

IEEE Guide for Load Modeling and Simulations for Power Systems

IEEE Power and Energy Society

Developed by the
Smart Buildings, Loads, and Customer Systems Committee

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STANDARDS

IEEE Guide for Load Modeling and Simulations for Power Systems

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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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Jizhong Zhu, Chair
Zhaoyang Dong, Vice Chair

<i>Organization Represented</i>	<i>Name of Representative</i>
Beijing Sifang Automation Co., Ltd.	Liang Ge
China Agricultural University.....	Lin Ye
China Three Gorges University	Lei Xi
Chinese University of Hong Kong Shenzhen.....	Junhua Zhao
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Electric Power Research Institute, China Southern Power Grid	Pingping Xie
Harbin Institute of Technology	Jilai Yu
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Southeast University	Ciwei Gao
Southwest Jiaotong University.....	Xiaoru Wang
Tianjin University	Chengshan Wang
Tsinghua Shenzhen International Graduate School	Libao Shi
University of New South Wales.....	Zhaoyang Dong
Wuhan University	Hongkun Chen

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Alberto Borghetti	Junwei Liu	Zhao Xu
Yiping Chen	Mingbo Liu	Peizheng Xuan
Yuan Chi	Wei Liu	Koji Yamashita
Xiaopeng Fu	Jin Ma	Jiajia Yang
Wei Gu	Thongchai Meenual	Yi Yang
David Hill	Ke Meng	Ming Yang
Chao Hong	Jovica Milanovic	Hongming Yang
Yu Hou	Yunfei Mu	Hongming Yang
Ron Hui	Jong-Bae Park	Yuchen Zhang
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	Yan Xu	

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John D. Kulick	Jon Walter Rosdahl	Daidi Zhong

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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.

Acknowledgments

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}

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷The 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. They 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 (≤ 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

⁹The 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).

$$P = f_P(U, f) \quad (1)$$

$$Q = f_Q(U, f) \quad (2)$$

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]; Agüero, 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).

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

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

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).

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

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

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).

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

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

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).

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

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

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).

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

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

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

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

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

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).

$$P = P_n [P_{ZIP} + P_{EX1} + P_{EX2}] \quad (15)$$

$$Q = Q_n [Q_{ZIP} + Q_{EX1} + Q_{EX2}] \quad (16)$$

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).

$$P = (R_s + \frac{R_r}{s}) \frac{U^2}{(R_s + \frac{R_r}{s})^2 + (X_{js} + X_{jr})^2} \quad (17)$$

$$Q = (X_{js} + X_{jr}) \frac{U^2}{(R_s + \frac{R_r}{s})^2 + (X_{js} + X_{jr})^2} + \frac{U^2}{X_s} \quad (18)$$

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_{js} is the stator leakage reactance
- X_{jr} is the rotor leakage reactance
- $X_s = X_m + X_{js}$ 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).

$$T_p \frac{dP_r}{dt} + P_r = P_s(U) - P_l(U) = P_0 \left(\frac{U}{U_0} \right)^{\alpha} - P_0 \left(\frac{U}{U_0} \right)^{\alpha} \quad (19)$$

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

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

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

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).

$$u_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{d\tau} - \omega_s \psi_{qs} \quad (23)$$

$$u_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{d\tau} + \omega_s \psi_{ds} \quad (24)$$

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

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

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

$$\psi_{ds} = X_s i_{ds} + X_m i_{dr} \quad (28)$$

$$\psi_{qs} = X_s i_{qs} + X_m i_{qr} \quad (29)$$

$$\psi_{dr} = X_m i_{ds} + X_r i_{dr} \quad (30)$$

$$\psi_{qr} = X_m i_{qs} + X_r i_{qr} \quad (31)$$

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

$X_r = X_m + X_{jr}$ 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).

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

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

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

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

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

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

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

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

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).

$$i_{dr} = \frac{u_{ds}}{R} \quad (38)$$

$$i_{qr} = \frac{u_{qs}}{R} \quad (39)$$

$$i_{dc} = -\frac{u_{qs}}{X_c} \quad (40)$$

$$i_{qc} = \frac{u_{qs}}{X_c} \quad (41)$$

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).

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

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

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]).