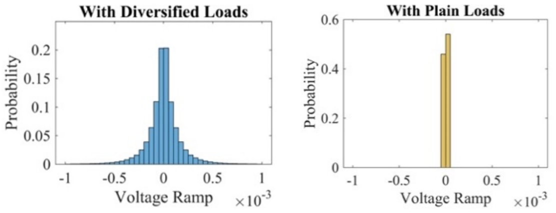
		Maximum Voltage (p.u.)	Minimum Voltage (p.u.)	Maximum Ramp (p.u./ Δt)
1-second	Diversified Loads	1.0338	0.9379	0.0258
	Plain Loads	1.0183	0.9720	2.9802×10^{-6}
1-minute	Diversified Loads	1.0331	0.9398	0.0258
	Plain Loads	1.0182	0.9720	1.4764×10^{-4}
10-minute	Diversified Loads	1.0299	0.9479	0.0246
	Plain Loads	1.0180	0.9720	0.0015
30-minute	Diversified Loads	1.0286	0.9495	0.0151
	Plain Loads	1.0179	0.9720	0.0042

TABLE III VOLTAGE REGULATOR MOVES COMPARISON FOR VARIOUS RESOLUTION (IEEE 123-BUS FEEDER MODEL)

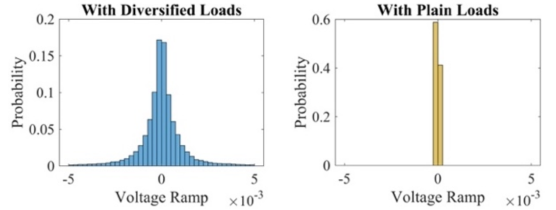
	1-second	1-minute	10 – minute	30 – minute
Diversified Loads	218	182	53	43
Plain Loads	31	31	29	29

Table III shows the comparison of the voltage regulator moves: diversified loads capture more regulator moves than plain loads in different temporal-resolution simulations. It could be observed that increasing temporal resolution does not help capture more feeder legacy device operations when performing simulation with plain loads.

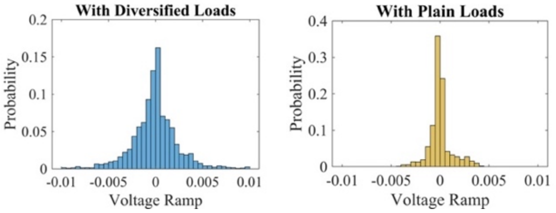
In total, the aforementioned analysis of the simulation results demonstrates that the diversified loads modeled by the proposed methodology greatly help capture more feeder and load characteristics in distribution system simulations, especially for high-resolution QSTS simulation.



(a) 1-second resolution



(b) 1-minute resolution



(c) 30-minute resolution

Fig. 9. Voltage ramp distribution for IEEE 123-bus system

B. *Case Study on Realistic Utility Feeder Model*

The 1-day simulation results for the realistic utility feeder models are discussed here. This feeder has 619 load nodes in total, and three regulators are installed.

Table IV shows the voltage results summary for different time resolutions. Because of space limitations, the maximum and minimum voltages are not shown here. Basically, they have the same characteristics as the IEEE 123-bus system: simulation with diversified loads could capture a higher voltage peak and lower bottom.

Similar to Fig. 9, Fig. 10 shows the voltage ramp distribution at various time resolutions. From the voltage ramp distribution shown in Fig.10 and the maximum voltage ramp shown in Table IV, it is observed that the diversified loads capture higher voltage ramps almost at all the times in a day, especially for high-resolution simulations.

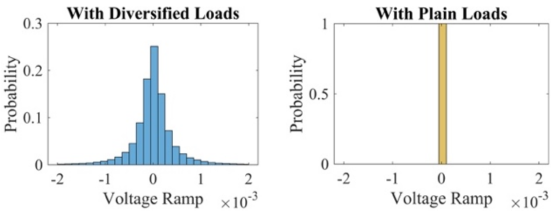
Table V shows the voltage regulator operations comparison. It could be observed that the diversified loads trigger more regulator operations in the QSTS and high-resolution simulations. Also, at different time resolutions, the system with diversified loads has different regulator operation numbers; however, similar to the IEEE 123-bus system, simulations with plain loads have almost same number for different time resolutions. Using plain loads did not capture system characteristics effectively when performing QSTS simulation. Instead, simulation with diversified loads effectively captured feeder characteristics and revealed more useful information.

TABLE IV VOLTAGE RESULTS COMPARISON FOR VARIOUS RESOLUTION (REALISTIC FEEDER MODEL)

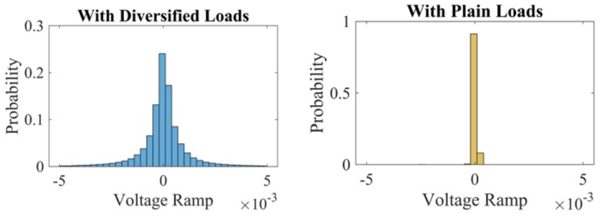
		Maximum Ramp (p.u./ Δt)
1-second	Diversified Loads	0.1270
	Plain Loads	0.0073
1-minute	Diversified Loads	0.0958
	Plain Loads	0.0072
10-minute	Diversified Loads	0.0691
	Plain Loads	0.0069
30-minute	Diversified Loads	0.0691
	Plain Loads	0.0069

TABLE V VOLTAGE REGULATOR OPERATIONS COMPARISON FOR VARIOUS RESOLUTION (IEEE 123-BUS FEEDER MODEL)

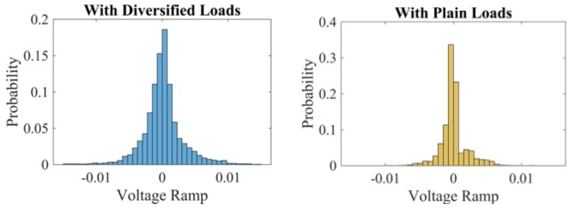
	1-second	1-minute	10-minute	30 – minute
Diversified Loads	18	14	7	4
Plain Loads	7	7	6	4



(a) 1-second resolution



(b) 1-minute resolution



(c) 30-minute resolution

Fig. 10. Voltage ramp distribution for IEEE 123-bus system

IV. CONCLUSION AND FUTURE WORK

This paper presents a data-driven load modeling methodology for distribution systems considering both diversity and variability. Based on high-resolution transformer-level load data, a DWT-based approach and k-means clustering method is used to build a variability library and a diversity library, respectively. The modeling methodology has been used to build diversified loads for both the IEEE 123-bus system model and an actual utility feeder model. The simulation results of these two feeders demonstrate that the proposed load modeling methodology can be effectively used for QSTS simulation for distribution systems. Future work includes developing a more delicate approach to populate the diversified loads onto the feeder node, with a number of parameters that researchers and grid operators could adjust as appropriate for modeling their systems.

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