IEEE Guide for Load Modeling and Simulations for Power Systems

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Smart Buildings, Loads, and Customer Systems Committee

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IEEE Guide for Load Modeling and Simulations for Power Systems

Developed by the

Smart Buildings, Loads, and Customer Systems Committee
of the
IEEE Power and Energy Society

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Abstract: Load modeling plays an important role in power system modeling, and the load model is an indispensable component in power system simulation. To get accurate load models and formulate a unified document, this guide has been developed to provide comprehensive policies and procedures of load modeling and simulations. A review and comparison of the two most widely used methodologies for load modeling is presented in this document, that is, the measurement-based and component-based approaches. A critical and updated overview of opportunities and challenges of load modeling with emerging networks and components is also provided. The guidelines for power system simulation with a variety of load models are proposed. A case study adhering to the proposed guidelines clearly indicates the need for a hybrid approach in the future that will combine the strengths of the measurement-based and component-based approaches with the data acquisition capabilities offered by modern measurement equipment.

Keywords: active distribution network, component-based approach, dynamic load model, IEEE 2781™, load modeling, measurement-based approach, microgrids, power system simulations, simulation, static load model

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Introduction

This introduction is not part of IEEE Std 2781-2022, IEEE Guide for Load Modeling and Simulations for Power Systems.

Load modeling plays an important role in power system modeling and simulation. It is a complex task considering many factors. The improper representation of system loads often leads to differences between recorded and simulated system responses, leading to errors and optimistic simulation results for stability analysis. This may misguide the operation of emergency protection and control systems, which in the worst case can cause large-scale power outages. With the emergence of new types of loads, load modeling is gaining more attention in the industry and academia. However, most load models currently in use were developed several decades ago and changes have not been updated in time. To get accurate load models and formulate a unified document, this guide has been developed to provide comprehensive policies and procedures of load modeling and simulations.

First, an overview of load models is summarized in this document. Except for the existing load models, that is, static and dynamic load models, some new emerging load models and standard requirements are also summarized.

Second, load model development methodologies are introduced. A detailed comparison of component-based and measurement-based approaches is provided. Then the standards and guidelines for the development of these two load models are listed. A critical and updated overview of opportunities and challenges of load modeling with emerging networks and components is also presented, considering the smart grid, microgrid, new data sources, active networks/elements, and customer-side dynamics.

Finally, the guidelines for power system simulations with various load models are proposed, including the simulation carriers, simulation models, and simulation environments, along with data treatment and analysis. A trial case study based on the hybrid approach is showcased to exhibit the potential of the combined load modeling approach (that consists of measurement-based and component-based approaches), which would be beneficial for future load modeling work.

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The definition of "load sector" in 6.3 and Table 6 are reprinted with permission from Yamashita, K., S. Djokic, J. Matevosyan, F. O. Resende, L. M. Korunovic, Z. Y. Dong, and J. V. Milanović, "Modeling and aggregation of loads in flexible power networks—Scope and status of the work of Cigre WG C4. 605," IFAC Proceedings, vol. 45, no. 21, pp. 405–410, 2012 [B81].

Table 7, Figure 9, Figure 11, Figure 12, Figure 13, and Figure 18 are reprinted with permission from CIGRE Technical Brochure 566 [B49].

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IEEE Guide for Load Modeling and Simulations for Power Systems

1. Overview

1.1 Scope

The scope of this guide is the definition of load models for various conventional and emerging elements in the generation, transmission, distribution, and customer sectors at all voltage levels. This includes guidance for developing load models, identifying load model parameters, and utilizing measurement data for load model development at various voltage levels. It also includes modeling practices for emerging elements such as power electronic connected elements, electrical vehicles and charging stations, better utilization of information and communication technology (ICT) infrastructures in load model development, and dynamics associated with customer involvement.

1.2 Purpose

Load modeling and simulation have been an established area with continuous development through research and engineering practices. Although there are different references and reports, there are emerging interests from the industry on standard practices with various load models and simulations to accommodate the rapidly evolving power industry incorporating both conventional and new inverter connected renewable elements. Development in power electronics, smart grid technologies, demand-side control, and increasing renewable energy uptake have made load modeling an increasingly challenging essential element for system operations and planning to ensure system security while maintaining economic efficiency and emission reduction objectives. The rapid deployment of IoT technologies through industry initiative brings new opportunities and challenges for load modeling; together with big data analysis and artificial intelligence methods, data obtained through the IoT sensors enable detailed modeling of loads behind the meters without customer survey. A guide for standard approaches within this domain will lead to new load modeling approaches beyond the conventional or component measurement ones, which will advance acceptance and interoperability.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).[6],[7]

[6]The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.
[7]The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

1.4 Load modeling overview

Load modeling plays an important role in power system modeling. Most load models currently in use were developed several decades ago, and load structure and load characteristics have gradually changed over time. However, load models have not been updated to keep pace with these changes. In the mid-1990s, the last systematic update of load models was conducted on an industry-wide level. In addition, the current load models and corresponding parameters used by utilities and system operators are usually not in the public domain, and within the industry, some uncertainty exists over applying for the research work in this field to conduct power system analysis. To solve these problems, some regions have recently made an effort to develop load models (e.g., Western Electricity Coordinating Council [WECC]). However, these concerted efforts are mainly focused on specific regions that they have developed rather than on those that have not yet been developed or are underdeveloped.

Although the importance of accurate load modeling for power system research has been recognized by most power system research and industry, the typical static load models with constant impedance/current/power are still used by them for power system analysis. If they use dynamic load models, standard induction motor (IM) models are usually used.

Load characteristics have an important impact on the steady-state and dynamic performance of the power system. Therefore, to properly analyze power systems, not only the accurate load models but also the suitable representations of the power generation, transmission, and distribution parts of the system are required. However, load modeling is a complex task because many factors need to be considered when modeling the load, such as the diversity of load types and characteristics, the lack of load structure information, and the correctness of evaluating and verifying the load model. In addition, due to the significant differences in system behaviors at different times of the year and at different times of the day and in different demographic and geographic regions, spatial and temporal load variability needs to be considered to accurately assess these system behaviors. Moreover, the aggregate load models of medium-voltage and high-voltage bulk supply buses for power system research that implicitly include distribution transformers, shunt compensation, and distribution network feeders are usually not properly considered for the possible operating dynamics of tap-changing transformers and other voltage regulators that are deployed at lower voltage levels.

The currently used load models are generally not capable of reconstructing the most recent blackouts by performing “postmortem” simulations and analysis on several unsuccessful attempts. Although researchers and the industry recognized the impact of load representation on stability a long time ago, in the analysis of power system stability, the focus is still mainly on modeling power generating units, and load models are considered to be secondary.

1.5 Significance of load model standards and guidelines for power system operations and planning

In power systems, computer simulation with appropriate component models is an important tool. It not only enables power system engineers to fully understand the dynamic behavior of the system, but it also guides the dynamic operation and planning of the system. In the computer simulation, the load model is an indispensable and important component. Computer simulation using different load models may lead to much different simulation results. However, in the establishment of the load model, the following two issues need to be considered. The first problem is that if the assumed load model is overly conservative, it may lead to a need for a serious overexpenditure or excessive investment to solve a problem that may hardly occur. The second problem is if the assumed load model is too simple and optimistic, then this can lead to some serious problems that cannot be identified, leaving vulnerabilities in the system and posing serious security risks. The effects of load model standards and guidelines on power system operations and planning have been well documented worldwide. The have also resulted in extensive discussions in the industry and academia, especially regarding serious concerns about the load modeling work.

In addition, in the past few years, due to the emergence of new types of loads, effective load modeling can greatly improve the efficiency and controllability of the grid. Therefore, load modeling is gaining more and more attention in the industry and academia. Today, in almost all load sectors, different types of modern nonlinear power electronic loads account for a non-negligible portion of the total demand. In addition, for small-scale distributed generation technologies with various direct connection and inverter interfaces, there is currently no suitable load model with distributed generators that is available to represent them correctly, but it is foreseeable that they will be installed in large numbers in the future in some future networks. The evolving grid code with new actual and reactive power requirements for distributed generators may be strongly affected in this scenario. Therefore, load model standards with the modeling guidelines on power system operations and planning are crucial to combat the future technical challenges.

1.6 Overview of associated work in load model standards and guidelines

Since the 1987 Great Blackout in Sweden, load modeling has gained increasing attention from power system engineers because the improper representation of system loads often leads to differences between recorded and simulated system responses leading to errors or even disasters.

On August 10, 1996, the WECC system had a serious power outage, causing it to split into four islands, not only losing 30 390 MW, but also affecting the electricity consumption of 7.49 million customers in western North America. As the oscillations gradually increased, the system slowly lost its stability. After the event, the Bonneville Power Authority (BPA) based on the postfault simulation, analyzed the event and showed a stable system using the WECC database. To solve this problem and match the simulation results with the measurement results, BPA experts modified the Pacific HVDC Intertie model, completed the modeling of automatic generation control, blocked some turbine governor models, and the voltage controls on Lower Columbia generators were changed. However, after completing these changes, the simulation results still showed that the damping in the system was more than the actual situation. In these simulations, the constant current actual power and constant impedance reactive power load models were originally used primarily to represent loads in the Northwest and Canada. When the load models are changed to the combinations of IM models and various static loads, the simulated and measured responses show excellent agreement. A similar analysis by Powertech Laboratories Inc. (see WECC Load Modeling Task Force [B76]) concluded:

> Our analysis shows that the two most critical modeling elements that reproduce this oscillation disturbance so far are load characteristics and generator excitation control. Both are relatively determined (especially the load), and both changes can profoundly change the system response.

CIGRE Working Group C4.605 established a milestone toward clarifying load models with their parameters that had been leveraged by transmission system operators across the globe (Yamashita Martinez Villanueva, and Milanović [B83]). The published technical report revealed that the constant real and reactive power load model (constant P and Q) is the most widely used load model for steady-state power system studies as of 2010. It also showed that static load models are still the most commonly used even for dynamic system studies and that only approximately 30% of utilities and transmission system operators represent dynamic load by some form of IM model. Therefore, it can be considered that the number of models used, in actual studies, is limited, although the variety of load models is wide. This technical report also indicates the need for a hybrid approach in the future that will combine the individual strengths of the existing two approaches, (i.e., measurement-based and component-based approaches) taking into account the data acquisition capabilities offered by modern measurement systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

There are no normative references in this standard.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[8]

active distribution network (ADN): A distribution network that has systems in place to control a combination of distributed energy sources including generators, loads, and storages.

active distribution network (ADN) cell: The collection of distributed energy devices in an active distribution network. The devices in an active distribution network cell are usually modeled as a single aggregated load entity.

basic load models: Including small induction motor (IM) model, large IM model, constant impedance load model, constant current load model, and constant power load model.

cold load: Refer to all variants of refrigerators and freezers. Such loads are expected to use an inductor-run, single-phase induction motor (SPIM), as well as use quadratic torque conditions to represent motor mechanical loading.

consumer electronics load: This mainly refers to television sets that are also divided into a single-phase induction motor (SPIM) load with active power factor correction (a-PFC) for the television sets with more recent technologies, passive power factor correction (p-PFC) for large television sets, and no-PFC for the television sets with smaller rated power ($\leq$ 75 W).

cooking load: Electric cooktops and ovens belong to resistive load category. Microwaves are categorized as passive power factor correction (p-PFC) switch-mode power supply (SMPS) loads.

five typical load categories for component-based load modeling: Defined based on the data provided in national statistics and associated legislation, including resistive loads, energy-efficient lighting, switch-mode power supply (SMPS) loads, directly connected motor loads, and drive-controlled motor loads.

information and communication technology (ICT) load: This load consists of all types of home computers and communication technology equipment. They are divided into single-phase induction motor (SPIM) load with active power factor correction (a-PFC), passive power factor correction (p-PFC), and no-PFC based on their embedded PFC circuit. p-PFC is typically incorporated for the loads with large rated power, such as desktop computers, monitors, and printers. a-PFC is typically incorporated for the laptop chargers because

[8] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

they do not have to satisfy harmonic legislation. All other ICT loads are expected to have low rated power (≤ 75 W), so they have no-PFC.

lighting load: The general incandescent lamp (GIL) lighting loads are modeled as resistive loads, while the compact fluorescent lamp (CFL) lighting loads are modeled as energy-efficient lighting loads.

load sector: Also known as “classes of customers” or “load classes,” which is an aggregation or collection of different types of loads, representing a typical structure and composition of electrical devices and equipment found in a specific end-use application, where similar activities and tasks are performed.

wet load: Refer to the motor loads related to water, such as dishwashers, tumble dryers, washer dryers, and washing machines. Among them, tumble dryers, washer dryers, and washing machines have high running torque, which means they will require run capacitors. Rather, the dishwashers do not require run capacitors but utilize inductor-run single-phase induction motor (SPIM). Constant torque mechanical loading is generally assumed for all wet loads.

ZIP model: The model consisting of constant impedance (Z), constant current (I), and constant power (P) load components.

3.2 Acronyms and abbreviations

ADN	active distribution network
ANN	artificial neural network
BPA	Bonneville Power Authority
CFL	compact fluorescent lamp
CHP	combined heat and power
CLOD	complex load model
CMLD	composite load model
CSCR	capacitor start-capacitor run induction motor
CSIR	capacitor start-inductor run induction motor
CT	current transformer
DE	differential evolution
DFR	digital fault recorder
DFT	discrete Fourier transform
EA	evolutionary algorithm
EHV	extra high voltage
EPSO	evolutionary particle swarm optimization
ESS	energy storage system
GIL	general incandescent lamp
HVAC	heating, ventilation, and air conditioning
ICT	information and communication technology
IM	induction motor
LED	light-emitting diode

LV	low voltage
MG	microgrids
MV	medium voltage
OLTC	on-load tap changer
PFC	power factor correction
PMU	phasor measurement unit
RSIR	resistor start-inductor run induction motor
SMPS	switch-mode power supply
SPIM	single-phase induction motor
TDNN	time delay neural network
TSI	trajectory sensitivity index
VT	voltage transformer
WECC	Western Electricity Coordinating Council

4. Overview of the existing load models and load model development methodologies

4.1 Summary

This clause provides a comprehensive overview of the existing load models and load model development methodologies. For the existing load models, both static and dynamic load models are summarized. For the existing load model development methodologies, both component-based and measurement-based approaches are briefed. And the advantages and disadvantages of using component-based and measurement-based approaches are listed. Moreover, some new emerging load models and standard requirements are also showcased and discussed.

4.2 Provide up-to-date list/overview of existing load models

Existing load models consist of two aspects: static load models and dynamic load models (Milanović et al. [B49] and EPRI, 2002 [B21]).[9] The static study represents the steady-state analysis, for example, the power flow analysis, whereas the dynamic study represents the stability analysis, for example, the transient responses of system and load when under disturbances. Different practical scenarios may be suitable for different load models.

The static load model provides analytical relationships for real and reactive power loads under a given voltage and system frequency in an algebraic equation form. Usually, static load models are modeling the loads that exhibit a single step change in power following the change in voltage or system frequency at buses. In particular, the static load model can be used to describe the electric component that can rapidly respond to voltage change, while the measuring equipment cannot capture this dynamic process. Resistive load devices, lighting, general residential load, and many other similar aggregated loads without the participation of large IMs and electrical drives in the load mix are often represented by the static load model (Hiskens and Milanović [B29]; Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]; and Pourbeik and

[9]The numbers in brackets correspond to those of the bibliography in Annex A.

Gaikwad [B56]). Mathematically, a static load model contains the real and reactive power dependences based on the voltage and system frequency, as shown in Equation (1) and Equation (2).

$$P = f_P(U,f) \tag{1}$$

$$Q = f_Q(U,f) \tag{2}$$

where

P is the real power flow
Q is the reactive power flow
U is the voltage
f is the system frequency
$f_P()$ is the relationship function for real power flow
$f_Q()$ is the relationship function for reactive power flow

Compared with the static load models, dynamic load models provide analytical relationships for real and reactive power loads under a given voltage and system frequency in a differential equation form. Usually, dynamic load models are modeling the loads that exhibit multiple step changes in power following the change in voltage or system frequency at buses; that is, dynamic load models describe a time-dependent response to a change in the voltage and system frequency. It is determined by the interactions and exchanges of energy between the system and load when the system operating condition is transited from one condition to another.

For both the static load model and the dynamic load model, it would be noticed that based on a dynamic load model, the corresponding static load model of this load can be easily derived. However, based on a static load model, the corresponding dynamic load model cannot be formulated. Furthermore, both static load models and dynamic load models can be used in dynamic studies (Yamashita, Tokumitsu, Koyama, and Tatematsu [B84]).

Existing static load models mainly contain the following six classifications: linear load model, polynomial load model, exponential load model, comprehensive load model, static model of IM, and power electronic interfaced load model (Milanović et al. [B49]). Existing dynamic load models mainly contain the following seven classifications: exponential dynamic load model, dynamic model of IM, transfer function of IM, CMLD, distribution load model, bulk power bus load model, and generic model of distributed electric storage system (Milanović et al. [B49]). The overall classification is shown in Table 1, and a brief introduction to each load model is listed.

Table 1—Overview of existing load model

	Main category	Fine classification
Load model	Static model	Linear load model
		Polynomial load model
		Exponential load model
		Comprehensive static load model
		Static model of IM
		Power electronic interfaced load model
	Dynamic model	Exponential dynamic load model
		Dynamic model of IM
		Transfer function of IM
		CMLD
		Distribution load model
		Bulk power bus load model
		Generic model of distributed electric storage system

4.2.1 Brief overview of the static load model

4.2.1.1 Linear load model

The linear load model is suitable for modeling the scenarios in which voltage has small fluctuations around the rated value, for example, the small-disturbance stability analysis (Ribeiro and Lange [B62]; Korunović and Stojanović, 2002 [B39]; Aguero, Beroqui, and Achilles [B1]; and Taylor [B72]). Although the linear load model is simple, for the scenarios of large voltage fluctuations, the linear load model will be inaccurate in calculating the result. The model is shown as follows in Equation (3) and Equation (4).

$$P = P_n\left[a_0 + a_1\frac{U}{U_n}\right], \quad \sum_{i=1}^{3} p_i = 1 \tag{3}$$

$$Q = Q_n\left[b_0 + b_1\frac{U}{U_n}\right], \quad \sum_{i=1}^{3} q_i = 1 \tag{4}$$

where

U_n and f_n are the rated voltage and frequency

P_n and Q_n are the real and reactive power at rated voltage and frequency

a_0, a_1, b_0, and b_1 are parameters

4.2.1.2 Polynomial load model

The polynomial load model is a widely used second-order polynomial model that has many types of variants. This model consists of constant impedance (Z), constant current (I), and constant power (P) load components, and therefore, it has been renamed the "ZIP model." The ZIP model can be identified at the bulk level and is usually considered the default model in simulation studies (Collin, Hernando-Gil, Acosta, and Djokic [B12]). The model is shown as follows in Equation (5) and Equation (6).

$$P = P_n\left[p_1\left(\frac{U}{U_n}\right)^2 + p_2\left(\frac{U}{U_n}\right) + p_3\right] \tag{5}$$

$$Q = Q_n\left[q_1\left(\frac{U}{U_n}\right)^2 + q_2\left(\frac{U}{U_n}\right) + q_3\right] \tag{6}$$

where

p_1 and q_1 are the relative participation of constant impedance load

p_2 and q_2 are the relative participation of constant current load

p_3 and q_3 are the relative participation of constant power load in the total load

In one variant of the ZIP model—the constrained ZIP model—every load component (Z, I, P) in total load is constrained in the range of [0,1] p.u., with the sum as 1 p.u. Another variant of the ZIP model released the constraint of the range of load components. The p_i and $q_i$parameters can be out of the range of [0,1] p.u, but their sum stays at 1 p.u. This model is usually considered to be an accurate ZIP model. Moreover, when the frequency dependence is considered, the variant of the ZIP model is shown as follows in Equation (7) and Equation (8).

$$P = P_n\left[p_1\left(\frac{U}{U_n}\right)^2 + p_2\left(\frac{U}{U_n}\right) + p_3\right](1 + k_{pf}\Delta f), \quad \sum_{i=1}^{3} p_i = 1 \tag{7}$$

$$Q = Q_n\left[q_1\left(\frac{U}{U_n}\right)^2 + q_2\left(\frac{U}{U_n}\right) + q_3\right](1 + k_{qf}\Delta f), \quad \sum_{i=1}^{3} q_i = 1 \tag{8}$$

where

k_{pf} is the real power frequency exponent

k_{qf} is the reactive power frequency exponent

Δf is the relative frequency change of $(f - f_n)/f_n$

4.2.1.3 Exponential load model

The exponential load model is the most widely used model because it usually performs very well in describing the relationship between real and reactive power flow. The exponential model is easy to identify and useful for analytical studies, but it is hard to interpret and generalize (Knyazkin, Canizares, and Soder [B37]). Compared with the change of voltage, the change of system frequency is not significant. Therefore, the load dependence of system frequency in the exponential load model is sometimes neglected. The model is shown as follows in Equation (9) and Equation (10).

$$P = P_n\left(\frac{U}{U_n}\right)^{k_{pu}}\left(\frac{f}{f_n}\right)^{k_{pf}} \tag{9}$$

$$Q = Q_n\left(\frac{U}{U_n}\right)^{k_{qu}}\left(\frac{f}{f_n}\right)^{k_{qf}} \tag{10}$$

where

k_{pu} and k_{qu} are the partial derivatives of real and reactive power

Because the fluctuation range of system frequency is usually small, compared with the fluctuation of system frequency, voltage fluctuations are more frequent and pronounced. Sometimes the frequency dependences can be modified at the rated voltage U_n to Taylor series, as shown in Equation (11) and Equation (12).

$$P = P_n\left(\frac{U}{U_n}\right)^{k_{pu}}(1 + k_{pf}\Delta f) \tag{11}$$

$$Q = Q_n\left(\frac{U}{U_n}\right)^{k_{qu}}(1 + k_{qf}\Delta f) \tag{12}$$

In some situations, the frequency dependence is neglected. The exponential load model is therefore simplified as follows in Equation (13) and Equation (14).

$$P = P_n\left(\frac{U}{U_n}\right)^{k_{pu}} \tag{13}$$

$$Q = Q_n\left(\frac{U}{U_n}\right)^{k_{qu}} \tag{14}$$

4.2.1.4 Comprehensive static load model

A comprehensive static load model is suitable for modeling the extremely LV scenarios in which both static and dynamic characteristics are considered. In these extremely LV situations, static loads drop off to some extent; for instance, power electronic devices may drop off when voltage is below 80% of the nominal, residential air conditioners may drop off when between 40% and 52% of the voltage nominal, compact fluorescent lamps may drop off between 17% and 35% of the nominal voltage, and so forth (Baghzouz and Quist [B5]). The comprehensive static load model contains one polynomial model and two exponential models. The model is shown as follows in Equation (15) and Equation (16).

$$P = P_n[P_{ZIP} + P_{EX1} + P_{EX2}] \tag{15}$$

$$Q = Q_n[Q_{ZIP} + Q_{EX1} + Q_{EX2}] \tag{16}$$

where

P_{ZIP} $= P_1\left(\frac{U}{U_n}\right)^2 + P_2\left(\frac{U}{U_n}\right) + P_3$

P_{EX1} $= P_4\left(\frac{U}{U_n}\right)^{a1}(1 + k_{pf1}\Delta f)$

P_{EX2} $= P_5\left(\frac{U}{U_n}\right)^{a2}(1 + k_{pf2}\Delta f)$

Q_{ZIP} $= Q_1\left(\frac{U}{U_n}\right)^2 + Q_2\left(\frac{U}{U_n}\right) + Q_3$

Q_{EX1} $= Q_4\left(\frac{U}{U_n}\right)^{b1}(1 + k_{qf1}\Delta f)$

Q_{EX2} $= Q_5\left(\frac{U}{U_n}\right)^{b2}(1 + k_{qf2}\Delta f)$

$a_1, a_2, b_1,$ and b_2 are voltage dependent and vary when voltage drops below a certain threshold to maintain the numerical stability in simulating the solutions

4.2.1.5 Static model of the induction motor

The static model of the IM is suitable when the perception of IMs in total loads reaches a very high percentage so that the static model of the IM has to be modeled separately (Cresswell and Djokic [B13]). The model is shown as follows in Equation (17) and Equation (18).

$$P = (R_s + \frac{R_r}{s})\frac{U^2}{(R_s + \frac{R_r}{S})^2 + (X_{\gamma s} + X_{\gamma r})^2} \tag{17}$$

$$Q = (X_{\gamma s} + X_{\gamma r})\frac{U^2}{(R_s + \frac{R_r}{S})^2 + (X_{\gamma s} + X_{\gamma r})^2} + \frac{U^2}{X_s} \tag{18}$$

where

R_s is the stator resistance

R_r is the rotor resistance

$s = \frac{\omega_s - \omega}{\omega_s}$ is the operating slip in which ω_s is the synchronous angular speed and ω is the rotor angular speed

$X_{\gamma s}$ is the stator leakage reactance

$X_{\gamma r}$ is the rotor leakage reactance

$X_s = X_m + X_{\gamma s}$ is the shunt reactance in which X_m is the magnetizing reactance

4.2.1.6 Power electronic interfaced load model

The power electronic interfaced load model is suitable when many nonlinear power electronic devices could be participating. The model mainly contains four kinds of load categories, that is, dc power supply loads, energy-efficient light sources, single-phase loads, and three-phase loads (Cresswell, Djokic, Ochije, and Macpherson [B14]). And all of the power electronic-interfaced loads need to be modeled separately. Generally, the power electronic-interfaced load model can be modeled with both polynomial model—Equation (5) and Equation (6)—and exponential model—Equation (9) and Equation (10). Moreover, considering the gradually increased penetration of electric vehicles in current networks, plug-in chargers for electric vehicles are also considered to be a component of the power electronic interfaced load model.

4.2.2 Brief overview of the dynamic load model

4.2.2.1 Exponential dynamic load model

The exponential dynamic load model is suitable when the voltage of IMs, heating loads, and tap-changers has experienced fluctuations (Karlsson and Hill [B36]; Price et al., 1993 [B59]; Yamashita, Kitauchi, and Katsuragi [B82]; Lu and Qiao [B46], and Yamashita, Asada, and Yoshimura [B80]). Since the exponential dynamic load model does not consider the inherent coupling between the real and the reactive power absorbed from the IMs, this model has drawbacks in producing the short-term dynamics of loads when there is a high penetration of IMs. However, this model has advantages for the long-term voltage stability study. The model is shown as follows in Equation (19) through Equation (22).

$$T_p\frac{dP_r}{dt} + P_r = P_s(U) - P_t(U) = P_0\left(\frac{U}{U_0}\right)^{\alpha_s} - P_0\left(\frac{U}{U_0}\right)^{\alpha_t} \tag{19}$$

$$T_Q \frac{dQ_r}{dt} + Q_r = Q_s(U) - Q_t(U) = Q_0\left(\frac{U}{U_0}\right)^{\beta_s} - Q\left(\frac{U}{U_0}\right)^{\beta_t} \tag{20}$$

$$P_l = P_r + P_0\left(\frac{U}{U_0}\right)^{\alpha_t} \tag{21}$$

$$Q_l = Q_r + Q_0\left(\frac{U}{U_0}\right)^{\beta_t} \tag{22}$$

where

P_r and Q_r	are the real and reactive power recovery
P_0 and Q_0	are the initial value of real and reactive power before the voltage change
U_0	are for the initial voltage value
T_p and T_Q	are the real and reactive power recovery time constant
α_s and β_s	are the steady-state real and reactive power voltage exponent
α_t and β_t	are the transient real and reactive power voltage exponent
P_l and Q_l	are the real and reactive power consumption

4.2.2.2 Dynamic model of the induction motor

The dynamic model of IM is suitable for scenarios when there is a high penetration of IM (Ma, Dong, and Zhang [B47]). Usually, the fifth-order model is often used for larger IMs or when the IM has an important response to the load. In some practical applications, the stator transients are neglected, and the third-order dynamic models are enough. Moreover, for low-voltage applications, single-phase IMs are often used (Karlsson and Hill [B36]; Yamashita, Asada, and Yoshimura [B80], Price et al. 1995 [B58]; Hill [B27], and Milanović [B48]). Here, a comprehensive fifth-order, three-phase IM model is shown as follows in Equation (23) through Equation (31).

$$u_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{d\tau} - w_s \psi_{qs} \tag{23}$$

$$u_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{d\tau} - w_s \psi_{ds} \tag{24}$$

$$u_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{d\tau} - (\omega_s - \omega)\psi_{qr} \tag{25}$$

$$u_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{d\tau} + (\omega_s - \omega)\psi_{dr} \tag{26}$$

$$\frac{d\omega}{d\tau} = \frac{(M_e - M)}{\omega_b T_m} \tag{27}$$

$$\psi_{ds} = X_s i_{ds} + X_m i_{dr} \tag{28}$$

$$\psi_{qs} = X_s i_{qs} + X_m i_{qr} \tag{29}$$

$$\psi_{dr} = X_m i_{ds} + X_r i_{dr} \tag{30}$$

$$\psi_{qr} = X_m i_{qs} + X_r i_{qr} \tag{31}$$

where

u_{ds}, u_{qs}, u_{dr}, and u_{qr}	are the stator and rotor voltage components
i_{ds}, i_{qs}, i_{dr}, and i_{qr}	are the stator and rotor current components
ψ_{ds}, ψ_{qs}, ψ_{dr}, and ψ_{qr}	are the stator and rotor flux linkages
ω_b	is the base angular frequency
$X_r = X_m + X_{\gamma r}$	is the rotor reactance
M	is the mechanical load torque
$M_e = X_m(i_{qs} i_{dr} - i_{ds} i_{qr})$	is the electromagnetic torque
$\tau = \omega_b t$	is the normalized time
T_m	is the mechanical time constant of the motor

4.2.2.3 Transfer function of the induction motor

The transfer function of IM is suitable when the IM is combined with the static load, which is a transition from the "single facet" dynamic load to a more complex one (Borghetti, Caldon, and Nucci [B6]). There are usually first, second, and third-order transfer functions. The first-order transfer functions are shown as follows in Equation (32) and Equation (33).

$$\Delta P(s) = \frac{k_{pf} + T_{pf}s}{1 + T_1 s}\Delta f(s) + \frac{k_{pu} + T_{pu}s}{1 + T_1 s}\Delta U(s) \tag{32}$$

$$\Delta Q(s) = \frac{k_{qf} + T_{qf}s}{1 + T_1 s}\Delta f(s) + \frac{k_{qu} + T_{qu}s}{1 + T_1 s}\Delta U(s) \tag{33}$$

The second-order transfer functions are shown as follows in Equation (34) and Equation (35).

$$\frac{\Delta P(s)}{\Delta U} = \frac{K_{pu}(1 + T_{3p}s)}{(1 + T_{1p}s)(1 + T_{2p}s)} \tag{34}$$

$$\frac{\Delta Q(s)}{\Delta U} = \frac{K_{qu}(1 + T_{3q}s)}{(1 + T_{1q}s)(1 + T_{2q}s)} \tag{35}$$

The third-order transfer functions are shown as follows in Equation (36) and Equation (37).

$$\frac{\Delta P(s)}{\Delta U} = \frac{K_{pu}(1 + T_{4p}s)(1 + T_{5p}s)}{(1 + T_{1p}s)(1 + T_{2p}s)(1 + T_{3p}s)} \tag{36}$$

$$\frac{\Delta Q(s)}{\Delta U} = \frac{K_{qu}(1+T_{4p}s)(1+T_{5p}s)}{(1+T_{1p}s)(1+T_{2p}s)(1+T_{3p}s)} \tag{37}$$

4.2.2.4 Composite load model

The CMLD is suitable when both static and dynamic devices are connected to the same bus in which the dynamic devices mainly stand for the IM. Usually, the third-order model of the IM is sufficient (Stojanović, Korunović, and Milanović [B70]; Iliceto and Capasso [B32], and Hakim and Berg [B25]). The *d* and *q* current components of resistive and capacitive load are shown as follows in Equation (38) through Equation (41).

$$i_{dr} = \frac{u_{ds}}{R} \tag{38}$$

$$i_{qr} = \frac{u_{qs}}{R} \tag{39}$$

$$i_{dc} = -\frac{u_{qs}}{X_c} \tag{40}$$

$$i_{qc} = \frac{u_{qs}}{X_c} \tag{41}$$

4.2.2.5 Distribution load model

The distribution load model is suitable for the scenarios with load influences from IMs, distributed feeders, and distributed transformers connected in the network (Rogers, Di Manno, and Alden [B63]). The load model would model each part of the load and then sum them up to form the distribution load model.

4.2.2.6 Bulk power bus load model

The bulk power bus load model is suitable when modeling a bulk power bus in which the load components and parameters of electrical power network elements between the nodes and the load need to be fully considered (Taleb, Akbaba, and Abdullah [B71]; Louie, Marti, and Dommel [B45]; and Aresi, Delfino, Denegri, Invernizzi, and Massucco [B3]). Specifically, this bulk power bus load model would take in account the impact of the reactance from one bulk power bus to the utilization bus, the net impact of saturation of distribution transformers, and the impact of shunt capacitors and cables. The load excluding estimated capacitive compensation is shown as follows in Equation (42) and Equation (43).

$$P(t) = \left[1 - k_p\{U(t) - 1\}\right](1 - P_{drop}) + P_{dyn}\{G(t) - 1\}\, U^2(t) \tag{42}$$

$$Q(t) = \left[1 - k_q\{U(t) - 1\}\right](1 - Q_{drop}) + Q_{dyn}\{G(t) - 1\}\, U^2(t) \tag{43}$$

where

k_p and k_q are the characteristic constants

P_{drop} and Q_{drop} are the load drops related to the minimum bus voltage

P_{dyn} and Q_{dyn} are the magnitudes of the dynamic load components

$G(t)$ is the conductance of the motor

4.2.2.7 Generic model of distributed electric storage system

The generic model of the distributed electric storage system is suitable when the ESS is connected to the network in which the network structure is flexible and allows the modeling of different types of storage technologies and control strategies. This model is designed for software-based system analysis and can outcome accurate results for a large power system with fast convergence. Three versions of the structure for the distributed electric storage system exist: the instantaneous/complete model for transient and harmonic analysis, the average model for electrical variables, and the model for small signal and transient stability analysis (Taleb, Akbaba, and Abdullah [B71], Louie, Marti, and Dommel [B45], and Aresi, Delfino, Denegri, Invernizzi, and Massucco [B3]).

4.3 Emerging load models and challenges and needs for standard approaches

Nowadays, some new emerging load model concerns have drawn increasing attention to both the research and industrial fields. The plug-in electric vehicles and vehicle-to-grid concepts have brought new impacts to load modeling. A simple battery model, a modified battery model, a Thevenin battery model, a dynamic battery model, a fourth-order dynamic model, an overcurrent battery model, an improved battery model, and so forth are all available (Tremblay, Dessaint, and Dekkiche [B75]). Moreover, the electric vehicles' battery charging and discharging cycles would take into full consideration the constant voltage charging, polarization voltage, battery capacity, and even no-load voltage (Chan [B10]). It is usually difficult to obtain the model parameters and hard to validate whether the obtained model parameters can appropriately represent the actual behavior of the corresponding battery system.

Beyond the electric vehicles, the charging stations for hybrid electric vehicles may consist of a housing, a controlled access power receptacle coupled to this housing, logic circuitry contained within the housing, the connector for receiving a connection to supply an electrical charge to a vehicle, an optical reader coupled to the logic circuitry for reading data associated with the vehicle from a data source remote from the optical scanner unit, and so forth (Pellegrino and Farrell [B55]). The complexity of the components for the charging station indicates the difficulty in modeling this kind of load.

In the future, there will be other new types of power electronic loads that are expected to combine more advanced electrical components and more complex compositions. Uncertainties from both the development of physical loads and the improvement of analyzing technologies are enormous challenges and obstacles for unifying the standard approaches to load modeling. Therefore, the need for providing comprehensive policies and procedures for the standards development based on existing models and approaches and predicted directions is urgent and vital.

4.4 Overview of load model development methodologies

The existing load model development methodologies are mainly based on two approaches: the component-based approach and the measurement-based approach. The component-based approach is also known as the "knowledge-based approach"; the measurement-based approach is also known as the "behavior-based approach". Usually, the former approach is more suitable for the load model that contains multiple load components, for example, the ZIP model. The latter approach is more suitable for the load model that contains both several components and a single component, for example, the IM.

4.4.1 Component-based approach for load model development

4.4.1.1 Overview of the component-based approach

The component-based approach represents a common aggregated load model structure in which the load categories (or classes), load compositions, and load proportions would be fully considered, as shown in Figure 1. The aggregate model usually incorporates the model of an individual load component, and it is represented by a second-order polynomial model and a motor model (Nguyen and Srinivasan [B52]).

Figure 1—Processes of the component-based approach

Specifically, the component-based approach follows three steps. First, the loads connected at the substation level are clearly categorized. From the perspective of load consumption, four types of load are aggregated at a distribution bus: residential load, commercial load, industrial load, and public infrastructure load (Dash, Pradhan, and Panda [B16]). Different types of load categories may require different kinds of power supply standards, which therefore has different requirements on its load modeling. For example, it requires as much detail as possible to model for the large industrial load. It is challenging work to model typical load classes because the load in different classes is naturally distributed and may have potentially onerous data requirements.

Second, the structure and composition of each load category are clearly considered. For example, for the residential load, the air conditioner, washing machine, clothes dryer, dishwasher, refrigerator, cooling or heating pump, lighting, and some other household-based electronics need to be addressed. Different end-users may have different appliances in use. Therefore, the specific composition of the load category would take into full consideration the practical application situations.

Third, the typical characteristics and proportion of each load category are clearly estimated. For example, for the residential load, the different household appliances have different power characteristics and may also have different performances according to different customers' electricity behavioral habits. The biggest challenge is to identify the percentage contributions of each load component within the considered load category (Mojiri and Bakhshai [B50]). However, obtaining this information relies on a large number of customer surveys, which is time-consuming and economically expensive.

4.4.1.2 Advantages and disadvantages of the component-based approach

The advantages of the component-based approach mainly concentrate on the benefit of load categories and load composition analysis. First, the component-based approach is effective from the perspective of load categories at the substation level to build the load model. And it can be easily applied to composite different types of load models. Second, since the component-based approach takes into full consideration specific system compositions and conditions, it is flexible for future model development and potential demand control management. Third, since the component-based approach is directly based on an individual load component, it promotes the development of system performance sensitivity to changes in load compositions. Last, measurements in the component-based approach are not required, which saves the measuring devices installation cost and corresponding data processing cost (Milanović et al. [B49] and Dash, Pradhan, and Panda [B16]).

The disadvantages of the component-based approach also concentrate on the weak points of load categories and load compositions (Milanović et al. [B49]). First, since substations are different, the structure and composition of one substation have many differences from another one; the known load model, therefore, cannot be directly applied to another substation. Second, although the load model for one certain load component is constant, the operating parameters may vary according to its specific environment; for example, the best temperature setting for a refrigerator is different between winter and summer conditions. Therefore, the characteristics, structure, and composition of one load model are sometimes changing, and additional information could be supplemented. Third, for higher voltage systems such as the transmission system, it is usually difficult for the system operators to access the load devices, making it hard to apply the component-based load modeling approach. Last, measurements are essential and valuable information for system operators to perceive the operating conditions that cannot be simply neglected.

4.4.2 Measurement-based approach for load model development

4.4.2.1 Overview of the measurement-based approach

The measurement-based approach has developed alongside hardware and software improvements since the 1980s. Measurement devices, transmission lines, and communication networks were extensively installed over the last few years, making the power system a data-based system. More importantly, the data quality of measurements is significantly improved, making it possible for precise modeling and accurate control (Karlsson and Hill [B36]; Price et al. 1993 [B59]; Yamashita, Kitauchi, and Katsuragi [B82]; Lu and Qiao [B46], and Yamashita, Asada, and Yoshimura [B80]).

The measurement-based approach mainly represents the parameter identification technique in which complicated parameters would be obtained based on a few processes. Specifically, there are six processes for the measurement-based approach: data collection, data processing, selection of load model structure, parameter derivation for the load model, model validation including event screening, and selection of derived load model parameters (Han Ma, He, and Dong [B26]; see 5.2 and Figure 3).

4.4.2.2 Advantages and disadvantages of the measurement-based approach

The advantages of the measurement-based approach are obvious. Compared with the component-based approach, the measurement-based approach is simpler because it can directly record the dynamic response of loads on a feeder, which captures the temporal changes of the load. Moreover, the measurement-based approach can be applied to any kind of load (Renmu, Jin, and Hill [B61] and Wen, Wang, Cheng, Wu, and Shimmin [B77]).

The disadvantages of the measurement-based approach are mainly concentrated on the recorded measurements (Renmu, Jin, and Hill [B61] and Wen, Wang, Cheng, Wu, and Shimmin [B77]). When appropriate disturbance measurement data are not available, there will be no result in appropriate load models. Since one cannot force the system to produce large disturbances, long-term observations are required until large disturbances are measured. Sometimes, for the measurement-based approach, there is a lack of sufficient disturbance information. Moreover, it is difficult for the load model identification when there are delays or discontinuities of load response. Third, similar to many other optimization problems, the obtained optimal parameters may not be the globally optimal result.

4.5 Conclusions

This clause briefly summarized two existing load models from the static load model and dynamic load model perspective. It then provided an overview of the two existing frequently used methodologies for load modeling: the component-based approach and the measurement-based approach. The analysis of advantages and disadvantages for both approaches clearly indicated the need for the combined approach in the future. The strengths of both model-driven and data-driven approaches would be integrated so that a hybrid framework could provide more reasonable and practical solutions to load models. Finally, new emerging loads and future-based uncertainties were showcased, emphasizing the need and importance of providing comprehensive policies and procedures for the standards development.

5. Standards and guidelines for development of measurement-based load models

5.1 Executive summary

There is a growing interest in both industry and academia for load modeling due to the prevalence of new load types with higher efficiency and greater controllability. The modern power electronic loads play a much bigger role in the total demand of almost every load sector. Unfortunately, there are no appropriate well-developed load models available currently for an accurate and reasonable representation of these new load types, and numerous micro- and small-scale distributed generations with direct connections to the utility grid. The absence of such a load model, in the near future, may have an adverse influence on the real and reactive power demands.

Most research has been focused on measurement-based approaches given the increasing availability of monitoring devices installed in the power systems. Measurement-based approaches leverage data from devices such as PMUs, smart meters, and so on. As one of the most prevalent load modeling methods, its main advantage is utilizing collected data from an actual system bus without requirements for the detailed actual load composition. This clause summarizes a critical overview of existing load models and their parameters for power system studies, including the most frequently used static load models (such as the exponential, second-order polynomial, and linear load model) and dynamic load models (such as exponential dynamic load model, IM model, and different variants of composite dynamic load model). Depending on the electrical characteristics of the models, this clause further recommends a set of guidelines for different load model development procedures, including the following aspects:

a) Types of signals/data to be measured/collected
b) Data collection procedure, measurement requirements, including sampling rate, duration, and location of monitoring
c) Processing method for handling and conversion of measured signals
d) Data filtering and processing including the required accuracy of filtering procedures
e) Type of field tests needed

5.2 Overview of the clause

Measurement devices such as PMUs and smart meters are widely installed in recent years, and the quality of the measurement has been improved continuously. Measurement-based load model techniques leverage data from such devices and follow a so-called "top-down" methodology; that is, the characteristics of the loads connected to a typical substation and feeders are derived based on the recorded system disturbances. Since the measurement-based approach is focusing on the static and dynamic responses of the loads, this methodology is also referred to as "behavior based." Ideally, the monitors and recorders will capture all responses of the loads connected to the feeders under all kinds of disturbances that occur at a higher voltage level, as illustrated in Figure 2. The solid blue square denotes a voltage monitor at the load bus, and the solid red circles represent current monitors at the feeders. The system is monitored during the normal operation, and the load responses, when a disturbance occurs, are also recorded by power quality monitor and DFRs.

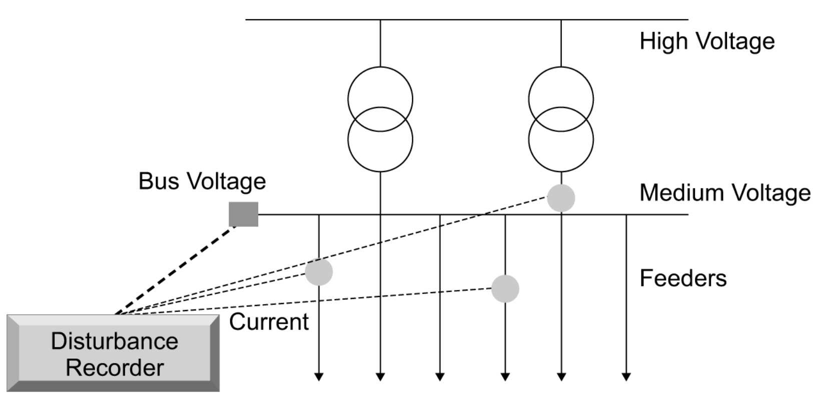

Figure 2—Outline of an example digital disturbance recorder

Figure 3 illustrates a representative flowchart of the measurement-based load modeling approach. It may be noted that Figure 3 is a generic flowchart, and the details of the load model structure and its key parameters can be found in 4.2.

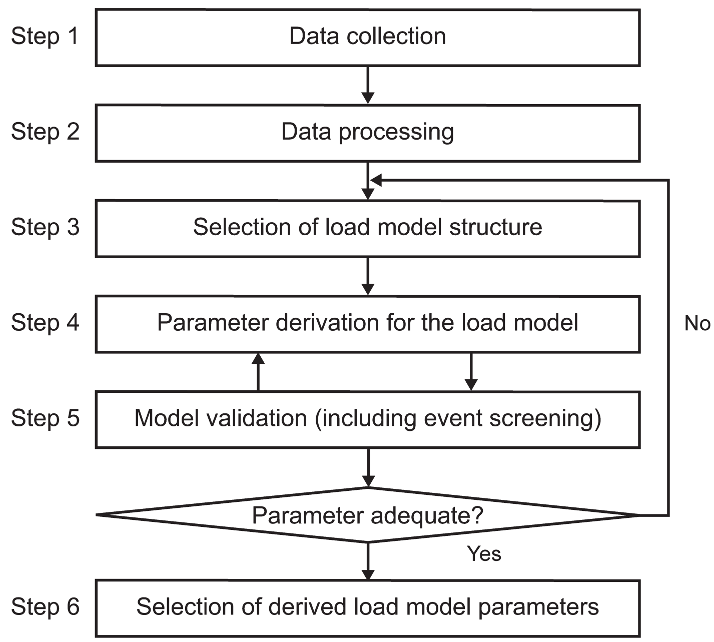

Figure 3—Typical procedures of measurement-based approach

Step 1

Collect system disturbance data, including timestamp, time-domain current and voltage for each phase, frequency, and real and reactive power. Normally, the monitor location is the secondary side of an MV transformer, as shown in Figure 2.

Step 2

A DFT signal processing algorithm or other similar signal processing techniques can be employed to calculate the fundamental components of current, voltage, real power, and reactive power. Different devices use different sampling rates. Typical sampling rates are listed in Table 3 and Table 4.

Step 3

Choose an appropriate load model and a corresponding load model structure. However, this is just an initial load model structure since the structure may be modified if the proper parameters of the load model are not obtained in Step 5.

Step 4

Run an optimization routine to identify/determine the parameters of the load models. Nonlinear optimization techniques, such as a genetic algorithm, simulated annealing, support vector machines, ANN-based methods, and a fuzzy inference system, have been widely used to estimate the parameters of the load models.

Step 5

Validate the derived load model. User-developed or commercially available time-domain simulation tools are employed for validation. The measured real and reactive power responses are compared with the corresponding simulated responses that were obtained based on the final parameters and recorded voltages and frequency. If the comparison results do not satisfy specific predefined criteria, such as an accuracy requirement, the procedure would be repeated with a set of new initial parameters or modified load model, if necessary.

Step 6

Select the final parameters of the load model if they are appropriate. Otherwise, a new load model may be selected, as well as the corresponding objective function (if an optimization method is used), and the procedure goes back to Step 3. In some cases, an appropriate load model cannot be obtained, and it is possible that the collected data are not proper for this measurement-based methodology.

Generally, the advantages and disadvantages of the measurement-based approach are summarized in Table 2.

Table 2—Advantages and disadvantages of the measurement-based approach

Advantages	Disadvantages
Collects dynamic responses from an actual system	Low frequency of disturbances
A generic method that could be applied to model any load	Lacks generalizability because collected data are from a specific location and certain time
Captures temporal changes in connected loads	Divergence of the performance of objective function leads to many sets of parameter values or even no identification of optimal parameters at all

In the rest of this clause, a set of recommendations for measurement-based load model development are introduced from the following aspects:

a) Types of signal or data to be measured and field test needed
b) Data collection procedures
c) Data processing and conversion procedures
d) Data cleansing procedures
e) Load model structure

5.3 Types of signals or data to be measured and field tests needed

The availability of measurement data from the electric power system is the cornerstone of the measurement-based load models. Generally, the types of signals (or data) to be measured are based on the fault measurement data from the operation department of a network service provider company. System frequency, phase, and rms values of three-phase currents and voltages are normally included in the measurement. Further calculations are needed for the values of real and reactive powers, which is necessary to identify load model parameters. For instance, with a two-channel measurement of current and voltage sinusoidal signals, the real and reactive power can be calculated as follows in Equation (44) through Equation (49)

$$P_a = |U_a| \times |I_a|_1 \cos(\theta_{Va} - \theta_{Ia1}) + |U_a| \times |I_a|_2 \cos(\theta_{Va} - \theta_{Ia2}) \quad (44)$$

$$P_b = |U_b| \times |I_b|_1 \cos(\theta_{Vb} - \theta_{Ib1}) + |U_b| \times |I_b|_2 \cos(\theta_{Vb} - \theta_{Ib2}) \quad (45)$$

$$P_c = |U_c| \times |I_c|_1 \cos(\theta_{Vc} - \theta_{Ic1}) + |U_c| \times |I_c|_2 \cos(\theta_{Vc} - \theta_{Ic2}) \quad (46)$$

$$Q_a = |U_a| \times |I_a|_1 \sin(\theta_{Va} - \theta_{Ia1}) + |U_a| \times |I_a|_2 \sin(\theta_{Va} - \theta_{Ia2}) \quad (47)$$

$$Q_b = |U_b| \times |I_b|_1 \sin(\theta_{Vb} - \theta_{Ib1}) + |U_b| \times |I_b|_2 \sin(\theta_{Vb} - \theta_{Ib2}) \quad (48)$$

$$Q_c = |U_c| \times |I_c|_1 \sin(\theta_{Vc} - \theta_{Ic1}) + |U_c| \times |I_c|_2 \sin(\theta_{Vc} - \theta_{Ic2}) \quad (49)$$

where P, U, I, and θ stand for real power, voltage, current, and phase angle, respectively. The subscripts a, b, and c stand for the three phases, and the subscripts 1 and 2 indicate channel numbers.

For load model identification, the average of the three-phase voltages is used as the load point terminal voltage.

For the development of the load models to collectively represent a system, the following data can be collected:

a) *Load composition data and load component information.* Generally, the load class that are classified according to buses can be collected at the typical time of the year, such as winter peak and summer peak, to track their temporal changes over seasons.

b) *System disturbance data.* Disturbance data are either collected from a PMU or a DFR and can be used for load model validation.

c) *Distribution network events data.* Event data are collected from power quality meters or other data acquisition devices installed at typical feeders.

In some cases, a continuous monitoring is not available (for instance, the monitoring device may not be installed at the bus of interest) and field tests may be used for the necessary data. However, considering the adverse impact on customers, the field tests are only utilized to record small disturbances. Specifically, the voltage step can be produced by tap changing (for single tap-changing transformer), or by switching off one of the paired suitably tapped transformers, where the switching off method could produce a slightly larger voltage change. To avoid high circulating currents of parallel transformers operating at different taps, the taps difference between transformers could be two to three taps at most. However, a principal disadvantage of the field test method is that it limits voltage variation to specific percentage (e.g., ± 7.5%) of the rated voltage. This limitation is in place to reduce disturbances to end-users to a minimum and to satisfy the voltage statutory requirements.

Equipment connections for field tests are illustrated in Figure 4, using a simplified one-line diagram. rms voltage and current values can be obtained with digital data acquisition devices, using VTs and CTs, respectively.

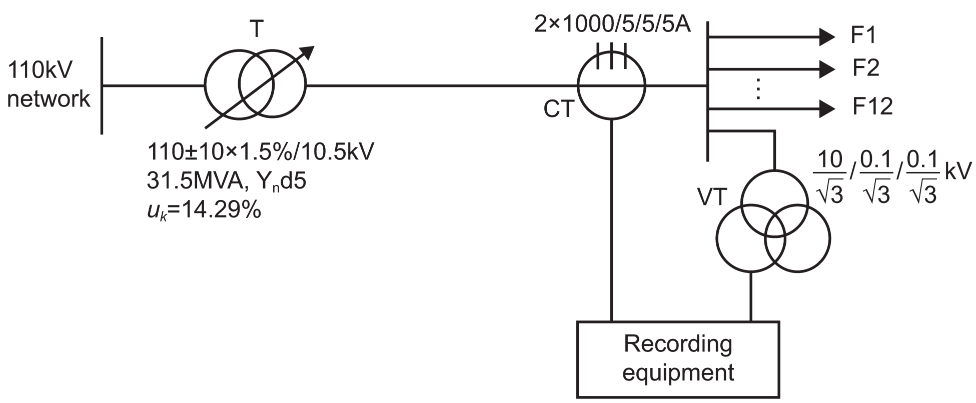

Figure 4—Simplified one-line diagram of equipment connections for field tests

Ideally, the field tests would be performed at different times of day, days of the week, and different seasons to obtain the corresponding load characteristics. To reduce the influence of natural load variations (e.g., rapid load decrease during midnight), the step change is recommended to be made during the time when load changes are not significant. These periods could be identified with the help of a daily loading diagram. This approach is important, especially when developing load models for long-term dynamic studies (e.g., voltage stability). In this case, several minutes or even hours of continuous monitoring periods are required to obtain the diversified response of an aggregate load, for example, variation caused by the operations of downstream tap changers. Since the downstream voltage regulation devices may be uncontrollable during the certain field test periods, there can be several consecutive voltage changes during each period to capture reliable data.

The length of measurement data for estimating load models requires the pre-event buffer to be sufficiently long for reliable estimation of load model parameters. The desirable lengths depend on the actual grid situation, type of load models to be estimated, and measurement devices used. As a general guideline, the length of measurement can be in the range of 2 s to 10 s, using protection relays with data logging capability or as long as 40 s to 70 s for a typical disturbance recorder with an analog interface (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]). A typical length of data measurement is ideally 10 s to 15 s although many of the recording devices may not be able to record that long (Zhang [B85]). Nevertheless, the length can be significantly longer for some power electronics connected loads—for example, the recorded data need to be longer than 70 s to cover a voltage profile over 60.5 s for CFL and HDTV model derivation. EPRI recommends two to five cycles of prefault data plus postfault recording depending on the maximum storage capability and the reset threshold as the minimum hardware requirement for EPRI's measurement-based load modeling work. However, 1 s prefault data are preferable to ensure the initial condition of electric quantities.

5.4 Procedures for data collection

Ideally, data collection includes time-stamped voltages and currents for each phase after a system disturbance. The LV side of a distribution substation transformer is the ideal monitoring location for monitoring either a single feeder or multiple feeders. PQ monitors, DFR, analog data acquisition hardware, and digital relays can be utilized as data acquisition devices. The monitoring device used for the measurement-based approach would satisfy a minimum set of requirements (see Table 3).

Table 3—Minimum requirement of hardware configuration for data recording devices

Specifications for inputs	
Numbers of analog channels	**6/9/12/15 Minimum six channels. Three of them for phase currents and the other three for phase voltages to monitor one feeder.**
Numbers of digital channels	Not necessary for load modeling.
Sampling rate	At least 960 samples per second per channel, or sampling rate of 1 kHz or higher.
Specifications for data sets	
Prefault Recording time (cycles)	Minimum two to five cycles of prefault data.
Postfault Recording time (cycles)	Maximum storage capability and reset threshold forms the function of postfault. For large disturbances (e.g., faults), several seconds of data would be sufficient. Several minutes' data set is needed to develop load models for long-term voltage stability studies.
Trigger condition	Under/overvoltage; Under/overfrequency.
Trigger threshold	User defined.
Reset threshold	User-defined (including specified recording duration).
Specifications for hardware	
Hard drive storage	Up to tens of seconds worth of data to capture slow voltage recovery events.
Serial ports	USB/RS232.
Ethernet connection, network protocols	Desirable.
Data file formats	
ASCII, binary, COMTRADE.	

Different sampling rates are required for different load models. The range varies from 1 ms (1 kHz) to 1 s (1 Hz). Dynamics catch the availability of data and capability of measurement equipment, and the sampling rate can be determined depending on the actual load models used. The sampling rate used for data collection determines the accuracy of the load model. For example, a slower sampling rate such as 1 s is used for static load models or exponential (first order) dynamic load models (for voltage stability studies). However, with this sampling rate, the quality of dynamic load models is insufficient to carry out transient stability studies, of which the recommended sampling rate is around 1 ms. A higher sampling rate may lead to failure in recording the multiple fault or disturbances occurring in a short time frame due to the limitation of the recorded time window. One potential solution for this problem is to utilize variable sampling rate monitors; a lower sampling rate is employed for long periods of time, and a higher sampling rate is used for data collection immediately after a fault or disturbance for shorter periods of time. Different sampling rates required for different load models are listed in Table 4. On the other hand, an alternative solution is to use analog data acquisition hardware that supports a higher sample rate and data transfer to a computer.

Table 4—Sampling rate versus load model development

Sampling rate up to	Load model obtained	Confidence level
1 ms	Static + Dynamic/ZIP + IM	High
	Harmonic load model (lower harmonics only)	Medium/Low
10 ms	Dynamic /IM	Medium
	Static/ZIP	High
100 ms	Dynamic /IM	Low
	Static/ZIP for frequency and voltage stability.	High
	Static/ZIP for transient stability	Low
1 s	Static/ZIP for frequency stability	Medium
	Static/ZIP for voltage stability	Medium/High
2 s	Static/ZIP for frequency stability	Low
	Static/ZIP for voltage stability	Medium
1 min –15 min	Static P, Q Load	Low/Medium

Measurements are performed at critical load points and regions for industrial load modeling since these loads exhibit typical dynamic behavior. For a better load model parameter identification, sufficient variations in voltage, real, and reactive power data series of the collected disturbance data are needed (e.g., 10% to 20%). Recommend types of faults are three-phase fault at an HV level, single-line-to-ground fault at an HV level, or line-to-line faults. Historical data of system faults could be used as system response data under specific disturbance, if a certain disturbance is difficult or even impossible to be captured.

5.5 Procedures for data processing and conversion

Before a load model identification analysis, the collected data following system disturbances need further processing and filtration. The essential steps include the following:

a) Identification of collected data at the LV or HV side

b) Data preprocessing procedure to filter data containing sufficient variations of voltage and power during the recording periods

c) Calculation of real and reactive power values based on originally collected data

d) Load model identification based on the processed measurement data

Three-phase voltages and currents data are converted into a positive sequence, per unit voltage, current, real power, and reactive power. A DFT sliding window algorithm is often used for the conversion. To apply this algorithm, a sampling rate of 1 kHz or 2 kHz, is recommended. Note that the sliding window algorithm will filter the input data inherently.

5.6 Procedures for data cleansing

Collecting all the required data accurately is a challenging and costly mission. Missing and corrupted data in the process of collection and transfer are ubiquitous due to various reasons including the malfunction of monitoring devices, communication failures, and equipment outages. Poor quality data may lead to misleading data analysis. It is crucial that low-quality data (noise) is accurately identified and corrected. However, to keep the useful transient information in the data sets, a data cleansing procedure has to be carefully performed. Since the measurement noise is, in most cases, a Gaussian noise, a simple averaging filter is a potentially effective method to filter the collected data. For instance, for a data set measured at 100 Hz, values of 5 to 10 adjacent data points can be averaged; then the averaged value, replacing the original data, can be used to identify the load model. For higher sampling rates, the averaging filter approach is still effective as long as the random noise is the major source of data noise. A positive sequence component of collected currents and voltages data can be extracted by fast Fourier transform for further processing.

5.7 Determination of load model structures

Most frequently used load models can be divided into two groups: static load models and dynamic load models as shown in Figure 5. The former group includes exponential, polynomial (ZIP), linear, comprehensive, static IM, and power electronic-interfaced models, whereas the dynamic load models include exponential dynamic load models, dynamic IM models, transfer function IM models, composite, distribution, bulk power bus loads, and distributed ESS models. Details of the mathematical description of these models are showcased in 4.2.

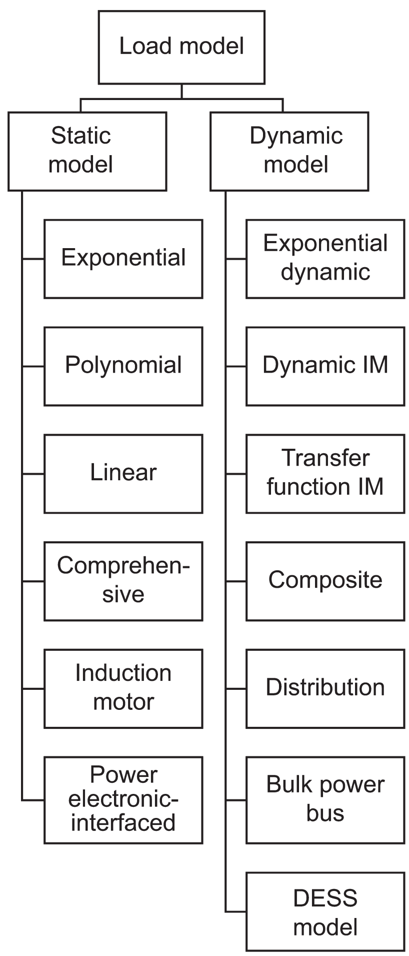

Figure 5—Load model classification

To integrate the physical load models into the power system analysis platforms, the following two recommended load model structures can be used. They incorporate both static and dynamic characteristics of the loads:

a) Polynomial static, ZIP, model augmented with third-order (differential equation-based) IM model

b) Exponential static model augmented with a difference equation (representing input–output, second-order model)

Once the load model structure is determined, the model parameters could be estimated through an optimization problem as shown in Equation (50), where superscript *m* and *e* stands for measured and modeled, respectively, while the subscript *i* and *n* stands for the load model and the total number of load models, which aims to reduce the difference between the response of the load model and the collected data. The *P* and *Q* are averaged active and reactive load power over a certain measurement time window. As the output of the optimization, the parameters to be estimated are the respective composition portions of static and dynamic loads, the coefficients of the static models, and the individual parameter of the dynamic model.

$$\min \frac{1}{n}\sum_{i=1}^{n}\left[(P_i^m - P_i^e)^2 + (Q_i^m - Q_i^e)^2\right] \tag{50}$$

Like other optimization problems, the initial values of the parameters are of great importance and would be predetermined before the optimization process. Appropriate initial values, as well as reasonable bounds, can have positive impacts on the convergence and the accuracy of the optimization.

Equation (50) is based on the assumption that the *P* and *Q* are a function of *V*. In fact, there is an interaction between the power quantities (*P* and *Q*) and the bus voltage, which cannot be neglected, especially when IM loads occupy a considerable proportion. Following a large disturbance, such as a short-circuit fault, the motors decelerate drastically due to the voltage dip or may stall if the electrical torque cannot overcome the mechanical load. This in turn draws high current that affects significantly the voltage magnitudes and impedes the voltage recovery on fault clearing. In extreme conditions, a fast voltage collapse can be caused by the motor stalling

A recommended method is to incorporate the *V* into the load model output and rely on time-domain simulation to obtain the dynamic response of the three variables (*P*, *Q*, and *V*). The optimization problem can be formulated as Equation (51), which aims to search a set of load parameters that can best fit the model responses from time-domain simulations and field measurements.

$$\min \frac{1}{n}\sum_{i=1}^{n}\left[(P_i^m - P_i^e)^2 + (Q_i^m - Q_i^e)^2 + (V_i^m - V_i^e)^2\right] \tag{51}$$

The quasi-Newton methods such as the Levenberg–Marquardt algorithm are usually applied to solve the optimization model defined by load modeling problems. However, the classic programming methods only work for differentiable equations and they usually suffer from high sensitivity with respect to the starting point; besides, global optimal solution cannot be guaranteed. Because the detailed mathematical functions for *P*, *Q*, and *V* are unavailable, it may be challenging for classic optimization algorithms to solve such problems. EAs, on the other hand, do not have convexity or a continuity requirement for the optimization problem to be solved. They provide an easy-to-use alternative approach to solve complex optimization problems. Different EAs can be used for this propose. Hereby a parallelized DE is given as an example solver that is suitable for online applications. The implementation structure of a parallel-DE is given in Figure 6. The parallel structure and the population-based approach of the algorithm can be used to improve computational efficiency. A typical computation flowchart of the optimization method is given in Figure 7.

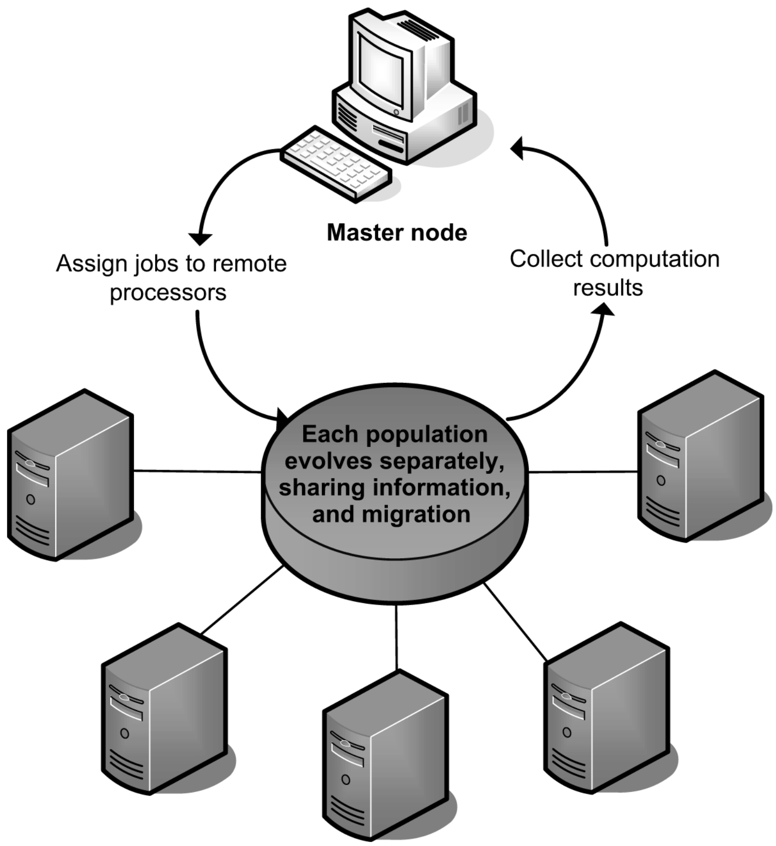

Figure 6—Implementation structure of parallel-DE

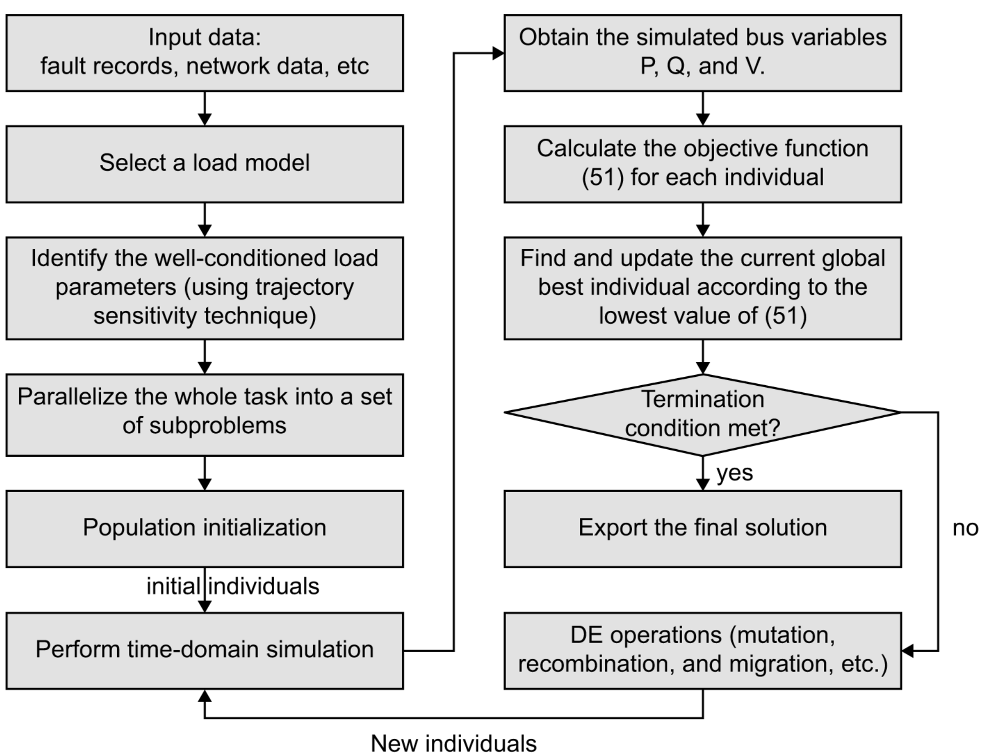

Figure 7—Computation flowchart of a parallel-DE method

5.8 Load model validation

With an appropriate set of parameters for the load models, a series of power system analysis can be conducted in commercial time-domain simulation tools, which will be introduced in 8.3. First, the real and reactive power model responses are derived based on the parameter values and recorded voltage. Then simulated responses and measured responses are compared. If these responses do not match well according to a set of predetermined criteria, such as an accuracy requirement for a specific load model application, further tuning of the model parameters or even modification on the load model structure would be performed. It is noted that step and ramp responses can be used to validate the models developed for dynamic loads. If the difference between these responses is acceptable, detailed system studies can be carried out based on the load models.

Specifically, at an individual bus or feeder level, data for the load components, load classes, and load characteristics would be collected as much as possible and measured at different times of the year. Disturbance data would be collected at typical feeders representing the various mixture of load classes. With the increasing distributed generation sources such as rooftop PV generations, an active cell with decent parameters may be included in the load model developed. Load components, load class, and load characteristics data are used for estimation of load composition. If appropriate disturbance data are applicable, a comparison can be conducted between these percentages and the percentages from the measurement-based approach. It is important to perform the comparison in an “apples-to-apples” manner. For instance, a comparison between a typical summer day event and a freezing winter day could be avoided. Due to the inherent uncertainty of load components and load classes, and the temporal variations in loads, it is impossible to make a perfect match between the two approaches. However, it is still of great significance whether the results are of the same order of magnitude and whether they have the same trend.

As for model validation at the system level, the following two steps are involved:

a) Collect system disturbance data at one or several EHV buses through either DFRs or PMUs. Depending on the load model and data collection system, the collection periods of these devices range from tens of seconds to tens of minutes.

b) If an event recording after a major disturbance is available, the actual recorded responses and the simulated data would be compared. Modification of the load model may be needed if there is no satisfactory match. Engineering judgment is also needed in this iterative process, as well as further information about the system, such as the generator status. Also note that, for an accurate comparison, other power system equipment in the nearby region would faithfully simulate the disturbance.

In practice, a perfect match between recorded data and simulated responses is unrealistic. A satisfactory match between them suggests that the load model is sound for the system with certain accuracy. If the discrepancy is not acceptable, further modifications of the load model parameters will likely be required.

Throughout the model validation procedure, sensitivity assessment using different parameters is significant since removing all the uncertainties involved is impossible. A set of critical parameters needs to be identified as the focus of the sensitivity analysis. Normally, the following assessment items are included in the sensitivity analysis:

c) The effects of changing the amount of dynamic load component (particularly the IM load) in the model

d) The effects of different motor model parameters, for example, stalling voltage as a function of temperature or motor inertia

e) The sensitivity of the load model to self-disconnection and reconnection of part of the load

5.9 Conclusions

This clause provided a critical overview and clear identification of the pros and cons of the measurement-based approaches. The main advantage is the employment of collected data from an actual system bus without requirements for the detailed actual load composition. However, the lack of appropriate disturbance data, particularly large disturbance under different system conditions, is the main disadvantage that may result in poor model validation performance and in an inaccurate parameter estimation. Availability of suitable data is the key to a reasonable and appropriate measurement-based load model. Utilities sometimes have to use data from disturbance events years back to develop load models and corresponding parameter estimation. And the other aspect of the data availability is the continuous measurement, which is essential for developing accurate load models for different system operating conditions.

The first step in developing a measurement-based load model is data collection. Generally, load composition data, system disturbance data, and temporally and spatially distributed event data are keys for reasonable and accurate load modeling. Specifically, load composition and load component information are essential, while system disturbance data, despite its necessity in the performance test of the developed load model, is not so critical. Because of the stochastic nature of the disturbance, the collection of system disturbance data is laborious and takes a considerable amount of time. If loads are connected to a distribution feeder, their aggregate responses, due to either a fault on a nearby feeder or an upstream fault, can be utilized for the load modeling. Such data include both the dynamic response of the motor load and the static load responses. It is worth noting that there is a significant difference between load model validation at an individual feeder or bus level and at the system level.

The procedures for the selection of locations for monitoring and field tests are addressed. Guidelines for the selection and processing of monitoring data, selection of sampling rates for different devices, signal filtering procedures are also presented in detail. Several load models describing the static or dynamic behavior of different loads and load classes are presented, and load model structures for load model development of the measurement-based approaches are recommended.

Different kinds of load models can be established using the measurement-based approaches, including the CLOD, which is a composite load of IMs, lighting, and other types of equipment in a typical substation, and CMLD, which can simulate the dynamic behavior of an aggregate of three-phase motors, a single-phase air conditioner motor, electronic loads, and static loads. In addition, the energy storage can be modeled.

6. Standards and guidelines for development of component-based load models

6.1 Executive summary

When the recorded measurements are unavailable or insufficient, component-based load modeling is an alternative approach that combines the models of the various load components at the bulk supply system based on the load composition. The component-based load modeling approach is a bottom-up methodology, which derives the aggregate load model using the following information:

a) Information of the load sectors connected at substations
b) The load aggregation structure within each load sector
c) Electrical characteristics of each load component and/or load category

A load component is an individual electrical device or equipment, or a group of these, typically used in the same end-use applications, which consumes active/reactive power and responds to variations in voltage and frequency in a similar way. Some examples of load components are cooling/heating pumps, refrigerators, and so on. Load category refers to a group of different load components used in different end-use applications, which have the same or similar characteristics to be modeled by the same load model. Some typical load categories include motor loads, lighting loads, resistive loads, and power electronic loads.

A component-based load modeling approach divides the loads at bulk power point into different sectors and further into different categories, and it aims to provide accurate modeling of the loads within each sector and/or category. The developed aggregate load model incorporates the involved load components and categories based on the identified load structure and is usually formulated using a series of basic load models such as a second-order polynomial model and an IM model.

Compared with the measurement-based approach that uses the recorded measurement data, the component-based approach builds the load model based on the load structure data from end-use survey and/or existing literature and the electrical characteristics of participating load components. The main advantage of the component-based approach is the knowledge of the dynamic load characteristics to system disturbance. The main disadvantage is the difficulty in collecting accurate load structure data and handling the spatial-temporal variation in loads.

This clause provides an overview of the component-based load modeling approach and a series of guidelines on the following aspects:

d) Various steps that are required to develop aggregate load models

e) Classification of the load at the bulk supply system

f) Various types of data to be collected and their roles in the component-based approach

g) Data cleansing method

h) Aggregation of the collected data to develop the aggregate load model

i) Validation of the developed model

6.2 Overview of the clause

The suggested component-based load modeling approach can be broken into four steps, as shown in Figure 8.

The first step is data collection, that is, to collect the data required to build the aggregate load models. Such data include load structure, load categories, associated basic load models, and the network data.

The second step is to build an aggregate load model at the LV level based on the daily load curves, load categories, and the basic load models. This aggregate load model represents the load characteristics within the given load sector.

The third step is to connect the aggregate load models at LV to the MV distribution network, which ends up with a distribution-level network model with load integrated. This is achieved with the aid of the previously collected network data.

The fourth or final step is to develop a component-based aggregate load model at a medium/high-voltage level. Simulation is required in this step to examine the load characteristics seen at the MV buses. The information provided in the simulation will decide the actual form of the aggregate load model at the MV level. Such aggregation process can also be adapted to a high-voltage level.

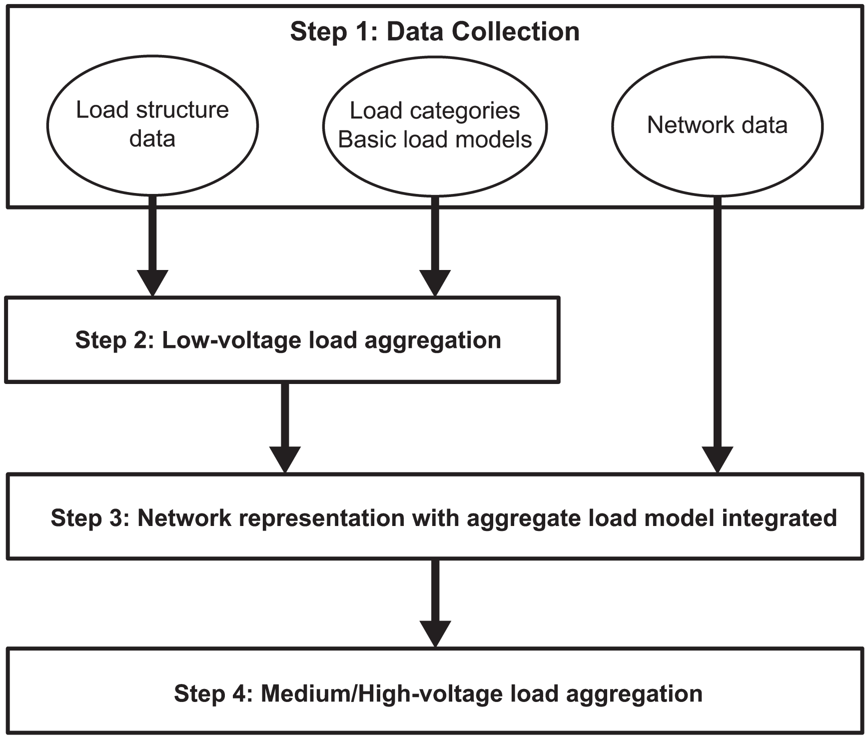

Figure 8—Suggested procedure for component-based load modeling

The pros and cons of the component-based approach are summarized in Table 5.

Table 5—Advantages and disadvantages of component-based load modeling approach

Advantages	Disadvantages
Correlate the mathematical formulation to the physical characteristics of the load components	Difficulty in handling temporal load variation
The load sector data are generally available	The load structure data is substation specific
Easy application to CMLD	Needs to carry out large-scale load surveys
No need for field measurements	Error in modeling the newly connected load components
Adaptable to different systems and conditions	The model parameters can vary greatly with age, the manufacturer, and so on
Flexibility in load/demand control	Difficult for transmission system operators to apply
Facilitates system performance sensitivity analysis	—

In this clause, the following guidelines are provided for component-based load modeling:

a) Load classification

b) Data collection

c) Data cleansing

d) Data aggregation

e) Model validation

6.3 Guidelines for load classification

The component-based load modeling approach classifies the load at a distribution bus using a three-layer classification paradigm, as shown in Figure 9. The first layer divides the load into different load sectors. The second layer categorizes the load component in each sector into different load categories. The third layer represents each load category as a mixture of the basic load models.

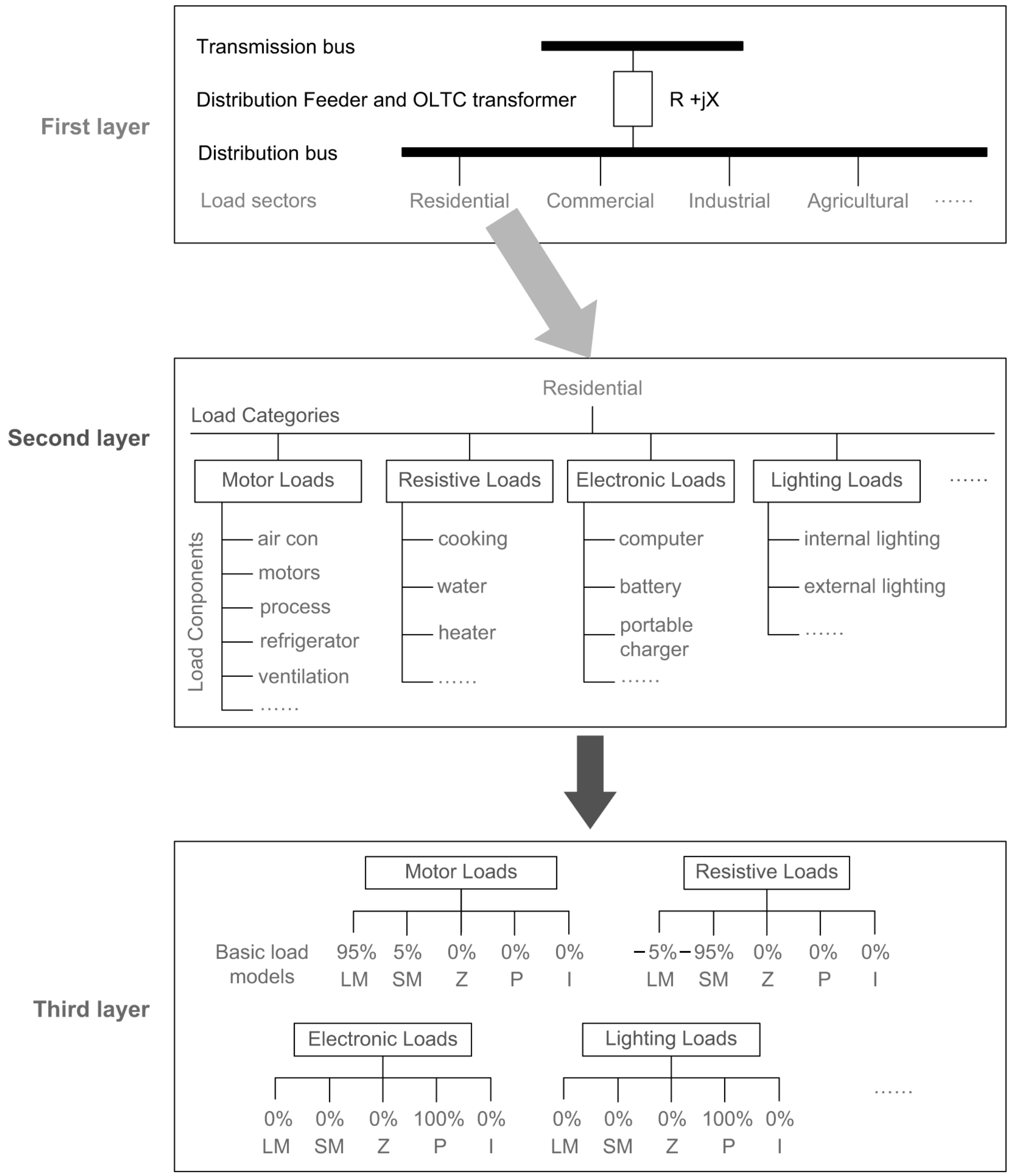

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Figure 9—Load classification using component-based load modeling approach

In the first layer, the load at each bulk power delivery point is divided into different load sectors in terms of the pattern of active and reactive power demand. A load sector is generally defined as follows (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong and Milanović [B81]):

> *An aggregation or collection of different types of loads, representing the typical structure and composition of electrical devices and equipment found in a specific end-use application, where similar activities and tasks are performed.* (reprinted with permission)

The end-use power demand pattern within a load sector is usually inherently similar; thus, the aggregate load model within the same load sector tends to be similar. The three typical load sectors are residential, commercial, and industrial. The residential load sector generally refers to the houses or buildings that provide residency to the occupants. The commercial load sector includes the businesses that aim to provide specific services to the public. The industrial load sector involves the equipment and devices for product manufacturing and material processing activities. Other load sectors, such as general lighting and agricultural, could be added where necessary. General lighting takes up a significant load overnight in a metropolitan area. In this case, it is suggested to identify general lighting as a separate load sector. Agricultural is generally recognized as an independent load sector in rural areas with major agricultural activities.

The second layer derives the load components based on the actual tasks or electrical activities performed within each load sector or subsector. According to electricity consumption statistics, the main load components involved in different load sectors are lighting, air conditioning, ventilation, space heating, water heating and refrigeration, and cooking.

Since the end-use applications are diversified over different load sectors or subsectors, the number of load components is considerable, and their composition can be greatly varied. Therefore, it will be inefficient and improper to propose a targeted mathematical model for each load component. Rather, for load modeling purposes, the third layer is to group the electrical behavior of the many load components into different categories, and develop basic mathematical models to represent the load characteristics in each category. Then the load within a sector or subsector is represented as an aggregation of the basic mathematical models. In general, the load components are represented by static and dynamic load models. The static models include constant impedance load, constant power load, and constant current load. The dynamic models mainly refer to the IM loads.

6.4 Guidelines for data collection

The first step in component-based load modeling is data collection. To achieve an accurate estimation of the aggregate load model, the following data are recommended for collection:

a) The load structure within each load sector or subsector, which can be represented by the daily load curves, including the available submetering data collected from end-users' premises

b) Load categories and the associated basic load models, which represents the electrical characteristics of the load components

c) The network data, which are required for the load aggregation at medium- or high-voltage levels

6.4.1 Load structure data

Load structure refers to the load components and their composition within a load sector or subsector. Load composition here means the contribution of each involved load component to the total demand. The collection of load structure data is an essential requirement for individual load component modeling, load model aggregation, and simulating the load response to system disturbances at different time points.

Considering the temporal variation of the load sector composition, it is recommended to define various representative loading levels to reflect the daily, weekly, and seasonal variations of the load. As shown in Figure 10, a practical way of defining such loading levels is to set a light and a heavy loading level for each season. This loading level information is generally provided by the distribution companies to facilitate the load aggregation at the substation level.

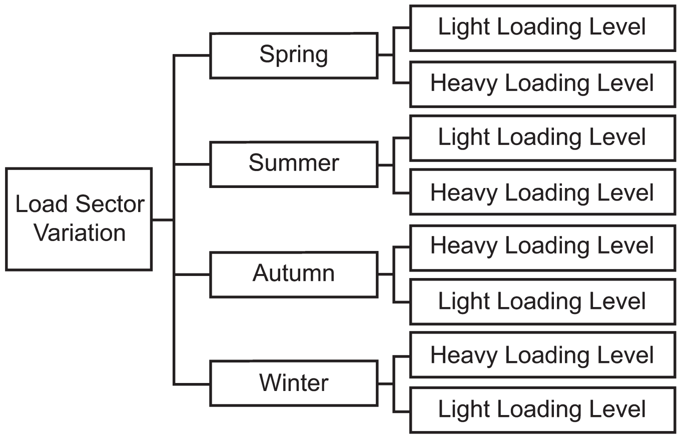

Figure 10—Loading levels to reflect load sector variations

A direct load modeling for each load sector is challenging due to the distributed nature of the load and the complicated load variation; therefore, it is recommended to divide each major sector into multiple subsectors to achieve more accurate load modeling. For example, depending on the location, size, and type of dwelling, the residential load sector can be divided into four subsectors: highly urban residential, urban residential, suburban residential, and rural residential. The commercial load sector can be divided with respect to the functions of the buildings and businesses, which generally results in more subsectors compared to the case of residential load. The possible subsectors of commercial load include, but are not limited to, commercial office, communication and transportation, education, health, hotel and catering, retail, sport and leisure, and warehouse. The industrial sector is different from the residential and commercial sectors in the sense that the industrial sector generally involves diversified industrial processes and activities that are specific for each site; thus, it is recommended to model the industrial load sector in as much detail as possible to accurately reflect the practical circumstances. This requires site-specific load models that are devised based on the registered plant data and the actual manufacturing processes (Aguero, Beroqui, and Achilles [B1]). The definition and the load trends of each subsector will be provided in Clause 7.

Each load sector or subsector is also further divided into several load components. The participation factors of the load components are generally similar for a certain loading level within the same load sector, but they can be significantly deviated over different load sectors and different loading levels. Similar to the load sector composition, the composition of different load components within each load sector also poses spatial-temporal variations. Since such variation is weakly correlated over different networks and geographic locations, it is generally a time-consuming and expensive task to capture the load variation pattern and identify the load structure within each load sector.

Based on the collected data, the load structure can be represented by a set of daily load curves. The information to estimate the daily load curves is mainly obtained from the government-level reports (Zimmermann [B86]; Pout, MacKenzie, Olloqui [B57]; and Stamminger, Broil, Pakula, Jungbecker, Braun, Rüdenauer, and Wendker [B69]), research papers (Jardine [B35] and Brown and Koomey [B9]), end-use survey (Yamashita, Kitauchi, and Katsuragi [B82]; Brooks 2009 [B7]; Brooks 2007[B8]; Yamashita, Martinaz Villanueva, and Milanović [B83]; and EPRI, 2004 [B22]), and other representative and detailed statistical data (Lader, Short, and Gershuny [B42]). The hourly, daily, weekly, and seasonal variation in the power demand could be considerably reflected in the daily load curves. A daily load curve based on the load components within the commercial load sector is shown as an example in Figure 11, where the fraction of each load component is normalized.

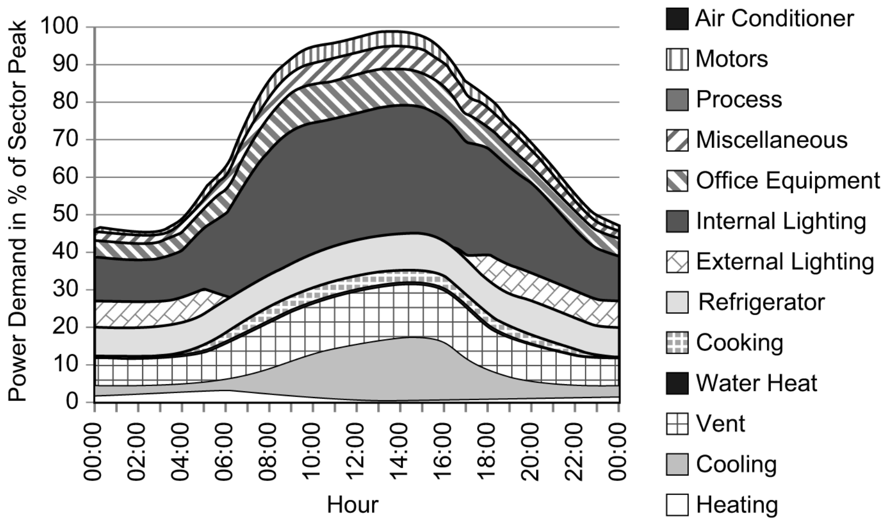

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Figure 11—Example of daily load curves for commercial load sector

6.4.2 Load categories and the associated basic load models

The load components are identified based on the statistical data of the specific activities performed by the end-use devices and appliances. Such classification of the load in a sector is generally inconvenient for mathematical modeling that requires generic formulation of the static and dynamic load characteristics. To develop the aggregate load model, a more practical and more efficient approach is to collect the information on the type and composition of different load categories. Various load components are grouped in one category due to their similar electrical characteristics, and each load category can be mathematically represented by a mixture of basic load models. The load category information is generally available in national statistics (Department for Business, Energy and Industrial Strategy [B19] and Defra: Market Transformation Programme [B17]) and associated legislation (IEC 61000-3-12 [B31]), while the basic load models are commonly obtained from the existing literature or built through detailed simulations and laboratory tests.

6.4.2.1 Load categories

It is recommended to define the following five typical load categories for component-based load modeling (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]):

a) Resistive loads

b) Energy-efficient lighting

c) SMPS loads

d) Directly-connected motor loads

e) Inverter-interfaced motor loads

Due to the variations in harmonic legislation, technologies, and circuit topology, each load category can be further divided into multiple subcategories, as shown in Figure 12. The further explanation of each category and subcategory is provided in Table 6.

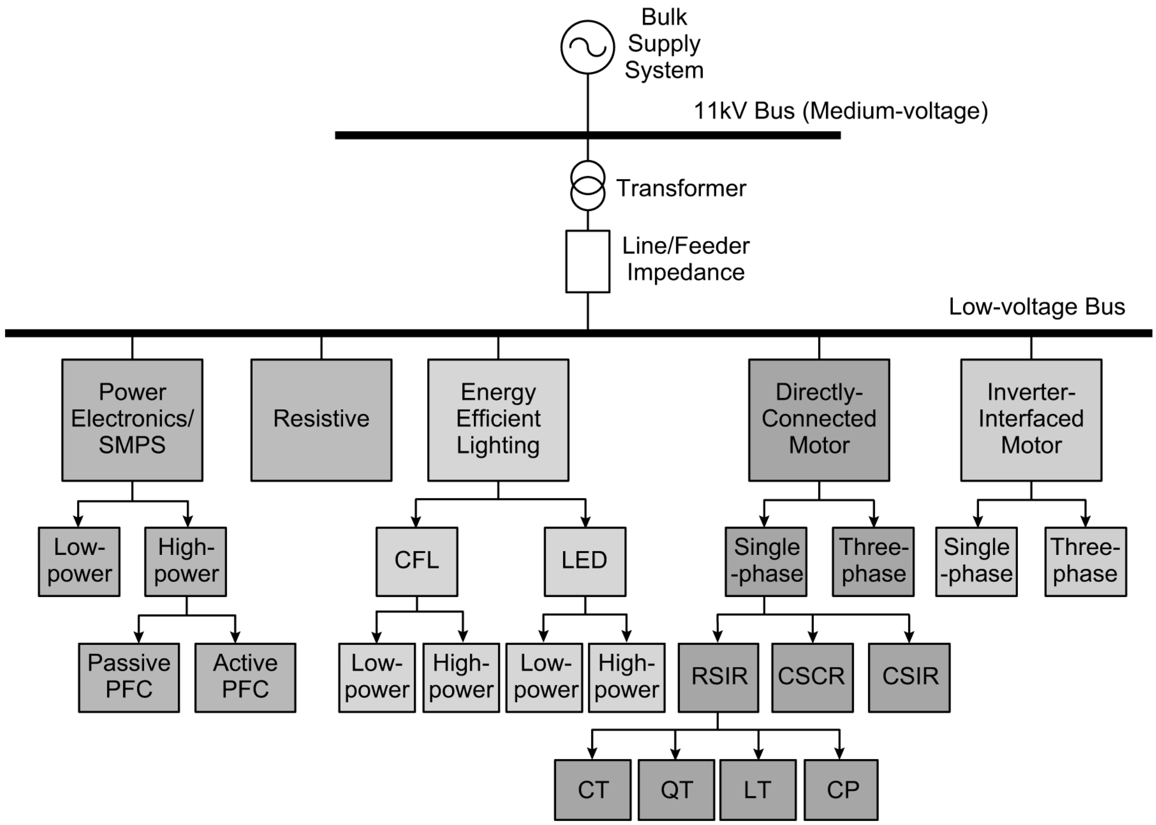

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Figure 12—Aggregate load model based on the five typical load categories and their subcategories

Table 6—Five typical load categories and their subcategories

Load category	Subcategories	Comments
Resistive loads	Cooking Heating GILs	Cooking is assumed to be ideally resistive. The exponential coefficient of general incandescent lamps (GIL) is 1.55.
Energy-efficient lighting loads	CFL LED	Low- and high-power variations are possible. For CFL, high-power devices are expected to contain a PFC circuit. The details of LED lighting loads are unavailable due to the immaturity of this technology.
SMPS loads	no-PFC a-PFC p-PFC	Devices with rated power less than or equal to 75 W are not expected to contain a PFC circuit. Above 75 W, p-PFC is currently more common, but the contribution of a-PFC is expected to increase in the future.
Directly connected motor loads	Single/three-phase Low/high-power Constant/linear/quadratic torque mechanical loading Constant power mechanical loading RSIR/CSCR/CSIR	It is possible to have any combination of motor type and mechanical loading condition, but specific motors are generally needed for specific applications.
Drive-controlled motor loads	Single/three-phase Low/high power Open/closed-loop control Scalar/vector control	

Reprinted with permission from Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong and Milanović [B81].

6.4.2.2 Basic load models

The basic load models to model each load category are selected based on the electrical characteristics of the load. The typical basic load models are a large IM model, small IM model, constant impedance model, constant power model, and constant current model. The contribution of the basic load models in representing each load category can be obtained from generic data in the existing literature or through laboratory tests. The percentages of the basic load models to represent each load category in the US residential sector are listed in Table 7 as a guideline. It is recommended to aggregate the basic load models specifically for each load component in the motor load category. The formulations of different basic load models have been provided in Clause 4.

Table 7—Percentages of the basic load models to represent each load category in residential sector

Categories	Motor			Electronic	Resistive	Lighting
	Cooling/ heat pump	Ventilation	Refrigeration			
Large IM	5%	100%	5%	0%	0%	0%
Small IM	95%	0%	95%	0%	0%	0%
Constant impedance	0%	0%	0%	0%	100%	0%
Constant current	0%	0%	0%	0%	0%	100%
Constant power	0%	0%	0%	100%	0%	0%

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After defining the basic load models, the model parameters would be properly selected to accurately model the load characteristics. Since the characteristics of each load component deviate even if they are grouped in the same load category, it is recommended to collect several model parameters for each load component, especially the IM loads, so as to achieve higher modeling accuracy. The parameters of each load component can be obtained from the existing literature and/or through laboratory testing results. Artificial intelligence techniques, such as fuzzy regression (EPRI, 2004 [B22]), can also be used for model parameter evaluation.

In Table 8, the electronics (i.e., SMPS) loads, resistive loads, and lighting loads can be represented as a single basic load model, while the modeling of IM loads is more complicated as their electrical characteristics vary over different load components. Moreover, a disturbance in the system may cause the stalling of IMs based on their protection and control functions. Therefore, it is recommended to include the protection and control circuit in dynamic IM models to reflect the stalling behavior of IMs, especially for long-term-stability studies. Besides the dynamic IM model, a static model is also necessary for IMs to derive the initial steady-state condition. In Morison, Hamadani, and Wang [B51], the following exponential model is formulated for IMs, based on the *P*-*V* and *Q*-*V* characteristics obtained through time-domain simulations in Equation (52) and Equation (53).

$$P = P_n\left(a\,U^{\alpha} + b\,U^{\beta}\right)/\left(a\,U_0^{\alpha} + b\,U_0^{\beta}\right) \quad (52)$$

$$Q = r\,U_0^{\beta} P_n\left(c\,U^{\gamma} + d\,U^{\delta}\right)/\left(c\,U_0^{\alpha} + d\,U_0^{\delta}\right) \quad (53)$$

Table 8—Fitted parameters for static IM models

	a	α	b	β	c	γ	d	δ	r
Small IM	0.86	0	0.14	0.09	0.8	1.6	0.2	–3.3	$0.627U_n^{0.6}$
Large IM	0.86	0	0.14	0.09	0.747	1.54	0.253	–3.07	$0.519U_n^{0.35}$

Reprinted with permission from Morison, Hamadani, and Wang [50].

Morison, Hamadani, and Wang [B51] also provides the parameter selection for Equation (52) and Equation (53), which are listed in Table 8 as an example. In Table 8, the parameters are the fitted results for the data in Taylor [B72], and the parameters for small and large IM loads are provided separately.

6.4.3 Network data

The network data refer to the network configuration and network component values. The typical network components include, but are not limited to, substations, feeders, OLTCs, and reactive power compensators. Based on the network data, the power system simulation software can be used to build a network model to represent the distribution and subtransmission network. The network data are essential in building the medium/high-voltage aggregate load models. The following aspects are typically considered for network data collection:

a) Accurate equivalence of the feeder to reflect the voltage drop and power losses in the primary distribution network, distribution-level transformers, and secondary distribution network

b) The reactive power compensation at both the substation and the feeder ends with appropriate regulation

c) The tap-changing operation in OLTC

6.5 Guidelines for data cleansing

In component-based approach, the load composition is different for different load sectors, and each load sector is subject to different loading levels. Moreover, the load structure (including the composition of load sectors and load components) greatly varies with time and geographic locations. All those concerns pose significant challenges to collect comprehensive and timely load structure data. To compensate missing information in component-based approach, some guidelines on data sources and load modeling method are given as follows:

a) The load structure can be obtained not only by conducting end-use survey but also by monitoring the power usage of sampled customers, including the submetering data collected from end-users' premises.

b) Useful information is available in end-use load research programs that are conducted by some distribution companies (Kosterev, Meklin, Undrill, Lesieutre, Price, Chassin, Bravo, and Yang [B40]; Price, Wirgau, Murdoch, Mitsche, Vaahedi, and El-Kady [B60]; and Nozari, Kankam, and Price [B54]).

c) The load could be modeled via a simpler approach which is based on the following:

   1) Typical fraction of each load component within each load sector.

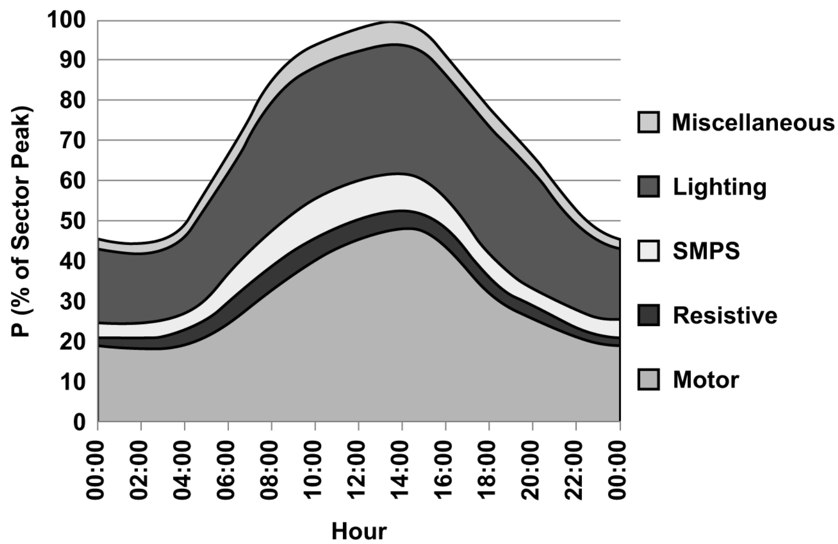
   2) Composition of load sectors at each bus (Han, Ma, He, and Dong [B26] and Brooks [B7]).

d) The missing information could be interpolated using data-driven approaches. An example is the method proposed in Nijhuis, Gibescu, and Cobben [B53], which a synthetic process based on a Markov chain Monte Carlo approach, could be adopted for residential load modeling. This method requires the knowledge of publicly available data, such as the socioeconomic and demographic characteristics, the Unitary Energy Consumption, and the load profiles of individual household appliances.

6.6 Guidelines for data aggregation

After data collection, this guideline provides recommendations on how to aggregate all the raw data to achieve the aggregate load model. Such data aggregation refers to step 2 to step 4 in Figure 8.

The generally available statistics usually provide load structure data based on the composition of different load components, which cannot be directly used for category-based load aggregation. The load components would be aggregated according to the defined load categories, and then the conventional daily load curves can be converted into a set of daily load curves presented by load categories, which reduces the data dimension for aggregate load modeling. For example, the load components in Figure 11 can be grouped into the five typical load categories, and the daily load curves are converted into a category-based version, as shown in Figure 13. Such conversion results in fewer elements to be modeled, and the standard basic load models in Clause 2 can be immediately used to represent each load category, which significantly reduces the workload of estimating the aggregate load model.



CIGRE Technical Brochure 566 [B49].

Figure 13—Converted category-based daily load curves for commercial load sector

Some guidelines for converting the typical load components into the load categories are given as follows (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]):

a) *Wet load*—Wet load refers to the motor loads related to water, such as dishwashers, tumble dryers, washer dryers, and washing machine. Among them, tumble dryers, washer dryers, and washing machine have high running torque, which means they will require run capacitors. Rather, the dishwashers do not require run capacitors but utilize inductor-run SPIM. Constant torque mechanical loading is generally assumed for all wet load.

b) *Cold load*—Cold load refers to all variants of refrigerators and freezers. Such loads are expected to use inductor-run SPIM and to use quadratic torque conditions to represent motor mechanical loading.

c) *ICT load*—This load consists of all types of home computers and communication technology equipment. They are divided into SPIM load with a-PFC, p-PFC, and no-PFC based on their embedded PFC circuit. The loads with large rated power, such as desktop computers, monitors, and printers, are recommended to incorporate p-PFC. The laptop chargers are recommended to have a-PFC because they do not have to satisfy harmonic legislation. All other ICT loads are expected to have low-rated power ($\leq$ 75 W), so they are recommended to have no-PFC.

d) *Consumer electronics load*—This mainly refers to television sets that are also divided into SPIM load with a-PFC, p-PFC, and no-PFC. Large television sets are recommended to incorporate p-PFC; the television sets with more recent technologies are recommended to have a-PFC, and the television sets with smaller rated power ($\leq$ 75 W) are recommended to have no-PFC.

e) *Cooking load*—Hobs and ovens belong to resistive load category. Microwaves are recommended to be categorized as p-PFC SMPS loads.

f) *Lighting load*—According to Table 6, the GIL-based lighting loads are modeled as resistive loads, while the CFL-based lighting loads are modeled as energy-efficient lighting loads.

After resolving the load structure into load categories, the basic load models for different load categories are aggregated based on their identified contribution within each load sector or subsector. The aggregate load model is estimated as the weighted sum of different load categories at every 30 min or 1 h.

As mentioned earlier, the aggregate load model derived based on load structure data and basic load models only represents the load characteristics at the LV level. To produce the aggregate load model at medium/high-voltage levels, the network data, including network configuration and network component values, would be leveraged to build a network model using power system simulation software.

After connecting the low-voltage aggregate load model over different load sectors or subsectors to the network model, a medium-voltage aggregate load model can be estimated as follows:

g) Instigate the supply voltage change by varying the aggregate power demand while keeping the same mixture of loads, or by setting the supply voltage using transformers.

h) The medium-voltage aggregate load model is then formulated based on the relationship between the power demand changes at medium-voltage bus and the supply voltage.

This process is also applicable to a high-voltage level, which develops the high-voltage aggregate load model.

6.7 Guidelines for model validation

The commercial software can use the model parameters for power system analysis. First, the load models can be validated against recorded responses. If the match between simulated and recorded responses is acceptable, the system studies can be carried out. Otherwise, if it is not matched, the further tuning of parameters or changing load model structure are required.

The model validation is essential, and it consists of two levels. At the local level, the measured load dynamics can be used to check whether the load model built on the measurements could describe the load dynamics; on the system level, the simulations on the whole system, including the load models on all the load buses, will be made to check whether such load clustering is good to reflect the system dynamics. The load model validation work may be combined with the sensitivity analysis to adjust the load clustering if necessary.

6.7.1 Model validation at bus/feeder level

At an individual feeder or bus level, the data of load class, load component, and load characteristics need to be collected for different seasons of the year. Moreover, monitors can be installed at a few representative distribution feeders (representing a different mixture of load classes in the system) to collect disturbance data. Data of load class, load component, and load characteristics would be used to obtain the best estimates of load composition. If appropriate disturbance data are available, then these percentages can be compared with those obtained by measurement-based methods. For example, events acquired on a hot summer day cannot be used to compare the percentage of load components on a cold winter day.

It is also noted that there are some uncertainties due to the time variations in loads as well as the load class and load component data. No matter how hard people try to get the information, they cannot use the two methods to obtain the same answer. Importantly, the results of these two methods have the same order of magnitude and the same trend, and they are consistent with the engineering judgment of power system planners.

6.7.2 Model validation at the system level

Validating any load model at the system level is the ultimate aim of developing load models. The steps involved in the system-wide model validation are as follows:

a) Using DFR or PMUs to collect system event data on one or more EHV buses in the system. These devices are set to collect data for tens of seconds.

b) If a historical event recording is available for a major fault event, at one or more EHV buses in the system. Then by comparing the actual recording with the simulated response, we can gain a better understanding of how accurate the load model is for certain appropriate metrics. The specification for these accuracy metrics, such as the metering index and the required accuracy level, largely depends on the specific load model application. If the measured and simulated responses do not match closely for the chosen metrics, the load model per se needs to be improved. This is an iterative process, which requires engineering judgment. Additional work is needed to obtain the system information, such as the status of generators and other devices in the surrounding area at the time of the event, so that the event can be faithfully represented in the simulation and compared meaningfully with the measured system response.

It is also emphasized that there is variability (i.e., temporal and spatial variations in load due to climate and human behavior) and uncertainty in the load model data in real power systems. On each load bus in the system, it is impossible to match the simulation and measurement data completely, and there may be some errors. This error would be compensated with the increase in the load aggregation level. It is more important to compare the measurement and simulated responses on several EHV buses in the system. If there is a reasonable match between two sets of data/responses, then it shows that the developed load model is suitable for the system. If the matching is not satisfactory, the load model parameters (most likely percentages of static and dynamic load components) would be adjusted as needed.

In the process of model validation, it is particularly important to evaluate its sensitivity to the variation in different parameters. Despite the best efforts in modeling, the characteristics of actual loads make it difficult to eliminate all the uncertainties involved. To deal with these uncertainties, sensitivity analysis is recommended for assessing the impact of model parameter changes on the ability to reproduce actual recorded responses.

The sensitivity analysis can identify the set of key parameters for the study of interest, so that following tuning of load models focuses on refining those key parameters. Generally speaking, sensitivity analysis includes the assessment of the effects of dynamic load components, especially the IM load, in the aggregate load model and the assessment of the effect of changes in motor parameters, such as stall voltage as a function of temperature or motor inertia. Additional analysis may include the sensitivity of load models to self-disconnection and reconnection of some loads, which may have a significant impact on long-term dynamic studies, especially voltage and frequency stability studies.

6.8 Conclusions

This clause provided an overview of the component-based load modeling approach and a series of guidelines with respect to load modeling procedures, load classification, data collection, data cleansing, and data aggregation. Compared with the measurement-based approach, the component-based approach classifies the load at the bulk supply system into different categories, and models the load in individual categories using their corresponding basic load models. The different load categories are aggregated based on the identified load structure to develop the aggregate load model. The main advantage of the component-based approach is the ability to model the dynamic load behavior in response to any system disturbances, while the main disadvantage is its difficulty in obtaining accurate load structure information and handling the spatial-temporal variation in load. Component-based load modeling is generally implemented via four steps, which are data collection, low-voltage load aggregation, network representation, and medium/high-voltage load aggregation.

Data collection serves as the key step that decides load modeling accuracy. The required data for collection is generally the load structure within each load sector or subsector, the load categories and their associated basic load models, and the network data. By conducting end-use surveys, load structure information can be collected and is represented by daily load curves that reflect the temporal variation of the load composition. The load categories are defined based on the data provided in national statistics and associated legislation. The recommended basic load models are small IM model, large IM model, constant impedance load model, constant current load model, and constant power load model. The network data, including the network configuration and network component information, is generally provided by the distribution company and is essential in medium/high-voltage load aggregation.

In low-voltage load aggregation, the various load components need to be converted into the identified load categories based on their electrical characteristics. Guidelines have been provided for the conversion of the typical end-use appliances. The low-voltage aggregate load model is estimated as the weighted sum of different load categories at every 30 min or 1 h. After connecting the low-voltage load model to the distribution or subtransmission network, the *P-V* and *Q-V* characteristics of the load can be investigated via time-domain simulation, which provides a clue for estimating the medium/high-voltage aggregate load model.

The step-by-step recommendations and guidelines provided in the clause could be used by distribution and transmission companies for component-based load model development.

7. Standards and guidelines for load model development in emerging networks and components

7.1 Executive summary

The recent renewed interest in load modeling is also fueled by the appearance of new types of loads, offering increased efficiency and controllability. Different types of modern nonlinear power electronic loads are now responsible for a significant part of the total demand of the residential load sector in many power systems. No widely accepted appropriate aggregated load models are currently available for the correct representation of various directly connected and inverter-interfaced micro- and small-scale distributed generation technologies, which, in some of the future network scenarios, will strongly impact real and reactive power demands, as they will be installed in large numbers.

This clause first provides a critical and updated overview of opportunities and challenges of load modeling with emerging networks and components by considering the smart grid, microgrid, new data sources, active networks/elements, and customer side dynamics. Then, it presents two approaches for development of dynamic equivalents of ADN cells and MGs, namely the black box (ANN based) and gray box (physical) approaches. Considering that this is a new area of power system modeling work with very few reports and research papers available and that currently there are no aggregated models of ADN cells and MGs that are in practical use by utilities, recommendations for development of aggregate models of ADN cells and MGs presented in this clause are based on findings of academic research and corresponding conclusions can be summarized as follows:

a) Both the black box (the recurrent ANN based) and gray box (based to a certain extent on physical understanding of the structure and composition of the network) approaches can be used for development of the aggregate dynamic model.

b) Both derived dynamic equivalent models are in a simple linear or nonlinear form, for example, state space form, which is flexible and compatible with various commercial simulation tools.

c) The input data for both approaches can be either simulated or measured network responses at the boundary buses regardless of the size and complexity of the network.

d) The models facilitate significant simplification of dynamic analysis of large and complex power systems with interconnected ADN cells containing DG of several technologies.

e) A considerable computational effort and frequent user interaction are required to derive the TDNN-based MG dynamic equivalent, which is a very time-consuming task. Moreover, the initial values of both inputs and outputs of TDNN as well as their maximum deviations from the initial values, have to be updated whenever the initial steady-state conditions are changed. The domain of validity of the model is restricted to the test system used to generate the data set.

f) The gray box approach requires significantly less computational effort to develop the model, and the model domain of validity is largely extended.

In addition, accurate representation of aggregate loads for power system analysis requires detailed analysis of the loads connected downstream of the point of aggregation. Although system loads are typically classed in one of the three general load sectors (residential, commercial, and industrial), this is not sufficient to accurately describe the diversity in load structure and load composition, as well as the typical load profiles within each load sector. The general load sectors may be further divided into subsectors, where similar generic aggregate load models can be developed. Therefore, this clause then presents a detailed description of the two most diverse load sectors (classes of customers) that are most likely to undergo biggest changes in load types participating in load class mixture in the future; namely, the commercial and residential load sectors (classes of loads) are described in detail, including all relevant subsectors.

7.2 Overview of the clause

In response to this renewed interest in load modeling, this clause first provides a critical and updated overview of opportunities and challenges of load modeling with emerging networks and components by considering the smart grid, microgrid, new data sources, active networks/elements, and customer-side dynamics. Then this clause presents equivalent mathematical models of ADN cells and MGs suitable for representing ADN cells and MGs in steady-state and dynamic studies of large power networks. It also provides models of different load sectors, also known as “classes of customers” or “load classes”, which are generally defined as an aggregation or collection of different types of loads, or load categories, representing the typical structure and composition of electrical devices and equipment found in a specific end-use application, where similar activities and tasks are performed.

7.3 Overview of opportunities and challenges of load modeling with emerging networks

Large-scale integration of inverter interfaced small generation units with power ratings less than a few tens of kilowatts in LV networks and DG in MV networks calls for the development of equivalent mathematical models of ADN cells and MGs suitable to represent ADN cell and MGs in steady-state and dynamic studies of large power networks. As specific ADN cell and MG properties cannot be adequately modeled using conventional dynamic aggregation methods, this clause suggests exploiting systems identification techniques for this purpose. Two approaches are recommended to derive dynamic equivalents for DNC and MG. The first one is a black-box modeling approach based on ANN that tries to exploit the full response of the MG when excited after a disturbance. The second one is a gay box modeling approach exploiting the physical behavior of the different components of the ADN cell or MG. Recommended equivalent models reduce the complexity of the ADN cell and MG models and make them computationally feasible for application in large power system steady-state and dynamic studies.

Active distributed network cells are the network buses, or parts of the network consisting of several buses, where a significant amount of DG is connected and which at specific periods of time (e.g., at minimum loading conditions) is a net exporter of active power, but at other time periods (e.g., at maximum loading conditions) may be a net importer of active power.

The MG is a particular type of ADN cell. The MG comprises a LV network with loads and several microgeneration systems (with power electronic interfaces) connected to it, and a hierarchical control and management system comprising two main control levels: the local and central, allowing the MG operation to operate as a flexible active cell either when interconnected with the MV distribution network or when isolated from it.

Many DG technologies are based on induction machines or connected to a network through power electronic interfaces and have much different control systems that can be difficult to aggregate (Azmy, Erlich, and Sowa [B4]). Some DG technologies do not have rotating parts such as fuel cells and PV systems. Therefore, the term "coherency" widely adopted by classic reduction methods becomes less meaningful since induction generators do not have synchronizing torques and the power electronic interfaces can almost completely separate the dynamic behavior of the generator from the network, resulting in much different dynamic behavior of DG strongly influenced by the controllers of power electronic converters. Therefore, system identification techniques have spread for deriving aggregated models of complex power systems, including distribution networks integrating large amounts of generation provided from DG units not limited to synchronous generators.

Since ADN cells are no longer passive networks, the DGs have to be also considered in developing equivalent ADN cell models. A reasonable balance between detail ADN cell model and simplified model can be found to avoid computational constraints and to preserve required accuracy. Linearization and model reduction of ADN cell are only appropriate under certain conditions (Shinners [B67] and Tomiyama, Daniel, and Ihara [B74]) as they generally limit the application of the model and render it unsuitable for large disturbance studies (Shinners [B67], Tomiyama, Daniel, and Ihara [B74], and Eurostag [B23]).

System identification techniques in combination with some general knowledge of network structure, if applied adequately, are suitable for ADN cell model development as they rely on actual measured system responses and can be easily validated (Kundur, Balu, and Lauby [B41], Ljung [B44], Coker and Kgasoane [B11], Sarachik [B64], Korunović and Stojanović [B39], and Soliman, Abbasy, and El-Hawary [B68]).

Generally, most of the work done in this area has only considered the static loads as the load models in the dynamic equivalent model of ADN cell (Shinners [B67], Tomiyama, Daniel, and Ihara [B74], Hiskens and Hill [B28], Liu, Chen, and Duan [B43], and Akbaba, Taleb, and Rumeli [B2]).

7.4 Standards and guidelines for load model development for emerging networks and elements

7.4.1 New methodologies for developing load model of emerging networks

As DG proliferates in LV distribution networks, emerging networks such as ADN and MG, which can be a particular subclass of and, have been continuously increased in the power system. The ADN is connected to the system as a net exporter of active power in conditions such as off-peak load periods and as a net importer of active power during other periods, such as peak load periods. MG has high flexibility in energy management that is achieved by a hierarchical coordination of local and central local. In addition, MG can operate with interconnection to the MV distribution network or in isolated mode.

Many DG technologies allow the ADN and MG to operate actively and flexibly. The ADN and MG with various DG units are regarded as active load entities to the power system. The approach based on the identification procedure with ANN and component-based model concept could be employed for the ADN cell modeling.

7.4.2 General framework of system identification approaches

Generally, system identification approaches have the following four steps:

a) Design of the identification experiment
b) Selection of model structure
c) Identification method
d) Model validation

First, the identification experiment with proper excitation signals is required to be designed, aiming to collect a set of data that can assess the behavior of the system. Sampling time and various measurements are required to be defined. With these definitions, data collection progress can be implemented to obtain paired inputs and outputs.

Second, a load model structure is selected considering prior knowledge, engineering expertise, and physical insights about the system dynamics. After the data collection, the relationship between the past and the future outputs, that is, model structure, is required to be determined. Herein, the selection of regression vector and nonlinear mapping play key roles in finalizing the model structure.

Third, the identification procedure is carried out by using the collected data set and the model structure to estimate the model parameters. The outputs of the parameterized aggregated model is compared to the system to be reduced, and an error signal is generated. This error signal is checked by a suitable criterion that assesses the suitability of the aggregated model. The framework of this identification procedure (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]) is demonstrated in Figure 14.

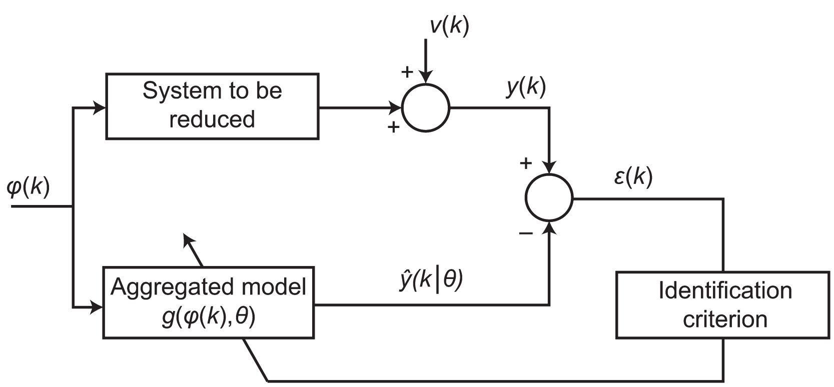


Figure 14—System identification procedure

Last, model validation is implemented to verify the performance of the aggregated model with practical information. The original problem that motivated the load modeling is to be solved with the aggregated model, and the result would be the ultimate validation indicator.

Based on the system identification techniques, an advanced approach called "gray box" is suggested, which can be applied for load modeling of ADN and MG.

7.4.2.1 Gray box approach of dynamic equivalent models of ADN

Based on the assumption of the known structure of the load model rather than on the exact composition of components, a gray box approach is developed to estimate the model parameters. The model structure is expected to express the predominant characteristics of the ADN. In addition, an optimization method can be applied to estimate the mismatch of part of the system. The dynamic equivalent model can replace ADN in large-system stability studies, leading to improved overall accuracy and the reduced order of the simulation model.

The gray box approach applies the system identification method with the assumed load model structure, and it can develop the load model by the following steps.

Step 1: Preparation of data

Many scenarios in different operating conditions, including contingency conditions, are required. They can be generated for each second for different operating conditions; for example, the rate of 10 samples per second is sufficient to extract the simulation data. A higher sampling rate can cause problems such as inaccuracy (Wen, Wu, Nuttall, Shimmin, and Cheng [B78]).

Step 2: Selection of model structure

The ADN dynamic equivalent model would contain various components such as ZIP loads, IMs, and converter-interfaced generators. An example of aggregated load models (Soliman, Abbasy, and El-Hawary [B68]) is shown in Figure 15. This structure is developed based on the following assumptions:

a) The ZIP load model with constant impedance, power, and current replaces the CMLD, presenting the static load part
b) the IM model that is connected in parallel with the ZIP load model accounts for the dynamic load part (Jang, Ahmed-Zaid, Taylor, and Sobajic [B77])
c) the converter-interfaced generator model consists of a full converter model and a third-order generator model
d) both the generator and IM have constant mechanical torques.

The converter-connected generator model can express DG units such as wind turbines and micro-turbines (Yamashita, Asada, and Yoshimura [B80]). In addition, the converter model can preserve the dynamic behavior of the dc-link equation (Xu, Chen, Liu, and Gao [B79]).

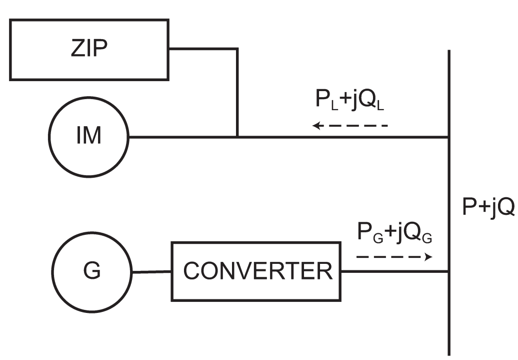


Figure 15—Aggregated dynamic equivalent model

Step 3: Estimation of parameters

For this gray box model, input and output signals include voltage, frequency, real power, and reactive power, and they require preprocessing to filter out the noise first. Second, the preprocessed voltage and frequency are assigned to the gray box model with initial parameters. Then the simulated outputs (real and reactive power) from the gray box model are compared with the preprocessed outputs to generate errors. Last, the errors are checked by a preset criterion for parameter updating, and the updated parameters are used in the gray box model. The procedure terminates until the errors reach the preset threshold. The full procedure framework is illustrated in Figure 16 (Korunović and Stojanović [B39] and Soliman, Abbasy, and El-Hawary [B68]).

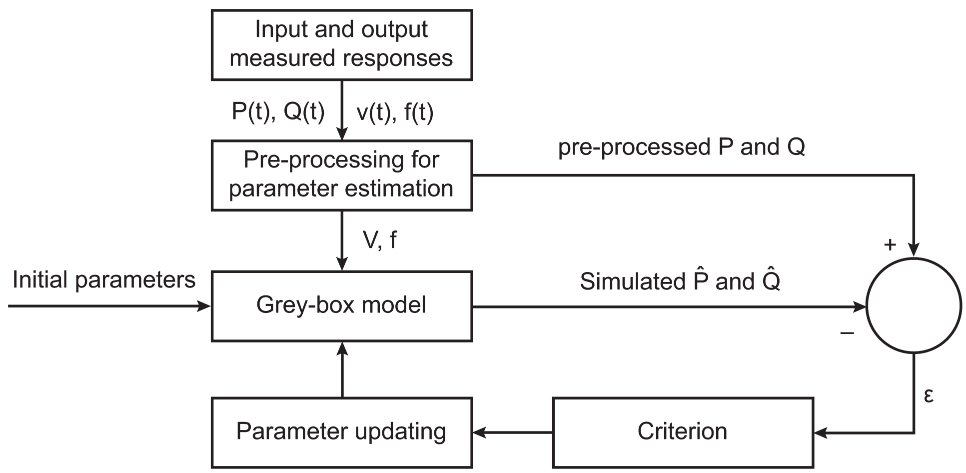


Figure 16—Parameter estimation procedure

Generally, a nonlinear least-square optimization approach is applied to reduce the difference between the physical observation and prediction from the mathematical model. This would help estimate the nonlinear parameters. The nonlinear least-squares problems can be solved by trust-region, Levenberg–Marquardt, and Gauss-Newton algorithms (De Leon and Kehrli [B18]).

Step 4: Model validation

The model validation can be conducted through comparison of the original and simulated outputs of the model. Additionally, the developed dynamic equivalent model can be further checked compared to the responses from the original external system, verifying the accuracy and efficiency.

7.4.2.2 Gray box approach of dynamic equivalent models of microgrids

Similar to the ADN load modeling, a gray box approach based on the known physical structure of dynamic equivalents may be adopted. This approach has an advantage in that the data set requirements are less demanding. The gray box approach can be achieved by the following steps.

Step 1: Selection of physical-based model structure

If knowledge of the specified physical model structure is available, the mathematical formulation of the MG slow dynamic equivalents can be achieved by a continuous state-space model. Some specific physical laws similar to those controlling the active power of diesel units are applied to formulate the MG slow dynamic equivalents (Fletcher and Saeed [B24]). Thus, the model structure parameters can be derived based on physical laws and characteristics. The parameters are required to be estimated in the system identification procedure.

Step 2: Identification method

In this step, EPSO is adopted to estimate the physical-based model structure parameters with sum square error criterion (Shinners [B67]). The EPSO aims to decrease the sum square error by optimizing the parameters. Here, the sum square error can be computed by a suitable evaluation function that can be a cost or loss function. Different from the black box approach, the estimation of parameters is implemented online. Thus, the optimization problem with the criterion is taken into account in the dynamic simulation platform. Additionally, the EPSO algorithm and the dynamic simulation platform are conducted iteratively with model validation involved. The full procedure of the parameterization for the physical-based model structure (Yamashita, Djokic, Matevosyan, Resende, Korunovic, Dong, and Milanović [B81]) is demonstrated in Figure 17.

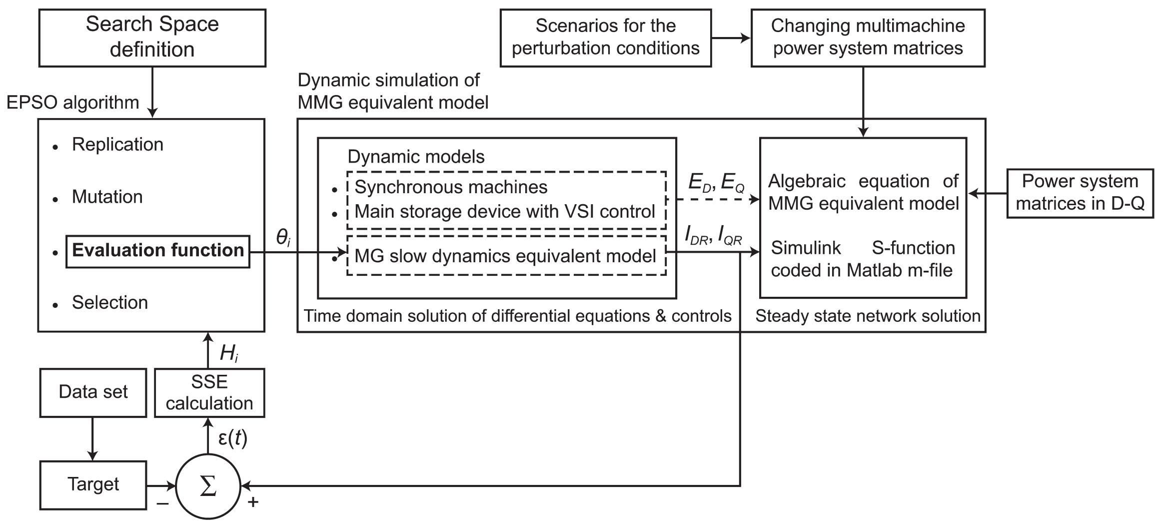


Figure 17—Procedure model structure parameter estimation

The EPSO algorithm is expected to obtain the global or a good local optimum with the sum square error criterion. In this algorithm, after mutation is completed, the evaluation function first delivers the particle object parameters to the MG slow dynamic equivalent model. Second, disturbances are simulated during a certain period. Third, the MG slow dynamic equivalents respond to the disturbances, and the corresponding performance is compared to the target response. Then, the sum of square errors is calculated and passed to the evaluation function. Finally, the EPSO algorithm selects good particles and builds the swarm for the next generation. This iteration procedure would continue unless a termination condition is satisfied.

Step 3: Model validation

Since the system identification is conducted online to estimate the parameters, the model validation is enabled simultaneously with the estimation procedure. By doing so, the poor performance in some models is directly detected, and the corresponding models are eliminated. Furthermore, the MG slow dynamic equivalent model response performance under the disturbances is also assessed as a final validation after the identification step.

7.4.3 Load model development with load sectors

A load sector is defined as an aggregation or collection of various types of loads, and it can efficiently present the typical structure and composition of electrical equipment and devices. By using load sectors, patterns and characteristics of end-user load demand in the same load sector can have the same or similar load models, which help efficiently load modeling for the same load sectors. To improve accuracy of load model development, subsectors are divided from one typical load sector.

To reduce the computational burden of the power system analysis, aggregated load models that represent various loads at a single bus are suggested. The aggregated load models can be developed based on different load sectors. Generally, there are three load sector classifications: residential (or domestic), commercial (or general service), and industrial. This subclause introduces aggregated load models for the residential and commercial load sectors.

7.4.3.1 Residential load sector and subsectors

Individual residential loads are generally similar, but they vary depending on location, size, and type of dwelling.

According to 6.4.1, the residential load sector can be further classified into four subsectors considering the location, size, and dwelling type, that is, highly urban, urban, suburban, and rural subsectors, as shown in Table 9.

Subsector 1: Highly urban residential

The highly urban residential subsector is defined as a metropolitan area that contains high power-density, multistory, flat-type buildings. In these areas, transformers have higher power ratings within the strong and meshed network. Three-phase motors used for lifts, elevators, and central air-conditioning systems only exist in the highly urban subsector rather than in the others, and they are expected to be specially considered. In addition, micro- and small-scale generation technologies and micro-CHP systems also exist, for which particular component models are required.

Subsector 2: Urban residential

The urban residential subsector usually is in a large town with house-type and few-story dwellings. The supplying network is still strong with the meshed configuration. The power density is reduced to a medium level as the distance to the cities increases. In addition, transformer ratings are lower than those in the highly urban subsector. Similar to the highly urban subsector, only micro- and small-scale generation technologies are major concerns in load modeling.

Subsector 3: Suburban residential

Similar to the urban subsector, the suburban residential subsector contains house-type and few-story dwellings in suburban areas out of cities and large towns. In these suburban areas, networks become radial such that the network strength decreases. Power density and transformer ratings also decrease due to the low density of residential housing. Micro- and small-scale generation technologies are still major concerns to be modeled.

Subsector 4: Rural residential

The rural residential subsector exists in remote areas where electricity in house-type dwellings is supplied by weak radial networks. Power density is low, and transformers have low power ratings. Three-phase motors used for horticultural or agricultural activities contribute to this subsector. In addition, medium- to large-scale winds or PV systems are installed such that their characteristics are considered in the load modeling in this rural residential subsector.

The overall load structure of these subsectors is similar except for some three-phase motors. The components of these subsectors are analyzed in Table 9. It is worth noting that the components are similar, but the proportion of these components to make load compositions can be much different.

Table 9—Residential load components

Load type	Load category/subcategory	Residential sector classification			
		Highly urban	Urban	Suburban	Rural
Cooking	Resistive	√	√	√	√
Heating	Resistive	√	√	√	√
HVAC	Directly connected three-phase motors	√	×	×	×
	Directly controlled three-phase motors	√	×	×	×
ICT equipment	SMPS	√	√	√	√
Interior lighting	GIL	√	√	√	√
	Energy-efficient lighting-CFL and LFL	√	√	√	√
Lifts/elevators	Three-phase motors	√	×	×	×
Power electronics	SMPS	√	√	√	√
Refrigeration	Single-phase motors	√	√	√	√

Two peaks in residential sector loads are predominant. One is in the morning before the population majority goes outside to work, while the other one is in the late afternoon and early evening after the population majority comes back to homes.

Daily and seasonal variations also can be taken into account. Daily variations mainly occur between weekdays and weekends/public holidays, and they are mainly dependent on dwelling occupancy difference. Additionally, seasonal variations are obvious with comparison between winters and summers. In winters, heating, lighting, and cooking devices take longer and require more power, while the air-conditioning and refrigerator consume more power in summers.

7.4.3.2 Commercial load sector and subsectors

Depending on the service types, the commercial load sector has more subsectors that have different devices and load compositions, and these subsectors are shown in Figure 18. The commercial subsectors can also be defined based on the building size (small, medium, and large). However, the commercial loads are more various locations than the residential loads such that the subsectors are not defined with locations.

Different subsectors classified according to service types are summarized as follows.

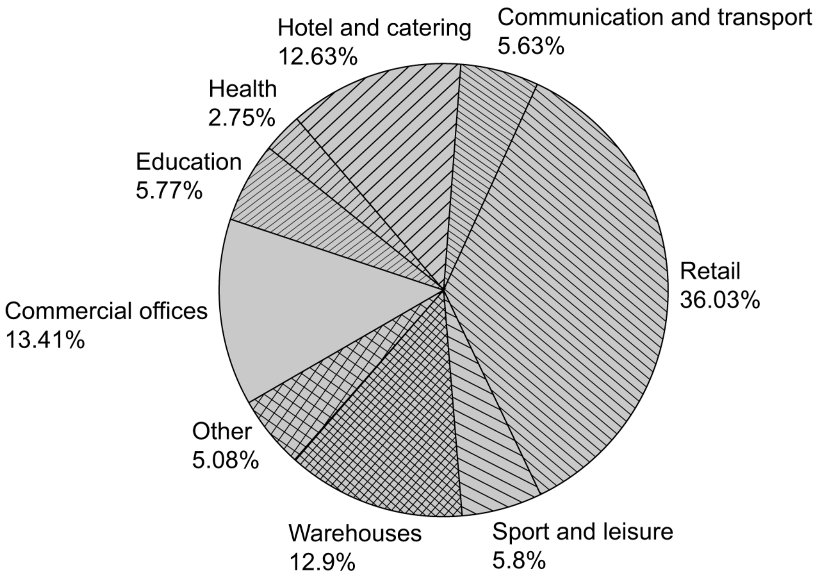
Subsector 1: Commercial office

Load variety among different building sizes is obvious. Large commercial buildings contain three-phase heating, HVAC units, and lifts, but small and medium ones do not. In addition, large commercial buildings have much higher power density. In addition, electricity consumption percentages of the power electronics and ICT devices increase as the building size increases.

Peak load hours depend on the opening hours, and during the night hours, there is still a base load made by ICT and lighting devices. Seasonal variations for the commercial office subsector are smaller except for the small offices that do not have air-conditioning systems.

Subsector 2: Communication and transportation

The communication subsector includes post, media, and courier service departments. These load models are similar to the commercial offices, and so are their load trends.



Reprinted with permission from CIGRE Technical Brochure 566 [B49].

Figure 18—Subsectors and their electricity consumption percentages

Load models for transport services such as railways, taxis, buses, and air transport have much different load behaviors. One difference is outdoor illumination, which takes more power consumption. In addition, the large transportation subsector usually has three-phase HVAC equipment.

Large transportation subsectors for bus/railway/metro stations and airports have little daily variation due to all-year opening hours. But seasonal variations impacted by the lighting power consumption are significant. In addition, the transportation subsector takes into consideration the holiday impacts.

Subsector 3: Education

Most load devices of the education subsector are the same as those with commercial offices. However, for universities, large three-phase equipment for experiment use, which is connected to higher voltage levels, is expected to be carefully considered. It is also possible to install CHP systems in the large education subsector.

The weekday case of the education subsector is similar to that for commercial offices. But it is worth noting that the schools and universities have significant longer holiday periods. During these periods, the load demand is extremely reduced, and the variation compared to study periods is very large. Seasonal variations would also be considered.

Subsector 4: Health

The health subsector has two facility types, namely, local health facilities (doctor and dental surgeries) and regional ones (hospitals and clinics).

Local health facilities have normal devices like power electronics, motor, interior lighting equipment, and special medical equipment. They have similar variations compared to commercial offices. Seasonal variations also depend on heating and HVAC systems.

For the regional health facilities, three-phase supply for high-power special medical equipment is required and some on-site CHP systems and stand-by generators can also be applied. As they are open 24 h, night lighting and critical medical devices are usually used as base loads.

Subsector 5: Hotel and catering

The hotel and catering subsector can contain few-story small buildings and high-density, multistory, large buildings. Herein, the large buildings are expected to contain three-phase motor loads.

The hotel and catering subsector has specific variations that are impacted by the business nature, such as tourism season. In the tourism peak season and the weekends, power consumption obviously increases.

Subsector 6: Retail

Normal business retail loads include small shops and shopping centers. For the shopping centers, power consumption from outdoor illumination like in car parks would be considered. Moreover, retail food shops are a specific type due to their high concentration of lighting, cooling, and cooking.

The daily variations are still dependent on opening hours, and the seasonal variations depend on HVAC system use, lighting in winters, and refrigerator use in summers.

Subsector 7: Sport and leisure

The sport and leisure subsector have two types, namely, public/community recreation facilities and sport stadiums. The device types in these two facilities are similar, but the power consumption percentages are different. Compared to other subsectors, lighting in sport and leisure buildings takes the dominant load demand. In addition, HVAC use difference is significantly large for the different sizes of the facilities.

The load trend of the sport and leisure subsector is similar to that of the retail one but with longer opening times in the evening. Additionally, variations are also dependent on events during specified periods.

Subsector 8: Warehouse

The warehouse subsector may require devices to control the storage environment for the nondurable goods. For these warehouses, refrigeration devices are required and take large power consumption. In addition, the warehouses may have transportation facilities, which is expected to be considered.

Similarly, daily variations depend on opening hours. But variations of the warehouses with environment control are much less. Seasonal variations depend on heating, HVAC, and lighting demand in different seasons.

7.5 Conclusions

This clause first provided a critical and updated overview of opportunities and challenges of load modeling with emerging networks and components by considering the smart grid, microgrid, new data sources, active networks/elements, and customer-side dynamics. Meanwhile, large-scale integration of inverter interfaced small generation units with power ratings less than a few tens of kilowatts in LV networks and DG in MV networks calls for the development of equivalent mathematical models of ADN cells and MGs suitable to represent ADN cell and MG in steady-state and dynamic studies of large power networks. As specific ADN cell and MG properties cannot be adequately modeled using conventional dynamic equivalencing methods, this clause suggested exploiting systems identification techniques for this purpose. Considering that there is no current industrial practice on development or use of this type of aggregate model, the recommendations made in this clause were limited to academic research experience. Two approaches were recommended to derive dynamic equivalents for ADN and MG. The first one is a black box modeling approach based on ANN that tries to exploit the full response of the MG when excited after a disturbance. The second one is a gray box modeling approach utilizing the physical behavior of the different components of the ADN cell or MG. Finally, the clause also provided standards and guidelines for load model validation for emerging networks and elements.

In addition, accurate representation of aggregate loads for power system analysis requires detailed analysis of the loads connected downstream of the point of aggregation. Although system loads are typically classed in one of the three general load sectors (residential, commercial, and industrial), this is not sufficient to accurately describe the diversity in load structure and load composition, as well as typical load profiles within each load sector. The general load sectors would be further divided into subsectors, where similar generic aggregate load models can be developed. Therefore, this clause then presented a detailed description of two diverse load sectors (classes of customers) that are likely to undergo the most significant changes in load types participating in load class mixture in the future; namely, the commercial and residential load sectors (classes of loads) are described in detail, including all relevant subsectors.

8. Standards and guidelines for power system simulations with various load models

8.1 Overview of the clause

The behavior and performance of load modeling during steady-state and emergency conditions draw major importance in planning, controlling, and operating systems. However, the simulation environments are still far from real-world situations, and their results are not close enough to online operation results.

With the advantages of rapid speed and low cost, simulation is still a necessary means for stability, reliability, and performance of components, although the performance of some power system components such as solar panels and wind turbines is not yet well understood.

Simulation models include polynomial models, exponential models, ZIP models, generic dynamic models, physically based models, and equivalent circuit models, which could be identified by load surveys, system tests, field tests, and natural disturbances.

By installing data-acquisition systems, developing modeling and identification methodology, and creating specific models, it was discovered that it is impossible to identify load models with any consistency. Due to this circumstance, load models derived from small disturbances causing limited voltage magnitude changes cannot be applied with any confidence to situations involving severe disturbances.

This clause briefly describes the simulation carriers, simulation models, and simulation environments, along with data treatment and analysis.

8.2 Overview of power system simulations, both steady-state and dynamic

8.2.1 Objectives and motivation

The objective of the power system simulations here was to develop techniques for developing load models during natural disturbances and staged evaluations. The acquired models are to be used in power system simulation studies, both for dynamic and steady state (Ellis, Kosterev, and Meklin [B20]).

Various types of load models have been created and tested through software-based simulation over the years.

8.2.2 Load model requirements and approach

This approach consists of the following steps:

- Development of a data-gathering system
- Load model development
- Preliminary load model identification using conventional techniques

These will be briefly described as follows.

Step 1: Data gathering

Data gathering systems were installed at different levels in the systems with representatives of commercial, commercial/industrial, and residential devices, respectively. Several other locally available meters were used to record data during staged tests.

Step 2: Load model development

The subject of load modeling and load model identification has long been an area of active research. Various studies have been applied, and simulation results with different load models have been analyzed. The ZIP model is one of the most widely used load models. The methods for determining the parameters in these load models can be broadly classified as those based on measurements and those based on end-user survey data.

The physically based model, formally proposed by Liu, Chen, and Duan [B43], or an analytical model derived from a physically based model is intuitively the most appealing.

In this work it applies a physically based model as described in the previous clauses. The model predicts the real and reactive power variation for each phase of a feeder in terms of the real and reactive power drawn by the physical components connected to the model.

The dynamic response of each component to a change in voltage is assumed to be generically aware.

Step 3: Model identification

The model identification setting is as follows. With the voltage profile, according to the time from evaluation or a disturbance, the assumed component models can be used to develop the response of each component. Treating these as "observations," the problem is to determine the composition coefficients so that the time profile of the load matches the measured profile.

There are two valuable goals and objectives of load models that lead to a trade-off, as follows:

- The model needs to be as simple as possible for practical implementation.
- The model needs to be accurate for credible scenarios other than the test data.

The last requirement implies that physical models are preferred. If representing the voltage- and frequency-dependent load behavior is the primary purpose, static models with various complexities are frequently used. Most commonly used models are reviewed in this clause.

Static model

There are two general structures of these models, referred to as "polynomial" and "exponential". Static load models are adequate for modeling loads that exhibit a single step change in power or no change at all in case of constant power loads following the change in voltage or frequency at the bus. There is no time-dependent evolution in real and reactive power responses following the initial voltage/frequency change. The detailed model (IEC 61000-3-12 [B31]) is outlined in 4.2.1.

Dynamic model

The dynamic load models include traditional motors, tap changers, and static loads. General models of these components are often applied to augment the ZIP models. Alternatively, a generic dynamic model may be used (Taylor [B72]). The detailed models can refer to 4.2.2.

CMLD

A model of an aggregate load, in which both steady-state and dynamic load components are included and classified, both influence the load dynamics (Siemens [B65]).

8.2.3 Suitable application scenarios of different load models

Table 10 exhibits application scenarios with suitable load models.

Table 10—Suitable application scenarios of different load models

Load model	Application scenarios		
	Residential load	**Commercial load**	**Industrial load**
ZIP	X	X	X
ZIP + motor	X	X	X
Exponential load model	X	X	X
Linear load model	X	—	X
Linear load model + polynomial model	X	—	X
Exponential dynamic load model	X	—	X

8.3 Standards and guidelines for system simulation with conventional load models

8.3.1 Identification of load model parameters

There have been some major efforts to derive load model parameters at the transmission level. Two basic approaches have been used: component or class aggregation and modeling from measurements.

It has improved the accuracy of system studies under disturbance conditions. However, model parameter identification is a costly endeavor, and it often yields inconsistent results. The critical perceptions toward the load model parameter identification are as follows:

- The demand varies from time to time. Selecting a particular load level for a study is equivalent to fixing the operating point in power systems. Results of system studies may vastly vary depending on the operating point, especially in heavy load conditions.
- The load structure is complex in nature. As more loads are aggregated, it becomes increasingly difficult to recognize individual load components from measured data since the load response reveals little detail about the load structure.
- Generally speaking, only simple load models can be used at all nodes in subtransmission and transmission grids. In these cases, we can only justify identifying simple load structures such as exponential models. Since these models are not physical, there is no guarantee that they are applicable in general at the feeder level in distribution grids. The load response to disturbances contains more information about the load content. Therefore, collecting more disturbance event data is essential to derive more reliable load model parameters.
- The data available are often insufficient, unreliable, or inconsistent. Unavoidably, this uncertainty carries over to the resulting load model constructed.

8.3.2 Combined measurement and component-based load modeling approach

One of the challenges in the load modeling work lies in the wide spatial distribution of the load structure. Using one single load model is obviously inappropriate in a bulk power system since the load characteristics are very different depending on locations. It seems more reasonable to build the individual load model at each load bus using measured data. However, it is impractical for the bulk power system that comprises enormous load buses. If the disturbance recorder is installed at each load bus, it would require immense investments and cause difficulties in updating and maintaining the parameter database of the load model.

A solution to this problem is to combine the measurement-based load modeling method with the component-based method. First, the component-based load modeling method is applied at the system level, and the information on the load classes is obtained from the system operators. In general, the load buses comprise five load classes, which are industrial, agricultural, commercial, residential, and others. Some load classes may be subdivided if more detailed characteristics are necessary. For example, the industrial load class can be further divided into the light industry, heavy industry, and so on. After taking into account the influence of seasonal changes on loads, 10 clustering indices were adopted, that is, maximum summer and maximum winter load proportion with the five load classes, respectively. Based on the load composition data, the load buses can be clustered. Various clustering algorithms, such as the fuzzy clustering technique, are available. Based on the load clustering results, the load bus close to the cluster center in each cluster group would be chosen as the typical load bus.

Then the measurement devices are deployed at the selected representative load buses. The measurement-based load modeling methodology is then applied to build the load model for the above load buses, which takes the same procedure as stated earlier. The built load model is expanded to all the other load buses in the same cluster.

The model validation work is necessary, which consists of two levels. At the local level, the measured load dynamics are used to check whether the load model built on the measurements can describe the load dynamics. In contrast, on the system level, the simulations on the whole system, including the load models on all the load buses, is made to check whether such load clustering is appropriate to reflect the system dynamics. The load model validation may be combined with the sensitivity analysis to adjust the load clustering, if necessary.

8.3.3 Data requirements for identifying load structure and load composition

The development of accurate aggregate load models for every load sector and load subsector requires either extensive long-term and wide-scale measurement campaigns or access to the representative and detailed statistical data. The data to be collected are usually related to active and reactive power demands of the aggregate with a certain resolution—typically 30 min or 60 min intervals, but sometimes shorter intervals are required.

If measurements with sufficient processing, storage, and metering resources are available, instantaneous current and voltage waveforms may be used to identify the actual load composition/mixture, using various noninvasive approaches. It is crucial for component- and measurement-based modeling approaches to allow the inclusion of hourly, daily, weekly, and seasonal variations in the final aggregate load model.

8.3.4 Main load modeling categories

Publicly available electricity consumption statistics usually divide loads into groups, based on the specific end use of electricity, or actual tasks and activities performed in a given load sector. However, this is not always a suitable categorization/classification of loads. From load modeling perspectives, loads are grouped into load modeling categories, based on the similarity of their electrical characteristics and/or circuit topologies, rather than on specific end-use applications. This approach allows using the same load model to represent different electrical equipment and devices in the same load category.

Practically all types of electrical equipment and devices that can be found in residential and commercial load sectors can be divided into the five following general load categories:

— Resistive loads
— Single-phase and three-phase induction (i.e., directly connected) motor loads

- DC power supplies, or SMPS loads
- Energy-saving lighting loads, consisting of compact fluorescent lamps and LED light sources
- Single-phase and three-phase drive-controlled (i.e., inverter-interfaced) motors, or adjustable speed drive loads

In addition to the loads, and as a part of the aggregate LV network/load representation, some micro- and small-scale distributed generations, such as PV and wind, are connected in parallel to the LV loads within the end-user's premises. On the other hand, medium- and large-scale distributed generating units are generally connected to the medium and higher voltage levels.

Load models of resistive and IM load categories are commonly available in the existing literature and easily implemented as they draw continuous sinusoidal currents from the supply. Accordingly, they can be accurately represented using the standard steady-state and dynamic load model formulations. The three other load categories, however, represent nonlinear power electronic equipment, which requires different load models and simulations with a shorter timestep for accurate representation. The fraction of loads in these categories have increased significantly in recent years, and their aggregate models for the use in power system studies and analysis are missing in the existing literature. Additionally, the influence of harmonic legislation, differences in technologies, and circuit topology variations effectively introduces several subcategories within each category of these loads.

An overview of the load categories with further details are described as follows.

8.3.4.1 Identification of load structure and load profile

It is generally possible to obtain information on load structure and composition from the measured data. However, the energy consumption of LV customers is not currently widely measured or available. This situation may change in the future when recordings and data collected from so-called "smart-meters" (that are recently being deployed and implemented or are planned to be deployed in high numbers) can be used for that purpose. It also enables the acquisition of wide-scale measurements in LV customers and, in this way, makes measured data available for improved load modeling. However, it is still uncertain whether instantaneous current and voltage are measured, or the operation of individual equipment is monitored, which is critical to determine structure and composition of the modeled load accurately.

Information on aggregate demands and load profiles is, generally, easy to obtain, as power flows are widely recorded in power systems. Often, these data are only recorded at higher voltage levels, with the lowest wide-scale measurements typically recorded at MV bulk load supply points. Therefore, these measurements represent an aggregate mixture of discussed load sectors and subsectors. Sources of load profile data include government-level reports, research organizations, or distribution companies. The ideal data resolution is 30 min or shorter, to match generator scheduling/balancing conditions, but it is suggested to be in no longer than 1 h.

If obtained from statistics, load information is usually given per "end-use load types" and can be further processed to build an aggregate load model.

8.3.4.2 Network configuration

Data on the network configuration and network component values for the modeled sector/subsector are collected and used to build a network model in suitable power system simulation software.

8.3.4.3 Connection of low-voltage aggregate model to network

The low-voltage aggregate load model is then connected at the designated load bus in the network model.

8.3.4.4 Formulation of medium-voltage aggregate load model

The low-voltage aggregate load is then used to create the medium-voltage aggregate load model. This model can be generated by increasing/decreasing the aggregate demand while keeping the load mixture the same to instigate changes in the load bus voltage, or by changing the load bus voltage with the step-down transformer. The changes in active/reactive power demands at the MV bus expressed as a function of voltage are then used to formulate the MV aggregate load model.

8.3.4.5 Simulation environment

8.3.4.5.1 Load characteristics

Load characteristics and load shedding models may be introduced as a subsystem. Subsystems can be designated as a bus, owner, zone, area, or all. Each load model is available as a family of models, one for each subsystem type. For example, the IEEE load characteristic model is available in five forms, as shown in Table 11.

Table 11—Load models

Subsystem type	Model name
Bus	IEEBL
Owner	IEELOW
Zone	IEELZN
Area	IEELAR
All	IEELAL

These models are collectively referred to as the "IEEL-type models" or as the "IEELBL family of models." The last two characters of the model name refer to the subsystem type. This convention is applied throughout the load model library.

Load-type models employ data sharing among the loads for which a model is applied. That is, one set of CON and ICON data is used for all applications of the model. However, if required, VAR, STATE, and reserved ICON space is allocated for each load to which the model is applied. In other words, VAR, STATE, and reserved ICON data are unique for each instance of the model's application. For example, if the user enters one CIM5BL model data record (IM model) with a wildcard load identifier, specified for a bus with three loads, then the model is applied to all three loads. Space is reserved for only one set of CON and ICON data, as that data are shared among all applications of the model. However, space will be reserved for three sets of VARs, STATEs, and reserved ICONs, one for each application of the model.

For each load, there is one available slot for a load characteristic model and one available slot for a load shedding model. That is to say, it is not permissible to apply more than one load characteristics model or more than one load shedding model to the same load. When the simulation tool runs with a dynamic file, and a load record is encountered in which the subsystem is not found, this record is ignored with no printed message, which is consistent with how machine models are handled if the machine does not exist.

Basic considerations

The package recognizes three fundamental algebraic loads versus voltage characteristics in its power flow database. These characteristics, that is, constant MVA, constant current, and constant impedance, are carried through to dynamic simulation. Activity CONL may be used either in power flow work before initialization of dynamic simulation or during dynamic simulation work, to change the mixture of the three fundamental components in the loads. These components, while useful in the absence of better information, do not always give an adequate characterization of a system's load versus voltage characteristic. They cannot recognize the dependence of load components, other than constant admittance, on bus frequency.

More detailed load versus voltage and bus frequency characteristics are handled by a set of load models that participate directly in the network solution at each time step. All of these models determine the values of load current based on local bus frequency, voltage, and the algebraic or dynamic characteristics of the model. All models, except the LDFR type models, will replace the characteristics of ALL components of load at loads for which the models are applied. The model's initial load level is determined by first reconverting all load components to constant MVA.

Complex models

The CLOD type of models replace the ZIP load with a composite load consisting of IMs, lighting, and other types of equipment as shown in Figure 19. It is intended for use in situations where it is desirable to represent dynamic load behavior without detailed dynamics data, as distinct from the algebraic characteristic level used in power flow. The models allow the user to specify a minimum amount of data stating the general characteristics of the composite load. It uses these data internally to establish the relative sizes of motors modeled in dynamic detail and to establish typical values for the detailed parameter lists required in the detailed modeling.

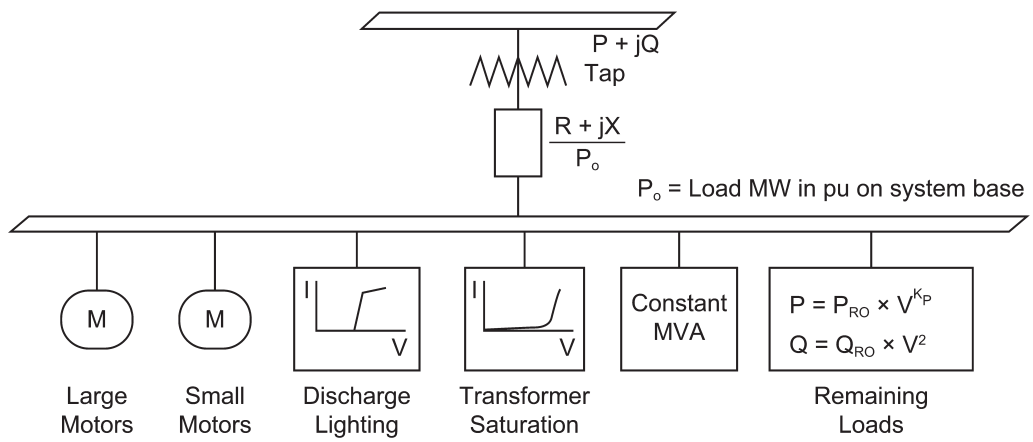


Figure 19—Complex load model

The models assume that all load components are connected at 0.98 per-unit voltage. At initialization, a tap is calculated to obtain that voltage based on the load and voltage shown on the connected bus. A user may add a specific distribution transformer impedance or distribution line impedance, inputting R and X values in the appropriate CONs. The load on the bus is then split according to the percentages given by the user.

The distribution network between the supply point and the load is not modeled explicitly in the power flow. The CLOD type models enable representation of the transformer current if the user wants to represent the saturation effects of distribution transformers. The discharge lighting part of the load is handled as follows:

a) Real part of load as the constant current.
b) Imaginary part of load as the voltage raised to the 4.5 power.
c) For voltage between 0.65 and 0.75 per unit, as step 1) and step 2) times a linear reduction.
d) For voltage below 0.65 per unit, the lighting is assumed to be extinguished (i.e., no load).

CMLDs

A new composite load, CMLD, has been developed to simulate the dynamic behavior of an aggregate of three-phase motors, a single-phase air conditioner motor, electronic loads, and static loads connected to a low-voltage load bus. The dynamic response is reflected in the high-voltage system bus. In addition to representing the mixture of loads at the low-voltage bus, this model also includes an equivalent circuit of distribution transformer, substation compensation, distribution feeder equivalent, and feeder compensation. The structure of the new CMLD, CMLDBL, is shown in Figure 20.

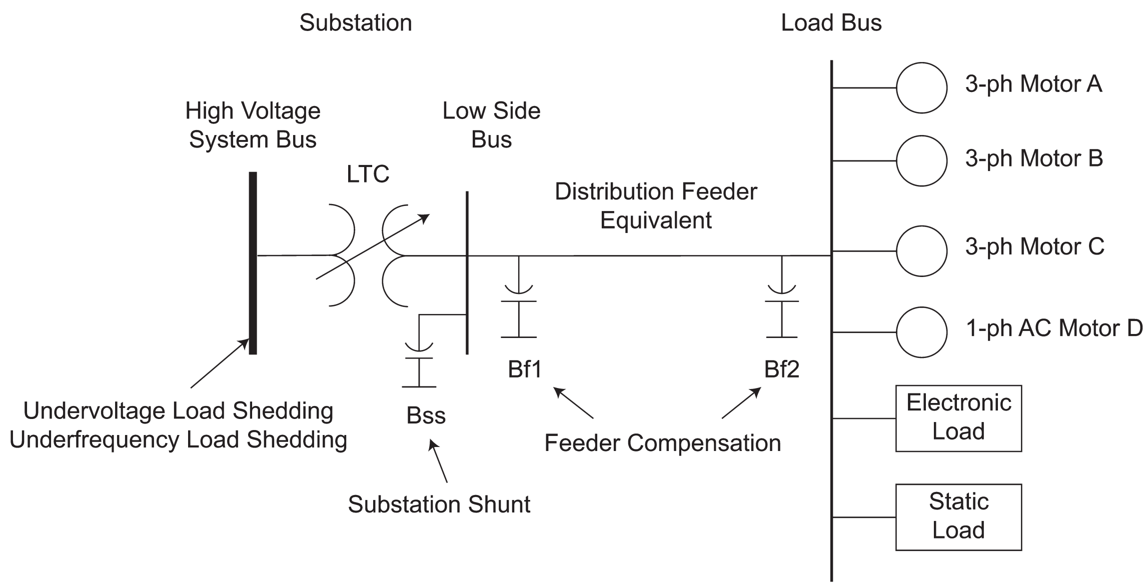


Figure 20—Structure of CMLDBL

The main components of CMLDBL are as follows:

a) Substation transformer with load tap changer control
b) Substation shunt
c) Distribution feeder equivalent
d) Feeder compensation
e) IM loads
   1) Up to three different types of three-phase IMs with built-in protection
   2) Single-phase air conditioner compressor motor with built in protection
f) Electronic loads
g) Static load
h) Load shedding

The electronic load component model is defined by the following parameters:

— Power factor, PF_{el}
— Voltage drop out values, V_{d1} and V_{d2}

The electronic load model varies the load as a function of voltage

— Constant P,Q down to $V = V_{d1}$
— P,Q reduces to zero linearly between V_{d1} and V_{d2}

Static load fraction F_s is computed as in Equation (54).

$$F_s = 1 - F_{mA} - F_{mB} - F_{mC} - F_{mD} - F_{el} \tag{54}$$

where

F_{mA}, F_{mB}, F_{mC}, and F_{mD}	are the motor load fractions A, B, C, and D, respectively
F_{el}	is the electronic load fraction

The static load component model is represented in Equation (55) and Equation (56).

$$P = P_0 \left[P_{1c} \left(\frac{U}{U_0} \right)^{P_{1e}} + P_{2c} \left(\frac{U}{U_0} \right)^{P_{2e}} + P_3 \right] (1 + P_{frq} \Delta f) \tag{55}$$

$$Q = Q_0 \left[Q_{1c} \left(\frac{U}{U_0} \right)^{Q_{1e}} + Q_{2c} \left(\frac{U}{U_0} \right)^{Q_{2e}} + Q_3 \right] (1 + Q_{frq} \Delta f) \tag{56}$$

where

P_0	$= P_{load} F_s$
Q_0	$= P_0 \tan(\arccos(PFs))$
P_3	$= 1 - P_{1c} - P_{2c}$
Q_3	$= 1 - Q_{1c} - Q_{2c}$
PFs	is the power factor
P_{1e}, P_{2e}, Q_{1e}, and Q_{2e}	are voltage exponential parameters
P_{frq} and Q_{frq}	are frequency sensitivity parameters
Δf	is the change of frequency

8.3.4.5.2 DSA Tools

DSA tools support a versatile load model. This subclause describes this load model and its data format. Load models with mixed formats cannot be used for a specific bus.

However, it is possible to use models for loads at some buses and third-party models for loads at other buses in a system. Note that in addition to the load models written here, synchronous motor models are also available.

a) Application notes
   1) Load ID matching
   2) Each load model can be specified at load buses for either a particular load component (identified by a load ID in the power flow data) or the entire consolidated load at the buses.

b) Application precedence

1) CMLDs can be specified for loads at individual buses, in zones, areas, or the entire system.

2) If a load is covered by multiple model specifications, the load netting rules are applied to determine the appropriate model.

3) If a load is not covered by any static load components, the default model case file is used for any load not covered by motor models. If the static load component definition in a CMLD is incomplete and is not equal to 100, then the static load component is ignored and the default model is applied.

8.4 Standards and guidelines for system simulation with emerging networks and elements

8.4.1 HVDS/VFD loads

This type of load is modeled by a solid-state converter, which supplies variable-frequency power to a motor load. The fundamental power factor is near unity, regardless of the voltage magnitude, so long as the voltage is not too low.

This type of load is commonly found in commercial and industrial heating and ventilation equipment. For simulation purposes, the simple model can be used. While the initial response is approximately constant current, the real power demand is constant in the long term. The model of HVDS/VFD loads is represented as the following transfer function in Equation (57).

$$\frac{P(s)}{V(s)} = \frac{s}{s+0.3}, Q = 0 \tag{57}$$

8.4.2 Electronic load

Electric loads include all electronic equipment with internal power supply. The fundamental power factor is near unity. Both real and reactive power is modeled as constant, for example, $P = 1$ and $Q = 0.1$, while the voltage is not too low. If the voltage falls below 0.9 p.u. or so, their real and reactive power can reduce linearly and the loads may drop out. The characteristics of electronic loads can be described as follows.

The electronic load component model is defined by the following parameters:

— Power factor, PF_{el}

— Voltage drop out values, V_{d1} and V_{d2}

The electronic load model varies the load as a function of voltage:

— Constant P,Q down to $V = V_{d1}$

— P,Q reduces to zero linearly between V_{d1} and V_{d2}

8.4.3 Aggregated wind farm models

A comprehensive literature overview of the modeling of the individual wind turbine generator and other distributed generation technologies is given. This subclause focuses on aggregated models of wind farms only. Depending on the nature of the studies and assumptions made, different aggregation approaches can be used.

The ultimate simplification is the aggregation of the entire wind farm into an equivalent wind turbine generator. Method 1 assumes either the same wind incident on all wind turbine generators or average wind incidents on individual wind turbine generators, which is applied to the aggregated model of the wind farm. The generator rating is scaled, and the rest of the individual wind turbine generator parameters remain unchanged in per unit on an aggregated machine base.

Method 2 is aggregating the wind turbine generators into groups. Wind turbines with similar input wind speeds can be grouped and represented by an equivalent wind turbine generator. Grouping can also be applied if the same or similar wind turbine generator technologies are used within a particular wind farm. Wind turbines with similar technology can be aggregated as an equivalent wind turbine generator.

To reflect different wind speeds in a wind farm, the mechanical system can be modeled separately for each wind turbine generator (Method 3). In contrast, the generator and electrical control system, such as converter controls, can be aggregated into its equivalent representation.

Methods 2 and 3 have an advantage of simulating fluctuation of the wind turbine generator speed more accurately, which may be necessary if overspeeding due to faults leads to individual wind turbine generator disconnection.

For planning studies involving future wind turbine generators, whose capabilities are still unknown or need to be defined, the most conservative assumption is a strict fulfillment of the grid code requirements.

For this type of system study, it might be sufficient to simply emulate the performance of a wind farm at the grid connection point, based on the different wind turbine generator technologies and their technical capabilities, such as LV fault ride through, reactive current support during faults, synthetic inertia, and so on, under grid code requirements.

It is assumed that individual wind turbine generator parameters are provided in the machine base per unit. This type of model is not component based but performance based.

A further consideration in aggregated modeling is the representation of the wind farm cable network. This reactance is placed in series with the wind farm transformer. The magnitude of the reactance is much smaller than that of the leakage reactance of the wind farm transformer. Therefore, it may also be neglected without deteriorating accuracy.

8.4.4 Equivalent models of microgrids

A large deployment of active distribution network technologies allows new system concepts to be implemented, such as the smart grid and microgrid concepts. Nowadays, microgrid has become a popular concept under the framework of setting up smart power grids and is used in many ways to describe the concepts of managing demand and supply at the distribution level. This is a broad definition also addressing the advanced metering infrastructures, demand response, energy efficiency, and the trend toward decentralization of the generation with the effective deployment of distributed generation and storage devices. The microgrid can be implemented by different owners to meet different objectives. Industrial and commercial users might implement the microgrid to provide cost-effective combined power and heat generation or for assuring them of a supply that meets their demanding specifications that cannot be realized by the utility grid. Government entities are especially interested in the microgrid to provide resiliency and security of the electricity supply as essential services, exploiting the microgrid capability to island from the utility. Therefore, there is not a single microgrid definition. Some authors discuss microgrid in terms of the residential-sized system while others discuss them as community-wide systems sharing, however, the following common features:

A microgrid is a localized group of electricity sources and loads operating interconnected to and synchronous with the traditional centralized utility grid. However, the microgrid can be isolated from the main grid and operate autonomously as physical islands in emergency conditions or when justified by market conditions, providing a way to improve the grid reliability and to reduce the dependency of long-distance transmission networks. IEEE Std 1547.4 [B32] provides alternative approaches and good practices for the design, operation, and integration of distributed generation islanded systems. It also addresses the ability to disconnect and reconnect to the primary grid.

The capability to control the balance of local demand and supply to achieve stable energy supply to the power consumers served by the microgrid according to their own requirements, regardless of whether the microgrid is connected to the main grid or operated autonomously, is also demonstrated.

8.4.5 Single-phase air conditioner load model

Motor D in CMLD is the single-phase air conditioner load. These motors stall when voltage drops below a set value, and a portion of these motors restart when voltage recovers. It is represented by a user-defined model. Some of the main features of the single-phase air conditioner load model are as follows:

a) Stall characteristics

   if $V < V_{stall}$ for T_{stall} sec

b) Restart characteristics

   if $V > V_{rst}$ for T_{rst} sec, F_{rst} fraction of motors restart

c) Undervoltage trip

   if $V < V_{tr1}$ for T_{r1} sec, F_{uvr} fraction trips

   if $V < V_{tr2}$ for T_{r2} sec, F_{uvr} fraction trips

d) Contactor

   trips linearly between V_{c1off} and V_{c2off}

   reconnects linearly between V_{c2on} and V_{c1on}

e) Thermal protection

   trips linearly between Th_{1t} and Th_{2t}

f) Real-time digital simulation

   1) Advantage of real-time simulation
      i) Parallel processing required for practical systems
      ii) Calculations completed in real world time, less than the timestep
      iii) Every timestep has the same duration and is completed in real-time
      iv) The I/O is updated at a constant period equal to the time step
      v) Real-time measured by counting clock cycles

   2) Advantage of hardware components
      i) Connects parallel processing hardware to computer workstation via Ethernet LAN
      ii) Provides communication to load, start, stop the simulation case
      iii) Enables user interaction with the simulation
      iv) Provides data exchange coordination and data record capability
      v) Direct fiber-optic connection to up to six other racks
      vi) Additional communication ports for interprocessor data exchange

vii) Increased network solution and component modeling capacity

viii) Function defined by software

3) Closed-loop testing

The difference between open-loop and closed-loop testing (take relay tripping as an example) is shown in Figure 21.

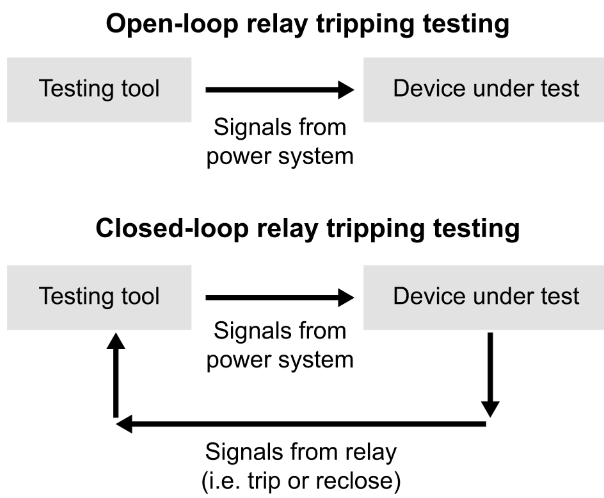


Figure 21—Comparison between open-loop and closed-loop testing

4) Real-time digital simulation power system solution process

i) Convert the user-defined power system to the equivalent network of only current sources and resistors

ii) Formulate conductance matrix for the equivalent network

iii) Using data from the previous timestep (or initial conditions for the first time step), compute new step i) values

iv) Solve for step v) using new values of step i)

v) Calculate branch currents with step v) and step i)

8.5 Case study

This case study shows the load modeling process of a 66 kV substation in Australia by incorporating the simulation tool for fitting the modeling error and parallel-DE (see Figure 7) as the optimization method for estimating load model parameters. The primary aim of this case study is to show how to identify the load model with the aid of dynamic simulations by industry-proof software, and present how time-domain simulation and optimization are incorporated to achieve the best load model.

The load modeling framework adopted in this case study is shown in Figure 22.

In the data collection stage, an advanced power quality monitoring system is deployed at a representative bus of the region to monitor and record time-synchronized quantities, including voltage and current rms values, frequency, and active and reactive power. The electrical quantities are transmitted over a certain communication gateway to the client-server for access. The remaining buses in the region are represented by the monitored bus. The time-domain simulation is performed, and the parallel-DE is implemented in MATLAB.

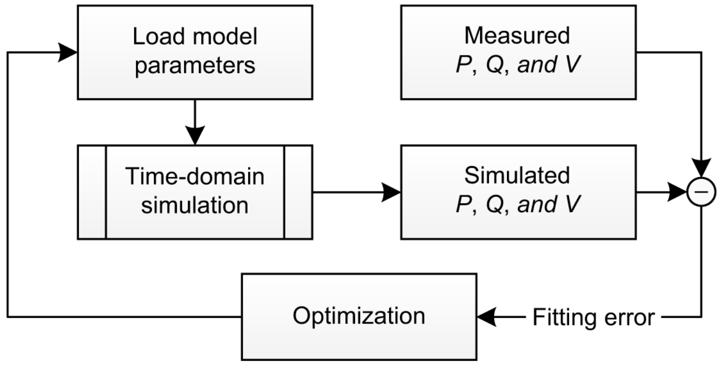
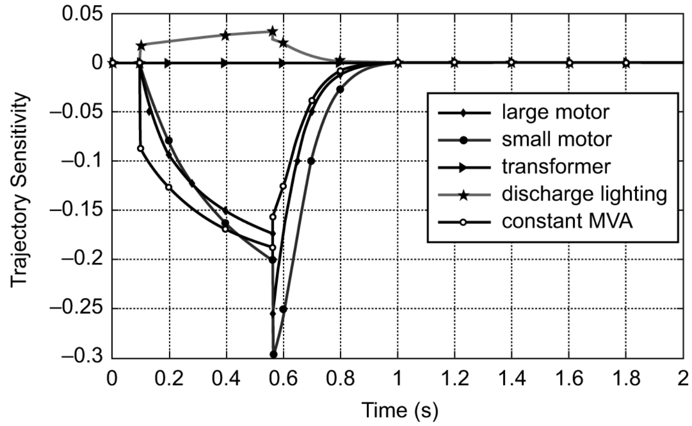


Figure 22—Load modeling framework

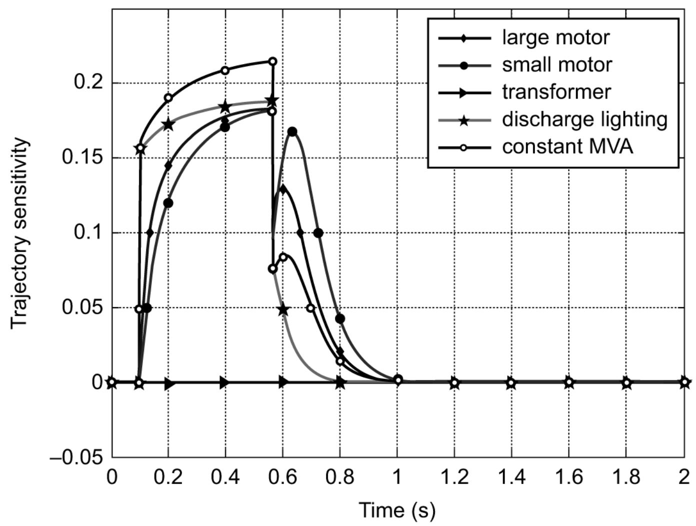
Considering the various types of loads involved with varying degrees of applicability, the CLOD (Figure 19) model is adopted as the aggregate load model in this case study. CLOD represents an aggregation of IMs, lighting, and other types of equipment that are fed from many typical substations. Rather than detailed model parameters, the CMLD is represented by an eight-dimensional vector $L = [\rho_L, \rho_S, \rho_D, \rho_T, \rho_C, K_P, R, X]$, which defines, respectively, the percentage value of large motors, small motors, discharge lighting, transformer energizing inrush current, and constant power load, the exponent of voltage-dependent active power, and branch resistance and reactance (p.u. on load MW base). The model is suitable in situations where the dynamic load behavior is to be represented without detailed dynamics data. Although the CLOD model is used in this case study, it is important to note that other types of load models can also be considered. In the practical operating stage, when the CLOD model is found to be no longer suitable (i.e., when the fitting error E is unacceptable), other models can be used.

In estimating the load parameters of a nonlinear system, different parameters may have varying impacts on the system trajectory. In this case, trajectory sensitivities (Hiskins and Pai [B30]) can be calculated as appropriate metrics to assess the identifiability of the parameters, from which the critical parameters for optimization can be selected. Generally, the trajectory sensitivity quantifies the influence of parameter small changes on the system dynamic behavior. Parameters with larger trajectory sensitivity values are well conditioned (or ill conditioned otherwise) and therefore can be reliably identified from available measurements.

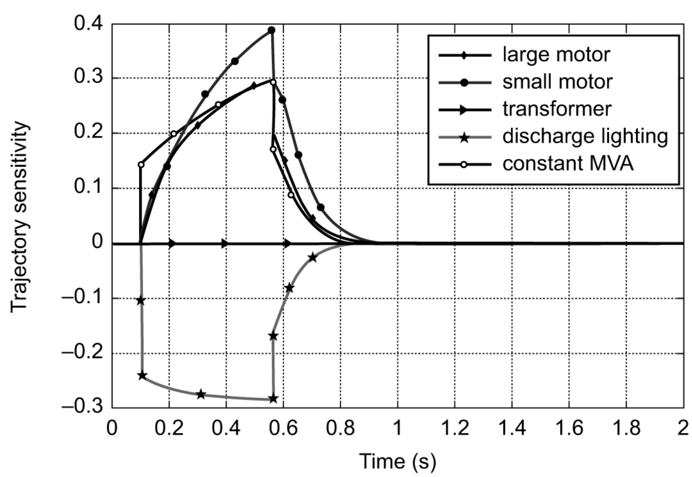
In the case study, the load parameters K_p, R, and X of the CLOD model are assumed to be 2, 0, and 0, respectively, leaving the five parameters that represent the proportion of each load type to be estimated in the model identification task. These five percentage parameters can be ill conditioned in the context of load modeling, which means that some components may occupy a very small proportion. Hence, it is needed to identify the well-conditioned load parameters and include only them in the optimization process; in doing so, the searching space can be dramatically reduced and deeper insight into the load components can be gained to capture the load characteristics. The trajectory sensitivities are calculated for all the remaining five load model parameters, and the values are compared in Figure 23.



(a) Trajectory sensitivities of different load parameters to voltage V



(b) Trajectory sensitivities of different load parameters to active power P



(c) Trajectory sensitivities of different load parameters to reactive power Q

Figure 23—Trajectory sensitivities of different load parameters to (a) V, (b) P, (c) Q

According to Figure 23, it can be seen that the trajectory sensitivities are much different for the three bus variables (P, Q, and V), and they vary significantly among different load parameters for each variable. In addition, it would be noted that the trajectory sensitivities are nonzero during the transient period (0.1 s to 1.2 s) and become zero during the steady state (0 to 0.1 s and 1.2 s onward). This also implies that the load models have an essential impact on system dynamics.

To capture the identifiability of the load parameters, the Trajectory Sensitivity Index (TSI) is calculated using Equation (58), and the results are compared in Figure 24.

$$\text{TSI} = \sum_{t=1}^{T} \omega_t \times [\Phi(t)]^2 \tag{58}$$

where ω_t is the weight factor to assign the importance of the time instant t (typically, higher weights are given to the transient period), T is the total number of samples along the timeline, and $\Phi(t)$ denotes the trajectory sensitivity of a variable at time t.

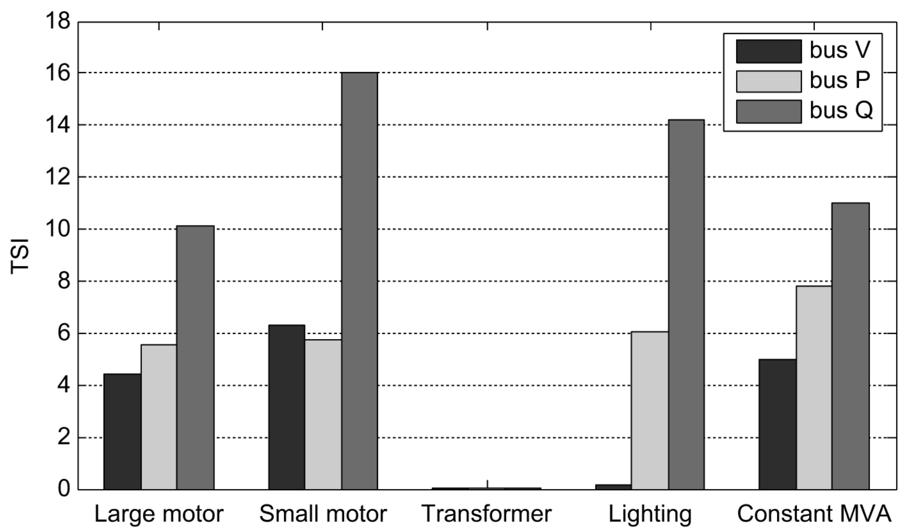


Figure 24—TSI of different load components with respect to *V*, *P*, and *Q*

It can be observed from Figure 24 that the TSI of the transformer component is very small, which implies that it represents a tiny proportion in the substation and could be excluded in the parameter optimization process. The remaining load parameters are well conditioned as their total TSI (the sum of all the three individual TSI) is high; therefore, they need to be included in the parameter optimization. Consequently, there are a total of four parameters to be estimated in the optimization process using the DE algorithm. In addition, the discharge lighting loads have a very small TSI for V but a large TSI for P and Q. This means this load component has a minimal impact on the dynamic bus voltage magnitude, but its impact on bus P and Q is still significant.

The final solution obtained from the parallel DE with 32 CPUs is given in Table 12.

Table 12—Estimated load model parameters

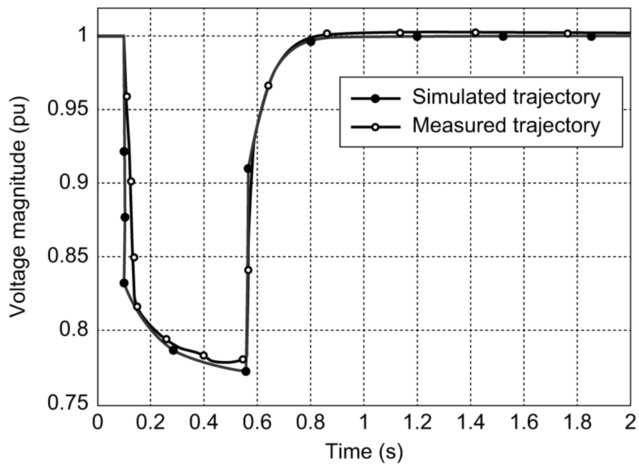
ρ_L	ρ_S	ρ_D	ρ_T	ρ_C	K_P	R	X
11.3	59.1	20.6	0.0	1.9	2.0	0.0	0.0

According to Table 12, the motor loads make up a major proportion in this substation. The final RMSE between the simulated and measured system responses is 0.096. The simulated and measured responses of *P*, *Q*, and *V* are shown in Figure 25, respectively. Note that for *P* and *Q* plots, the normalized values are shown. From Figure 25, it can be seen that, with the solved load model parameters, the dynamic simulation can nicely replicate the variation trends in the corresponding measurements. Hence, the identified load model can persist a high level of accuracy when adopted for dynamic simulation studies.

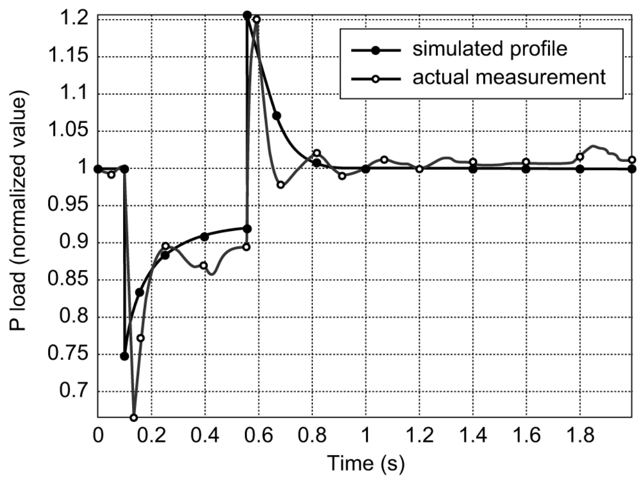
8.6 Conclusions

The clause presented an overview of the role of steady-state and dynamic power system simulations in load modeling, from which the guidelines for power system simulation for both conventional and emerging load types were provided. The clause also provided a critical view of two widely used methodologies for load modeling, the measurement-based and component-based approaches, and identified their major advantages and disadvantages. This critical overview of existing modeling approaches clearly indicated the need for a hybrid approach in the future that can combine the strengths of measurement-based and component-based approaches with data acquisition capabilities offered by modern measurement equipment. The case study in this clause demonstrated the load modeling process on a realistic substation in Australia, with an industry-proof simulation tool and a heuristic optimization algorithm. The load modeling results in this study provided a quantified evaluation on the identifiability of the model parameters and verified the sufficient accuracy of the load modeling approach in the clause to participate in power system applications in transmission and distribution networks.

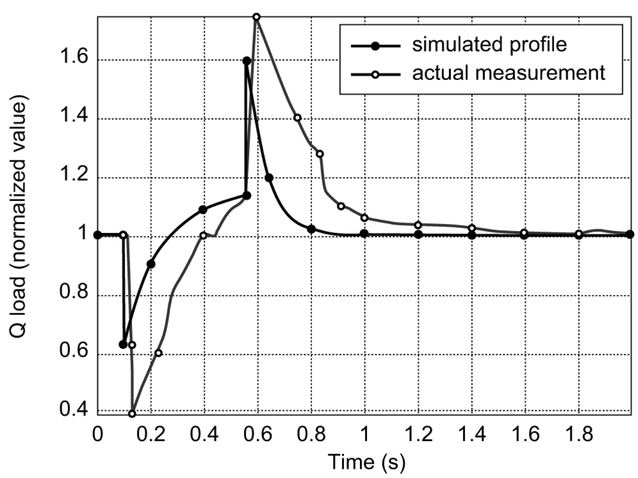
Although the load modeling area has undergone extensive development in recent years, more advanced modeling and identification technologies are imperatively needed to suit future grid needs. Future works should focus on adaptive tackling of the incoming load modeling challenges in energy system transition toward the low-carbon economy. These challenges would include but are not limited to 1) the real-time need of load modeling due to human intervention and weather uncertainties, 2) the precise dynamic modeling of distributed generation and power electronic loads to represent their control mechanism, 3) the identification of an increasingly large number of unknown parameters in load modeling due to the higher granularity of the distribution network, and 4) the higher reliability requirement of load modeling in the uncertain data environment with various measurement resolutions, bad data, missing measurements, and data noise.



(a) Simulated and measured responses of V



(b) Simulated and measured responses of P



(c) Simulated and measured responses of Q

Figure 25—Simulated and measured system responses: (a) V, (b) P, (c) Q

Annex A

(informative)

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