Recommended Parameter Values and Ranges of Most Frequently Used Static Load Models

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***Abstract*–This paper presents parameter values and ranges of static load models used in power system analysis for the representation of both individual electrical devices and aggregate system loads. The paper discusses and correlates load models and their parameters following statistical processing of the responses of around 100 transmission system operators and utilities around the world, who participated in a survey initiated by CIGRE Working Group C4.605, with the corresponding information on load models and their parameter values from the existing literature. According to the survey, the most frequently used static load models are voltage dependent, and voltage and frequency dependent exponential load models. The identified typical parameter values and ranges of these static load models, both for low voltage devices and for aggregate loads at higher voltage levels, are results of the analysis of a large number of data. Based on these results, the paper provides recommendations for their further use in power system studies and also introduces a novel method for obtaining the mean values and ranges of parameters of the aggregate system load models.**

***Index Terms* - Load class, load modelling, load parameter, power system analysis, static load model.**

I. Introduction

THERE are two general methodologies for load modelling: component-based and measurement-based approaches [1]. The first one assumes *a priori* knowledge as to what electrical device, i.e. load component, is to be modelled and represented with adequate load model(s) and corresponding load model parameters, while the second fits assumed load model to available measurement data. Numerous static and dynamic load models for quantifying real and reactive power responses to voltage and frequency variations are already developed.

After identifying adequate load models for all relevant individual components (e.g. from tests, or by adopting the models reported in the literature), static or dynamic characteristics of aggregate load at higher voltage levels can be derived by applying suitable aggregation method. This approach is typically referred to as component-based load modelling. Load composition and aggregate load model parameters at lower voltage levels can be derived straightforwardly from the individual load components (e.g. [2]-[3]). It is very difficult, however, to establish the exact load composition at medium and high voltage levels, [4]. Therefore, results obtained by the component-based load modelling approach at these voltage levels should be used with caution. In measurement-based approaches [5]-[8], normally occurring or intentionally produced disturbances and other suitable system events are recorded at representative buses. Relevant characteristics of the load are then derived by matching an assumed or postulated load model with parameters fitted to the measured data. As the load compositions at network buses change over time, it is recommended to identify load model parameters for all relevant loading conditions [9]. The results obtained for a specific load bus can be used for modelling load at other buses only if the load compositions at those buses are the same, or similar to load composition at the bus were measurements were taken.

The selection of a suitable modelling approach depends on type of obtained information, available measurements and target application. For both measurement and component-based approaches, the selection of the adequate load model is essential for the correct representation of the modelled load [6], [8]. It depends on both the characteristics of the modelled load and the application of the model.

There is currently a renewed interest for load modelling, which is mainly influenced by the appearance of new and non-conventional types of loads (e.g. power electronic-based or power electronic-interfaced) and increased penetration of renewable-based generation systems and power electronic energy conversion devices. It is expected that accurate modelling of loads and other network components will be even more important for realising increased flexibility and improved energy efficiency of future power supply networks. In response to this renewed interest in load modelling, a CIGRE Working Group (WG) C4.605: "Modelling and aggregation of loads in flexible power networks" was established in February 2010 and produced a Report TB 566 [10] in mid 2013.

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Numerous data and models presented in sections *Overview of Existing Load Models* and *Results of the International Survey on Load Modelling* of this report, related paper [11], and other available literature [12]-[15] and [16]-[24] are analysed and discussed in this paper. In order to draw proper conclusions and recommendations for power system studies, the parameters of different electrical devices are grouped in types in this paper and first analysed separately, and then as the contributing parts of aggregate demands of different load classes and aggregate system loads of different regions of the world. This paper considers only static load models, which are generally used to represent both static and dynamic loads in steady state power system analysis, but also to represent static loads, or loads assumed to have time-independent responses, in dynamic studies [10].

Considering that the number of currently used load models is significant, the paper summarizes only the most frequently used load models, especially these for which parameters can be found in available literature and these obtained from an international survey on load modelling practices in [10] and [11], completed by around 100 utilities and transmission system operators (TSOs) from around the World. Accordingly, this paper specifies typical parameter values/ranges of commonly used models, of voltage dependent, and voltage and frequency dependent exponential load models, identified on the basis of the analysis of numerous data. Also, paper makes the recommendations for their use in power system studies. A novel aggregation method that considers all available parameters of individual load types and load composition is also presented in the paper.

The rest of the paper is structured as follows. The most frequently used static load models are presented in Section II. Sections III and IV provide a detailed review of parameter values or ranges of models of individual devices and aggregate load from the literature, respectively, and give recommendations for their further use in power system studies. Section V introduces novel aggregation method that applies different parameter values of load components. The method is demonstrated on the two examples of aggregate residential and commercial load models under different loading condition, and the results are discussed. The major conclusions of the paper are drawn in Section VI.

II. Most Frequently Used Static Load Models

Static load models (of both static and dynamic loads) are used for steady state analysis of power systems and in dynamic studies for representing individual and aggregate loads with inherently static, i.e. time-independent, characteristics (e.g. resistive loads, or aggregate loads without (large) directly connected or drive-controlled induction motors, as in residential load class) [25]. Dynamic load model is mostly used for representing directly-connected and drive-controlled induction motor (IM) loads, or aggregate load in which IMs significantly contribute to the total demand.

Although the number of static and dynamic load models and their variants is large, typically only a few models are commonly used for modelling both low voltage individual electrical devices and aggregated loads at higher voltage levels. Most frequently used static load models for modelling individual low voltage devices are exponential and polynomial load models [5], [7], [10], [12], [13], [26]-[29]. Similarly, [1]-[6], [8]-[11] and [14] indicate that the most frequent static load models for representing aggregate loads at higher voltage levels are again exponential and polynomial load models, where former are predominant. Namely, according to [11], exponential models are used for steady state power system analysis by 86% surveyed utilities and TSOs worldwide, while polynomial (ZIP) model and other models are used by 8% and 6% of them, respectively. For dynamic power system studies, real power load is modelled by exponential models and polynomial models by 53% and 19% of surveyed utilities/TSOs, respectively. Almost the same industrial practice is found in [11] for reactive power modelling in dynamic studies.

One form of exponential static load model is given as:

$$P = P_n \left(\frac{V}{V_n}\right)^{k_{pv}} \left(\frac{f}{f_n}\right)^{k_{pf}}, \quad (1)$$

$$Q = Q_n \left(\frac{V}{V_n}\right)^{k_{qv}} \left(\frac{f}{f_n}\right)^{k_{qf}}, \quad (2)$$

where: P and Q denote real and reactive power, respectively, at voltage V and frequency f, P_n and Q_n are real and reactive power at rated voltage V_n and rated frequency f_n, k_{pv} and k_{qv} are real and reactive power voltage exponents and k_{pf} and k_{qf} are real and reactive power frequency exponents. Frequency dependence is often neglected, and simplified exponential static load model contains only voltage-dependent terms:

$$P = P_n \left(\frac{V}{V_n}\right)^{k_{pv}}, \quad (3)$$

$$Q = Q_n \left(\frac{V}{V_n}\right)^{k_{qv}}. \quad (4)$$

For voltage exponent values in (3) and (4) equal to 0, 1 or 2, the load model is denoted as "constant power" (CP), "constant current" (CC) or "constant impedance" (CI) type, respectively. Although these three load types have predominantly theoretical usage, characteristics of some actual electrical devices closely match these three load types (see further discussion in Section III). Frequency dependences in (1) and (2) can be modified at constant voltage V_n [15], since the frequency deviations from rated frequency are normally very small. Thus, an alternative form of this model is:

$$P = P_n \left(\frac{V}{V_n}\right)^{k_{pv}} \left(1 + k_{pf}\Delta f\right), \quad (5)$$

$$Q = Q_n \left(\frac{V}{V_n}\right)^{k_{qv}} \left(1 + k_{qf}\Delta f\right), \quad (6)$$

where Δf represents relative frequency change. Another commonly used static load model is second order polynomial model with frequency-dependent term neglected, often referred to as "*ZIP* model". It is not presented here due to space limitation.

The analysis of load model parameters and ranges of their values for individual electrical devices is performed in this paper for model (3)-(4), because it is simple and a large number of parameter values for this model can be found in literature. At higher voltage levels, models (3)-(4) and (5)-(6) are most frequently used for representing aggregate system load, which is also analysed in this paper.

III. Model Parameter Values/Ranges of Individual Devices

A. Model Parameters of Resistive Loads

It is noted that, very often, different parameters are reported in literature even for the same (general) type of a device. This is because the load model parameters will typically vary depending on: used electrical circuits, auxiliary components, operating conditions and a number of other factors. Some minor differences for k_{pv} parameter of resistive heating load are found in [5], where identified k_{pv} values of resistive hotplate and space heating loads are 1.95 and 1.93, respectively, indicating that these devices cannot be modelled exactly as a constant impedance load type (which is assumed in a number of references, e.g. [1], [2], [15]). However, since the parameter variations are small, it can be assumed that k_{pv}=2 and it is recommended to model resistive electrical loads by the constant impedance (CI) load type.

B. Model Parameters of Lighting Loads

Model parameters of lighting loads are strongly influenced by the type of the lamp, even for the same general load category. This is demonstrated on the example of "energy efficient lighting" type of load, as it is commonly denoted in the UK and Europe, which currently includes fluorescent lamps, compact fluorescent lamps (CFL) and light-emitting diode (LED) lamps. Table I lists parameters of exponential load model (3)-(4) of fluorescent lamps from [5], [7], [13] and [26].

TABLE I
Model Parameters of Fluorescent Lamps

Ref.	Type of lamp	k_{pv}	k_{qv}
[7]	electronic CFL 1	0.95	0.31
	electronic CFL 2	1.03	0.46
	conventional magnetic CFL	2.07	3.21
	electronically ballasted fluorescent	0.89	1.21
	fluorescent with external dimmer	1.00	5.84
[5]	conventional magnetic CFL	1.69	4.67
[26]	electronic CFL	0.94	0.52
[13]	electronic CFL	1.09	0.72
	power factor correction electronic CFL	0.95	1.76

Parameter k_{pv} takes values in the range 0.89-2.07, while k_{qv} varies from 0.31 for compact fluorescent lamp to 5.84 for fluorescent lamp with external dimmer. However, the same lamp types have parameter values within narrower ranges: k_{pv} for electronic compact fluorescent lamps from [7], [26] and [13] is close to 1, while k_{qv} deviates more, as its values are 0.31, 0.46, 0.52, 0.72 and 1.76, respectively. Parameter k_{pv} of older magnetic compact fluorescent lamp, according to [7] and [5], is 2.07 and 1.69, respectively, while k_{qv} changes significantly: it is 3.21 and 4.67, respectively. However, it should be mentioned that according to [24] the characteristic of the newest types of electronic ballasts is to control fluorescent lamp power with changes in input voltage. Therefore these lamps consume constant real power, while the reactive power demand decreases with increase of voltage.

LED light sources also belong to the energy efficient lighting load category, with parameters k_{pv}=1.32 and k_{qv}=2.06 according to [26], and parameters k_{pv} and k_{qv} that belong to the range from -0.01 to 2.40 and from -1.14 to 3.59, respectively, according to [13]. On the other hand, incandescent light sources only consume real power, and k_{pv} of general incandescent lamp (GIL) is 1.55 according to [1]. Parameter k_{pv} of mercury lamps used for outdoor lighting is around 2.52, while k_{qv} vary based on auxiliary components. Thus, two mercury lamps with different rated powers produced by the same manufacturer have k_{qv}=3.45 and k_{qv}=3.58 [5].

Therefore, for electronic compact fluorescent lamps (CFLs) it is recommended to use constant current load model for real power (k_{pv}=1), while k_{qv} can be assumed in the range from 0.5 to 0.7. Parameter k_{pv} of conventional magnetic compact fluorescent lamps varies in a relatively narrow range, from 1.7 to 2, so any value in this range could be used. For electronically ballasted fluorescent lamps, fluorescent lamps with external dimmer and CFLs with power factor correction it is also recommended to use k_{pv}=1.

In [30], parameters of linear fluorescent lamps (LFLs) and some high intensity discharge (HID) lamps are provided, noting that these lamps are predominantly used in commercial and industrial load classes. Thus, k_{pv} and k_{qv} of LFL are 1.88 and 3.90, while these parameters of HID lamp are 0.94 and -1.47, respectively. Additional parameter values of LFL found in [13] are k_{pv}: 1.7, 1.0, 0.96 and 0.38, and k_{qv}: 5.0, 3.0, 7.38 and 1.43.

C. Model Parameters of Power Electronic Load Category

Switch-mode power supply (SMPS) loads, which belong to general power electronic load category, are another example of loads with reported relatively wide variations of load model parameters. Numerous SMPS loads can be generally categorised in devices with power factor correction circuit (PFC, which is realised as either active or passive, i.e. a-PFC or p-PFC, respectively) and devices without PFC circuit (no-PFC).

Exponential load model parameters of different types of SMPS loads are presented in Table II. Real power of all three types of SMPSs is resembling constant power load (k_{pv}=0), while k_{qv} vary from -0.5 for SMPS with p-PFC to even 2.36 and -1.21, both for no-PFC SMPS load according to [10] and [13], respectively. Parameter k_{qv} is not given for SMPS loads with a-PFC, because these devices typically do not consume any significant reactive power (true power factor is very close to unity). Generally, real power of SMPS loads can be modelled using constant power load model, while k_{qv}= -0.5 should be used for reactive power of SMPS with p-PFC.

TABLE II
MODEL PARAMETERS FOR SMPS LOADS

Load Type	Ref.	k_{pv}	k_{qv}
SMPS with no-PFC	[10]	0	2.36
	[13]	-0.01	-1.21
SMPS with p-PFC	[10]	0	-0.5
	[13]	-0.01	-0.52
SMPS with a-PFC	[10]	0	N/A
	[13]	0	N/A

However, it should be noted that most of the other available literature that considers characteristics of power electronic load category specify that such devices (e.g. cathode ray tube and liquid crystal TV displays) have constant ([16], [18], [19]), or approximately constant (k_{pv}≈0.2 according to [7] for office equipment) real power characteristics, with displacement power factor PF_1=1. The exceptions can be found in [20] (PF_1=0.8) for TV and in [21] for TV and computer loads, where k_{pv}=2, and k_{qv}=5.1 and 5.2, respectively.

D. Model Parameters of Directly-Connected Induction Motors

Parameters of exponential static IM load model strongly depend on: motor rated power, driven mechanical load and supply voltage. These parameters are identified in a number of experiments with a range of motors operating at different rated powers and with various mechanical loads, supplied by different voltages, or by simulations using developed motor models. Quite different voltage exponents of real and reactive power were found for directly-connected three-phase and single-phase motors under different operating conditions [5], [12], [13], [23]. Thus, k_{pv} of directly-connected single-phase induction motors (SPIM) with resistor start - inductor run is 0.06 and 0.30 for motors driving constant torque (RSIR_CT) and quadratic torque (RSIR_QT) mechanical loads, respectively [13]. Parameter k_{qv} is 1.92 for motors with both types of mechanical load. Somewhat greater k_{pv} values are obtained for directly-connected single-phase induction motors with capacitor start - capacitor run, i.e. 0.38 and 0.53, for motors with constant (CSR_CT) and quadratic torque mechanical load (CSR_QT), respectively, while k_{qv} is 1.68 for both types of mechanical loads. Simulations on developed directly-connected three-phase induction motor model in [23] yielded k_{pv}= -0.10, and k_{qv} =1.44 for RSIR_CT.

Tables III and IV present some of the results obtained for supply voltage in the range 0.95 p.u.÷1.05 p.u. for four groups of directly-connected three-phase induction motors with different rated powers [12]. Mechanical constant power load, p, was changed in range from 1 p.u. (fully loaded motor), to 0 p.u. (unloaded motor, which has only theoretical significance). For the same group of motors operating again around 1 p.u. supply voltage, both k_{pv} and k_{qv} values are within narrow ranges for the same loading conditions. On the other hand, for the group of motors with rated power up to 3 kW, the minimum value of k_{pv} is -0.07 for p=1 p.u. and the maximum value is 3.9 for p=0 p.u. The variation of k_{pv} decreases as the rated power of the motors increases and it is the smallest for the largest IMs. Accordingly, k_{pv} for motors with rated power above 100 kW is approximately 0 for almost all loading conditions.

In general, parameter k_{qv} is greater than k_{pv} for all motors and for all loading conditions. Its minimum value is 1.38 for p=1 p.u. for the largest motors (above 100 kW), while the maximum value is 4.88 for unloaded motor from the same group. For the groups of motors with smaller rated powers, the range of k_{qv} is narrower, as presented in Table IV. Since power demand of directly-connected three-phase induction motor, and consequently its model parameters, also depend on the type of motor mechanical load, the variability of IM load parameters is even larger and specification of recommended parameter ranges is more difficult.

TABLE III
MODEL PARAMETER K_{PV} FOR IMS WITH DIFFERENT RATED POWERS AND AT DIFFERENT LOADING CONDITIONS

p [p.u.]	<3 kW	4-20 kW	22-100 kW	>100 kW
1	-0.07÷0.03	-0.04÷0.00	-0.01÷0.00	-0.06÷0.05
0.75	0.18÷0.30	0.07÷0.12	0.03÷0.03	-0.03÷-0.02
0.5	0.53÷0.90	0.23÷0.27	0.11÷0.13	0.00÷0.01
0.25	1.30÷1.45	0.60÷0.66	0.27÷0.30	0.07÷0.09
0	3.80÷3.90	2.40÷2.50	1.85÷1.90	1.00÷1.10

TABLE IV
MODEL PARAMETER K_{QV} FOR IMS WITH DIFFERENT RATED POWERS AND AT DIFFERENT LOADING CONDITIONS

p [p.u.]	<3 kW	4-20 kW	22-100 kW	>100 kW
1	1.80÷2.10	2.30÷2.50	1.78÷1.90	1.38÷1.42
0.75	2.40÷2.80	3.02÷3.52	2.56÷2.90	2.08÷-2.36
0.5	2.50÷3.20	3.68÷4.22	3.22÷3.94	2.84÷3.60
0.25	2.70÷3.50	4.00÷4.48	3.75÷4.58	3.48÷4.58
0	2.80÷3.60	4.26÷4.52	3.80÷4.80	3.76÷4.88

According to Table III, it can be assumed, with a small error, that the real power of fully loaded directly connected IMs (of different rated powers) with constant power mechanical load can be modelled using constant power load model. For large motors rated above 100 kW, it is appropriate to use k_{pv} =0 even for much smaller mechanical loads. For modelling of reactive power of IMs, it is recommended to use k_{qv} ranges listed in Table IV as a first approximation, or alternatively to identify the parameter through laboratory measurements for motor(s) of interest.

E. Model Parameters of Drive-Controlled Induction Motors

In order to improve controllability and efficiency in part-load applications, IMs are often drive-controlled (using adjustable speed drives, ASDs). Based on the power rating, ASDs can be realised either as a single-phase (small and micro) drives, or three-phase drives (medium to large powers). The parameters of corresponding static load models also depend on the operating conditions of the controlled motor. Table V lists parameters of various single-phase connected adjustable speed drives (SASD) for different mechanical loads of controlled motor [27]. The minimum value of parameter k_{pv} is around -0.19, corresponding to higher and lower power

V/Hz open-loop SASDs operating with constant mechanical power load and to higher and lower power V/Hz closed-loop SASDs operating with any type of mechanical load. The maximum value of k_{pv} is 0.22, corresponding to both higher and lower power V/Hz open-loop SASDs operating with quadratic torque mechanical load. On the other hand, all k_{qv} values from Table V are negative and the value of the parameter varies from -3.91 to -0.57.

TABLE V
MODEL PARAMETERS OF VARIOUS TYPES OF SASDS FOR DIFFERENT MECHANICAL LOADING

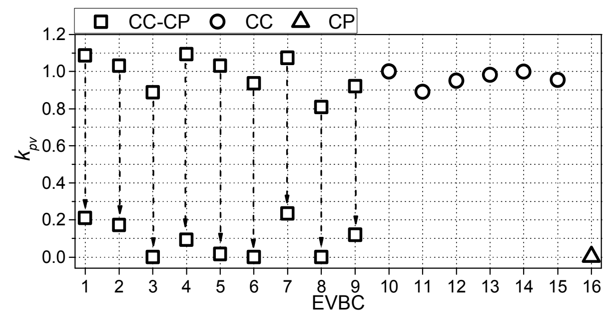
Loading	k_{pv}	k_{qv}
Higher power V/Hz open-loop SASDs		
Constant torque	-0.10	-0.88
Linear torque	0.08	-0.71
Quadratic torque	0.22	-0.57
Constant power	-0.19	-1.11
Higher power V/Hz closed-loop SASDs		
All types of load	-0.19	-1.11
Higher power V/Hz advanced SASDs		
All types of load	0	-0.73
Lower power V/Hz open-loop SASDs		
Constant torque	-0.10	-3.33
Linear torque	0.08	-2.72
Quadratic torque	0.22	-2.63
Constant power	-0.19	-3.91
Lower power V/Hz closed-loop SASDs		
All types of load	-0.19	-3.91
Lower power V/Hz advanced SASDs		
All types of load	0	-2.81

Exponential static model parameters for different types of three-phase ASDs with motors operating with different mechanical loads in continuous and discontinuous modes, are also presented in [27]. Parameter k_{pv} is within the range from -0.19 to 0.22, while k_{qv} changes from -0.98 to 0.35. Therefore, for single-phase and three-phase drive-controlled motors with different mechanical loading, k_{pv}=0 can be used as a valid approximation. Parameter k_{qv} varies significantly depending on type of mechanical load and there is no single generic value that would be most appropriate to use.

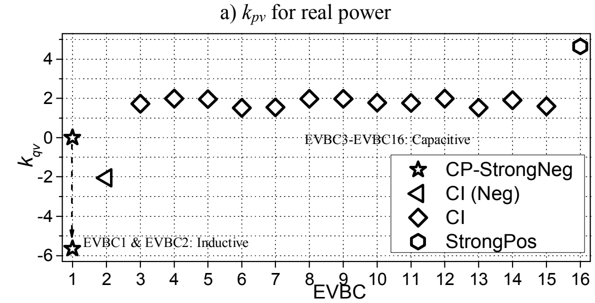
F. Model Parameters of Electric Vehicle Battery Chargers

Furthermore, there are new and emerging loads, such as electric vehicle battery chargers (EVBCs). Although the number of papers dealing with EVBCs is large, only a few specify their load models. The models and parameters in these papers are quite different, and additional comprehensive work on EVBCs load modelling is needed. For example, an analytical EVBC load model (5) with k_{pv}= -2 and modified simulation model are presented in [22]. On the other hand, [13] specifies exponential load model (3)-(4) and the parameters for two sub-types of one EVBC type: k_{pv}=1.05 and 1.08, and k_{qv}=1.56 and 1.78.

Fig. 1 illustrates results from [31] and [32] and additional results of testing of 16 on-board EVBCs (EVBC1-EVBC16). It can be seen that: real power demand characteristics for 9 of 16 EVBCs transfer from constant current "CC" to constant power "CP" load type at around 1p.u. supply voltage (i.e. their k_{pv} values change from k_{pv}≈1 for supply voltage less than 1 p.u to k_{pv}≈0 for supply voltage greater than 1 p.u), so they are denoted as "CC-CP" load; 6 EVBCs behave as constant current "CC" load, with k_{pv}≈1, and one EVBC behaves as constant power "CP" load with k_{pv}≈0. Voltage dependency of fundamental reactive power demand of the most of 16 tested EVBCs can be described with constant impedance "CI" load model (k_{qv} ≈ 2), with exception of one EVBC which behaves as a negative CI load "CI(Neg)" with k_{qv} ≈ -2, one EVBC which has k_{qv} ≈ 4 and behaves as strongly positive "StrongPos" load and one EVBC which transfers from CP to strongly negative "CP-StrongNeg" load.



a) k_{pv} for real power



b) k_{qv} for fundamental reactive power

Fig. 1 Exponential load model coefficients for 16 tested EVBCs.

IV. MODEL PARAMETER VALUES/RANGES OF AGGREGATE LOADS

Regarding the large dispersion of load model parameters for different types and categories of low voltage devices, the obvious question is whether it is possible to identify in a more reliable way parameters of aggregate load at higher voltage levels. This is discussed in the next section.

A. Model Parameters of Residential Load Class

Parameters of aggregate load models at higher voltage levels depend on the load composition and parameters of individual load components, i.e. connected electrical devices. The results presented in [8] and [14] confirm that parameters of static load model for predominantly residential (86 % of the total demand of one 110/10 kV transformer substation in the city of Niš in Republic of Serbia) aggregate load in MV distribution network can be identified with significant confidence. It is observed that normal probability distribution functions for k_{pv} and k_{qv} parameters fit actual data very well, with strong correlations. However, although specified values - the centres of probabilities, k_{pv}=1.55 and k_{qv}=4.91, and ranges ($k_{pv} \in (1.40;1.70)$ and $k_{qv} \in (4.33;5.49)$) are typical and can be recommended for use in probabilistic power system analysis and approaches based on interval mathematics [33]-[34], it should be noted that these parameters are related to predominantly residential load class in the city of Niš and can be used with confidence only for modelling the load with a similar structure in a similar geographic/climate area (e.g. for regions in Balkan peninsula).

Generally, quite different load model parameters can be found in literature for the same residential load class in different regions, for different seasons and for different heating energy sources/fuels [16]. This indicates important differences in residential load structure, based on, e.g. social, climate, economic and other factors, but also in the configurations of the supplying LV and MV networks. For comparison, Table VI lists parameter ranges of model (5)-(6) for residential load class in different regions of North America, for two seasons, as well as for electric and non-electric heating loads [16].

Further to Table VI, one response from survey in [10] from America was for residential load (season and heating source not specified), indicating values of k_{pv}=1.3, k_{qv}=3.0, k_{pf}=0.9 and k_{qf}= -2.0. Three parameter values are in the ranges that roughly correspond to residential loads with non-electric heating in summer season from Table VI, but k_{qv} is slightly higher, indicating that actual loads and/or load modelling practice can be different from the data previously published in [16]. On the other hand, these US-based values for summer season, particularly for reactive power, differ more from the corresponding parameters from other parts of the world [14], with different load composition.

TABLE VI
RANGES OF MODEL PARAMETERS OF RESIDENTIAL LOAD IN NORTH AMERICA

Heating	Season	k_{pv}	k_{qv}	k_{pf}	k_{qf}
Electric	*Summer*	0.9-1.3	2.4-2.7	0.7-0.9	-2.3-(-2.1)
	Winter	1.5-1.7	2.5-2.6	0.9-1.0	-1.8-(-1.5)
Non-electric	*Summer*	1.1-1.4	2.5-2.9	0.7-0.9	-2.3-(-2.0)
	Winter	1.5-1.6	2.8-3.1	0.7-0.9	-1.9-(-1.6)

B. Model Parameters of Commercial Load Class

The fact that the load compositions and, therefore, load model parameters of certain load class can be quite different is further confirmed by published data for commercial load class. In [16], specified k_{pv} and k_{qv} parameters of commercial loads for summer-winter seasons are in the ranges of 0.5÷0.8 and 2.4÷2.5, respectively. On the other hand, corresponding parameter ranges for the same load class listed in [1] are 0.99÷1.3 for k_{pv} and 3.1÷3.5 for k_{qv}. These results suggest that it is difficult to assume the ranges of parameter values even for specific load class, if information on load composition is not available. Therefore, it is recommended to determine load composition at the considered load bus either by surveying connected customers, or by applying suitable measurement-based approach.

C. Model Parameters of Industrial Load Class

Dependence of parameters of static industrial load model on loading conditions is confirmed in [17]. Representative parameter values for summer at one substation in Taiwan supplying industrial load are k_{pv}=0.84, k_{qv}=9.40, k_{pf}=0.39 and k_{qf}=7.47, while corresponding representative parameters for winter differ significantly, especially for reactive power: k_{pv}=1.17, k_{qv}=11.95, k_{pf}=0.42 and k_{qf}=3.09. For comparison, these and parameters of the same static model for industrial load class from [16] and [1], are presented in Table VII.

TABLE VII
EXAMPLES OF INDUSTRIAL LOAD CLASS MODEL PARAMETERS

Ref.	Season/type of industry	k_{pv}	k_{qv}	k_{pf}	k_{qf}
[17]	*Summer*	0.84	9.40	0.39	7.47
	Winter	1.17	11.95	0.42	3.09
[16]	-	0.1	0.6	2.6	1.6
	Primarily aluminium	1.8	2.2	-0.3	0.6
[1]	-	0.18	6	2.6	1.6

One response from the US to the survey in [10] specified that k_{pv}=1.18 is used for industrial load, while other parameters are the same as those listed in [1]. According to Table VII, k_{qv} varies in a very wide range, from 0.6 to almost 12; k_{qf} varies from 0.6 to nearly 7.5, etc. These wide ranges of industrial load model parameters are expected, considering variety of machines/processes and strong dependence of IM/ASD load model parameters on their rated and operating powers and mechanical load (see Sections III.D. and III.E.).

D. Model Parameters of Mixed Load Class

Since the model parameters of mixed load class depend on load composition and parameters of individual types of loads in related load classes, the results of aggregation method that provides parameters of composite load are presented in [2]. This method uses matrix calculation to obtain parameters of the load model (5)-(6),

$$[M]=[N^t]\times r[X]+[N^t]\times s[Y]+[N^t]\times z[W], \qquad (7)$$

where: $[M]$ is the column of the parameters of aggregate load; $[N^t]$ is transposed array of parameters of nine considered load components presenting one set of parameter values for each load component, without acknowledging reported ranges of parameter values; r, s and z are respectively the fractions (in p.u.) of bus load consisting of industrial, commercial and residential load classes; $[X]$, $[Y]$ and $[W]$ are the fractions of total demand of considered load components for the industrial, commercial and residential load class, respectively, also in p.u.

For the example of mixed load consisting of 32 % residential, 38 % commercial and 30 % industrial loads, k_{pv}=0.78, k_{qv}=3.29, k_{pf}=0.69 and k_{qf}= -8.89 are obtained for summer season, while k_{pv}=1.21, k_{qv}=3.88, k_{pf}=0.77 and k_{qf}= -10.85 are determined for winter season. However, since participation of different load classes in the total load can be quite different, where the composition of certain load class depends on many factors, and since the parameters of electrical devices even from the same load category can vary in relatively wide ranges, it is not possible to specify any reliable range of parameter values for mixed load.

E. Geographical Repartition of Parameter Ranges

The results of survey in [11] can be used as an indication of the range of variations of load model parameter values in different regions, as the total of 97 utilities and TSOs around the world sent their responses to this survey. Based on these responses, there is generally no discrimination in modelling practice neither between different load classes, nor between different voltage levels. This suggests that survey results can be used by utilities/TSOs that, for example, do not have, or cannot perform their own load modelling procedures, or have not identified correct load models and their parameters. Another use of these results is for various comparison purposes, as it is demonstrated in this paper.

The survey in [11] indicated that constant power load model (k_{pv}=k_{qv}=0) is used predominantly (by 84 % of surveyed utilities/TSOs) for steady state power system analysis on all continents. This result is expected, as a widely accepted practice is to assume that distribution system tap changing transformers and voltage regulators will control bus voltages close to nominal values, i.e. close to 1 p.u. value, when loads may be approximately treated as constant power loads. However, even in the case of a tight voltage control around 1 p.u., load models and their parameters discussed in the paper should be used for component-based load modelling approach and further for more accurate power system analysis, because voltage exponents k_{pv} and k_{qv} can be used to represent the percentile change of real and reactive power, respectively, for the percentile change of the voltage in the vicinity of rated voltage value.

The survey also indicated that static load models are frequently used in dynamic power system studies — 53 % and 54 % of all responses specified static exponential load model for modelling real and reactive power demands, respectively. Statistical analysis of responses from different continents and their average values ("the World") for real and reactive power static load models used for dynamic power system studies indicated that in all cases standard deviations of k_{pv} (σ_{k_pv}) are of the same order as the corresponding mean values ($\bar{k}_{pv}$) and that reported values of k_{pv} vary in a wide range (Table VIII). Mean, i.e. recommended values of k_{pv} are < 1 for all continents, except for Oceania, where k_{pv} = 1. Consequently, the mean worldwide value of k_{pv} is ≈0.7, with approximate range between 0 and 1.3. The recommended range of values of k_{pv} is the narrowest for Africa (-0.19÷0.85), and the widest for Europe (-0.19÷1.29).

More details are given in Table VIII, where it can be seen that the values of k_{qv} vary in wider ranges than the values of k_{pv}. Mean (recommended) values of k_{qv} are from 0.67 for Africa to 2.25 for Oceania, while the mean worldwide value is 1.35. Standard deviations of k_{qv} values are again of the same order as the corresponding mean values, confirming rather wide variations of k_{qv}, and resulting in similar discussion as in case of k_{pv}. Accordingly, and with all previously discussed caveats, these mean parameter values and corresponding ranges might be used for power system analysis, e.g. if particular data on actual load characteristics are not available.

TABLE VIII
VARIATIONS OF LOAD MODEL PARAMETER VALUES BETWEEN CONTINENTS AND THE WORLD

Continent/ World	$\bar{k}_{pv} \pm \sigma_{k\_pv}$	k_{pv} range	$\bar{k}_{qv} \pm \sigma_{k\_qv}$	k_{qv} range
Americas	0.56±0.56	0.00÷1.12	1.21±1.21	0.00÷2.42
Europe	0.55±0.74	-0.19÷1.29	0.91±1.13	-0.22÷-2.04
Asia	0.77±0.62	0.15÷1.39	1.55±0.94	0.61÷2.49
Africa	0.33±0.52	-0.19÷0.85	0.67±1.03	-0.36÷1.70
Oceania	1.00±0.54	0.46÷1.54	2.25±1.08	1.17÷3.33
World	0.67±0.66	0.01÷1.33	1.35±1.12	0.23÷2.47

V. AGGREGATION METHOD INCORPORATING DIFFERENT PARAMETER VALUES OF LOAD MODELS

A. Method Description

Taking into account the variability of load model parameters of aggregate load at higher voltage levels, which are present even for the same load class, the authors suggest a novel aggregation method. This method differs from the previously published ones as it considers not only the relative contribution of the particular load components in the total load, but also differences in the load model parameter values of these components, as discussed in Section III. The method implements statistical analysis of model parameter values from the literature for all load components that participate in the total aggregate load, acknowledging that the single-value parameters of individual load types (electrical devices) cannot correctly represent variations in their characteristics and that ranges of values should be used instead. The ultimate results are recommended mean values and ranges of load model parameter values for the considered aggregate load.

The basic assumption of the method is that percentage participation, p_i, of a load component i, in the total power or energy consumption, is known, and that j different parameter values of this load component are available and should be therefore considered in building model of aggregated load. In order to enable different treatment of parameter values of load component i, normalized weights, w_{ij}, should be introduced. The sum of weights for particular load component i is equal to 1. In the case of the same treatment of each available parameter of a load component i, all weights are equal to $1/n_i$, where n_i is the number of available parameters of this load component. When some parameter values are more relevant or more favourable, their weights are greater, and vice versa, with the sum of weights for each load component again equal to 1:

$$\sum_{j=1}^{n_i} w_{ij} = 1, \qquad \forall i . \tag{8}$$

According to the suggested method, each parameter value of $k_{pv,ij}$ (and $k_{qv,ij}$) should participate with $w_{ij} \cdot p_i$ percentage contribution in statistical analysis, i.e. it should appear $w_{ij} \cdot p_i$ times (in percent) in the analysis. Generally, the product $w_{ij} \cdot p_i$ is the number with k decimal places. In order to analyse the integer number of each of n_i distinctive parameter values of load component i, they should be used

$$N_{ij} = w_{ij} \cdot p_i \cdot 10^k \tag{9}$$

times. Under the assumption that $w_{ij} \cdot p_i$ is the number with two decimal places (or can be approximated in that way), it is sufficient to set k=2 for the purpose of obtaining an integer number of parameter sets. Afterwards, the total number of parameter values of a considered load component i used in the analysis is:

$$P_i = \sum_{j=1}^{n_i} N_{ij} = \sum_{j=1}^{n_i} w_{ij} p_i \cdot 10^k. \tag{10}$$

Consequently, the total number of parameter values of all load components is:

$$P = \sum_i P_i. \tag{11}$$

For known p_i, n_i and w_{ij} of all participating load components, the array of parameter values can be simply created and the subsequent statistical analysis can be used to identify the most probable values of analysed load model parameter, as well as their ranges, and then make suitable recommendations. The same procedure is equally applicable to all parameters of one load model and to different load models and their parameters.

B. Method Application to the Residential Load Model

For better understanding and demonstration, described aggregation method is applied to the UK residential load model. The composition of the residential load in the UK are taken from [13] and presented aggregation method is applied to the parameters of model (3)-(4) using corresponding k_{pv} and k_{qv} data from the references listed in this paper. For the aggregate load under maximum loading conditions, the load composition (with respect to real power demand) is: SMPS a_PFC 1.4 %, SMPS p_PFC 12.9 %, SMPS no_PFC 5.7 %, SPIM RSIR_QT 8.6 %, SPIM RSIR_CT 1.4 %, SPIM CSR_CT 7.2 %, resistive load 37.1 %, GIL 20 % and CFL 5.7 %. The parameters of SMPS loads are taken from Table II, of SPIMs from the first paragraph of Section III.D, resistive loads are modelled using parameters mentioned in Section III.A, GILs using k_{pv} =1.55, while the parameters of CFL load are taken from Table I.

All these parameters are listed in Table IX, along with: corresponding load component, i, its percentage participation in total load (p_i), order number of particular parameter value of a load component (j), its value ($k_{pv,ij}$), percentage contribution of each parameter value ($w_{ij} \cdot p_i$) presented as the number with two decimal places (k=2), the number of times the same parameter value is used in statistical analysis (N_{ij}) and the number of times different parameter values of the same load component are applied in the analysis (P_i).

In the considered case, each parameter value from the set of parameters corresponding to a load component is initially weighted equally, because of the limited availability of published parameter values to derive any meaningful probability distribution that can be used for weighting according to parameter likelihood. Accordingly, the use of equal weights was deemed to be the most appropriate. For example, the number of available parameter values from Table IX of five load components (i=1, i=4, i=5, i=6 and i=8) is only one, while for other components, i=2, i=3, i=7 and i=9, the number is: 2, 2, 3 and 9, respectively. It is obvious that distribution from the set of 2 or 3 parameters can not be established. In rare cases were more parameters were available, e.g., nine values of CFL parameters (k_{pv} and k_{qv}), the authors could not find appropriate probability distribution function to describe the distribution of parameters, therefore, discrete parameter sets are used.

The array of k_{pv} values used for the analysis is constructed from N_{ij} same values of all parameters k_{pv} from Table IX. Then, statistical analysis of the array is performed and the mean, i.e. the most probable value of k_{pv}, and its range, $\bar{k}_{pv} \pm \sigma_{k\_pv}$, are obtained. These are 1.16 and 0.34÷1.98, respectively. For comparison, the same value, 1.16, is found in [13] for k_{pv} under maximum loading conditions.

TABLE IX
VALUES OF K_{PV} FOR DIFFERENT LOAD COMPONENTS AND OTHER VARIABLES USED IN THE PRESENTED METHOD APPLIED TO RESIDENTIAL LOAD MODEL

i^{th} Load Component	p_i [%]	j	$k_{pv,ij}$	w_{ij}	$w_{ij} \cdot p_i$ [%]	N_{ij}	P_i
1. SMPS a_PFC	1.4	1	0	1	1.4	140	140
2. SMPS p_PFC	12.9	1	0	1/2	6.45	645	1290
		2	-0.01	1/2	6.45	645	
3. SMPS no_PFC	5.7	1	0	1/2	2.85	285	570
		2	-0.01	1/2	2.85	285	
4. SPIM RSIR_QT	8.6	1	0.3	1	8.6	860	860
5. SPIM RSIR_CT	1.4	1	0.06	1	1.4	140	140
6. SPIM CSR_CT	7.2	1	0.38	1	7.2	720	720
7. Resistive load	37.1	1	1.93	1/3	12.37	1237	3710
		2	1.95	1/3	12.37	1237	
		3	2	1/3	12.37	1237	
8. GIL	20	1	1.55	1	20	63	2000
9. CFL	5.7	1	0.95	1/9	0.63	63	567
		2	1.03	1/9	0.63	63	
		3	2.07	1/9	0.63	63	
		4	0.89	1/9	0.63	63	
		5	1	1/9	0.63	63	
		6	1.69	1/9	0.63	63	
		7	0.94	1/9	0.63	63	
		8	1.09	1/9	0.63	63	
		9	0.95	1/9	0.63	63	

The same procedure is used for determining the mean value and range of values of parameter k_{qv}. However, it is taken into account that the percentage participation, p_i, from Table IX is related to real power of the residential loads and that load components SMPS a_PFC (i=1), resistive load (i=7) and GIL (i=8) do not consume reactive power. Under the assumption that the differences in power factors of other load components are not large, the corresponding percentage participations of load components in total reactive power load is calculated according to formula:

$$p_{i\_Q} = p_i \cdot 100 / \left(p_2 + p_3 + p_4 + p_5 + p_6 + p_9 \right) . \tag{12}$$

Table X summarizes p_{i_Q} and $k_{qv,ij}$ values and other data related to the parameter k_{qv} that are applied in the presented aggregation method. Variables w_{ij_Q}, p_{i_Q}, N_{ij_Q} and P_{i_Q} are analogues to the variables w_{ij}, p_i, N_i and P_i, respectively, in (8)-(11). Again, equal weighting is applied initially on the available parameters within each parameter set. From all $k_{qv,ij}$ parameters repeated N_{ij_Q} times, the array of k_{qv} values is constructed. Using the same statistical analysis, the mean value of 0.96, and the range of -0.49÷2.41 are obtained. Somewhat higher value of k_{qv} of 1.10 is found in [13] for residential UK load under maximum loading conditions.

TABLE X
VALUES OF K_{QV} FOR DIFFERENT LOAD COMPONENTS AND OTHER VARIABLES USED IN THE PRESENTED METHOD APPLIED TO RESIDENTIAL LOAD MODEL

i^{th} Load Component	p_{i_Q} [%]	j	$k_{qv,ij}$	w_{ij_Q}	$w_{ij\_Q} \cdot p_{i\_Q}$ [%]	N_{i_Q}	P_{i_Q}
2. SMPS p_PFC	31.1	1	-0.5	1/2	15.55	1555	3110
		2	-0.52	1/2	15.55	1555	
3. SMPS no_PFC	13.7	1	-1.21	1/2	6.85	685	1370
		2	2.36	1/2	6.85	685	
4. SPIM RSIR_QT	20.7	1	1.92	1	20.7	2070	2070
5. SPIM RSIR_CT	3.4	1	1.92	1	3.4	340	340
6. SPIM CSR_CT	17.4	1	1.68	1	17.4	1740	1740
9. CFL	13.7	1	0.31	1/9	1.52	152	1368
		2	0.46	1/9	1.52	152	
		3	3.21	1/9	1.52	152	
		4	1.21	1/9	1.52	152	
		5	5.84	1/9	1.52	152	
		6	4.67	1/9	1.52	152	
		7	0.52	1/9	1.52	152	
		8	0.72	1/9	1.52	152	
		9	1.76	1/9	1.52	152	

The composition of the UK residential real power load under the minimum loading conditions is considered next: SMPS a_PFC 0.8 %, SMPS p_PFC 8.1 %, SMPS no_PFC 2.2 %, SPIM RSIR_QT 7.4 %, SPIM RSIR_CT 2.2 %, SPIM RSCR_CT 8.9 %, resistive load 59.3 %, GIL 9.6 % and CFL 1.5 %. According to (11), the composition of reactive power load is assumed as: SMPS p_PFC 26.7 %, SMPS no_PFC 7.3 %, SPIM RSIR_QT 24.4 %, SPIM RSIR_CT 7.3 %, SPIM CSR_CT 29.4 % and CFL 4.9 %. For these minimum loading conditions, the proposed aggregation method resulted in k_{pv}=1.38 and k_{qv}=1.11 (the ranges are 0.59÷2.17 for k_{pv} and -0.11÷2.33 for k_{qv}), while slightly higher mean values of k_{pv} =1.44 and k_{qv}=1.31 are found in [13].

It is clear from the above examples that the maximum differences in the results for the mean values of parameters k_{pv} and k_{qv} in the presented aggregation method from those presented in [13] are less than around 15%, i.e. they are rather small. The method can be simplified by using a single average-values parameter set for one load component. Such simplification yields the same mean k_{pv} and k_{qv} values for aggregate load model as obtained by the application of multiple equally-weighted sets, but standard deviations are significantly smaller. Therefore, the ranges are narrower than those obtained on the basis of multiple sets, especially for reactive power parameter. Under the maximum and minimum loading conditions, these narrower k_{qv} ranges are -0.12÷2.04 and 0.08÷2.14, respectively. Having in mind that the user typically does not have a reason to prefer any parameter from the set, the use of a single set of average parameter values will then result in a less realistic ranges of parameters of aggregate load than what they actually might be.

Furthermore, the method is also applied to all minimum and all maximum parameter values from the sets of load component parameters. In the first case the weights equal to 1 are assigned to minimum values and to single values where only one parameter is available. The weights that are equal to 0 are assigned to other values. For maximum loading conditions, mean value of k_{pv}=1.13 and range of 0.32÷1.94 are obtained, while established method with equally-weighted parameters yielded k_{pv}=1.16 and range of 0.34÷1.98 (literature data is k_{pv}=1.16). Analogue values of k_{qv} obtained with minimum parameters are 0.47 and (-0.74÷1.68), respectively. The values concerning reactive power are significantly different from the values specified in the paper on the basis of equally weighted parameters (k_{qv} mean value is 0.96, and its range is -0.49÷2.41) and from literature data (k_{qv}=1.10), indicating that wrong selection of the parameters might result in unacceptable large errors.

In the second case applied to maximum loading conditions, weights for maximum parameters of each load component are set to 1, and weights for other parameter values are set to 0. This weighting also resulted in differences: slightly greater mean value of k_{pv}=1.22 and much greater mean value of k_{qv}=1.72 are obtained then by the suggested method and from the literature. The ranges are also wider, especially for k_{qv} (-0.26÷3.7).

In the case of minimum loading conditions, significant differences from both results reported in literature and results obtained by established method with equally-weighted parameter sets are again obtained, especially for k_{qv}. Literature data for is k_{qv}=1.31, while established method yields mean value k_{qv}=1.11 and the range of -0.11÷2.33. When only minimum parameter values are used, k_{qv}=0.89 (-0.29÷2.07), while in the case of maximum parameter values k_{qv}=1.43 and range -0.02÷2.88, are obtained, demonstrating that k_{qv} of aggregated load strongly depends on the weights of parameters.

On the other hand, literature data for k_{pv} for minimum loading condition is 1.44, while established method with equally-weighted sets yields mean value k_{pv}=1.38 and range 0.59÷2.17. Using the minimum parameter values from Table IX, mean value k_{pv}=1.36 and range 0.58÷2.14 are obtained, while calculation with the maximum values results in mean value k_{pv}=1.42 and range 0.61÷2.23.

On the basis of the above results, it can be concluded that k_{pv} is almost insensitive to changes of parameters from Table IX, but this is not the case for k_{qv}. Therefore, the weights of k_{qv} values from Table X are systematically varied, in order to establish which parameter values from the Table X have the strongest impact on parameter k_{qv} of the aggregate load and to identify what are the acceptable ranges of weights for a sufficiently accurate estimation. The weights w_{ij_Q} are changed from 1 to 0 with respect to the equation analogous to (8). In the case of a load component with more than two available parameters, i.e. j>2, when one weight was changed the other weights are set to be equal with respect to (8). Load components that are not included in the particular weight change are set to have equal parameter weighting as in Table X.

It is found that parameter k_{qv} of the aggregate load under both maximum and minimum loading conditions is the most sensitive to weights of the smallest and greatest parameters from the Table X: -1.21, 5.84 and 4.67. Therefore, more accurate k_{qv} estimation is achieved by changing the weight corresponding to any of these parameters (w_{31_Q}, w_{95_Q} or w_{96_Q}), while other parameters remained equally-weighted. Under both maximum and minimum loading conditions, the ranges/values of weights for the estimation of aggregate load k_{qv} with less than 10% error compared to literature data are: w_{31_Q} ϵ(0; 0.2), or w_{95_Q}=0.5, or w_{96_Q} ϵ(0.6; 0.7). Since these weights correspond to the parameters from the literature of particular load device, it can be concluded that considered residential load mostly consists of SMPS with no_PFC and CFL electric devices, for which k_{qv} is the greatest, compared to parameters k_{qv} of other devices belonging to the same type of load.

C. Method Application to the Commercial Load Model

Described aggregation method is also applied to the UK commercial load, for which average daily load curve is presented in [30]. The maximum loading occurs during working hours, at 11:30 a.m., when the load composition with respect to real power demand is: SMPS a_PFC 19.2 %, SMPS p_PFC 5 %, SMPS no_PFC 2.5 %, SPIM RSIR_CT 2.3 %, CSR CT 3.3 %, 3PIM_CT 1 %, 3PIM drive 8.8 %, resistive load 22.5 %, LFL 18.3 %, HID 1 %, CFL 10.8% and LED 5.3 %. Components of commercial load class that are not listed for the residential load class are: 3PIM drive, 3PIM_CT, LFL, HID, and LED electrical devices. The parameters of 3PIM drive load, representing higher power drives typically used in commercial buildings, are taken from Table V, parameters of 3PIM_CT are given in the last paragraph of Section III.D and in Tables III and IV (mean values of the presented parameters ranges for fully loaded motors of rated powers greater than 3 kW), of LFL and HID from the last sentence of Section III.B, while the parameters of LED lamps are taken from the first sentence of the third paragraph of Section III.B.

Tables XI and XII list parameters k_{pv} and k_{qv}, respectively, of different load components of commercial load, along with other variables used in the presented aggregation method. Initially, the parameters of the same load component are equally-weighted, as for residential load model. The array of all k_{pv} values is formed according to described method, and its statistical analysis produced mean value of k_{pv} =0.83 and its range as 0.00÷1.66. For analysed load, k_{pv} =0.76 is found in [30]. Thus, mean value obtained by the presented method differs from the available literature value for less than 10%.

For reactive power, presented method yields mean value and relatively wide range of k_{qv}: 1.8 and -0.58÷4.18, respectively. The deviation from mean value of 1.68 given in [30] is around 7%, justifying again equal parameter weighting for both real and reactive power in the case of aggregate commercial load model.

TABLE XI

VALUES OF K_{PV} FOR DIFFERENT LOAD COMPONENTS AND OTHER VARIABLES USED IN THE PRESENTED METHOD APPLIED TO COMMERCIAL LOAD MODEL

i^{th} Load Component	p_i [%]	j	$k_{pv,ij}$	w_{ij}	$w_{ij}\cdot p_i$ [%]	N_{ij}	P_i
1. SMPS a_PFC	19.2	1	0	1	19.2	1920	1920
2. SMPS p_PFC	5	1	0	1/2	2.5	250	500
		2	-0.01	1/2	2.5	250	
3. SMPS no_PFC	2.5	1	0	1/2	1.25	125	250
		2	-0.01	1/2	1.25	125	
4. SPIM RSIR_CT	2.3	1	0.06	1	2.3	230	230
5. SPIM CSR_CT	3.3	1	0.38	1	3.3	330	330
6. 3PIM_CT	1	1	-0.1	1/4	0.25	25	100
		2	-0.02	1/4	0.25	25	
		3	-0.005	1/4	0.25	25	
		4	-0.005	1/4	0.25	25	
7. 3PIM drive	8.8	1	-0.10	1/6	1.47	147	882
		2	0.08	1/6	1.47	147	
		3	0.22	1/6	1.47	147	
		4	-0.19	1/6	1.47	147	
		5	-0.19	1/6	1.47	147	
		6	0	1/6	1.47	147	
8. Resistive load	22.5	1	1.93	1/3	7.5	750	2250
		2	1.95	1/3	7.5	750	
		3	2	1/3	7.5	750	
9. LFL	18.3	1	1.88	1/5	3.66	366	1830
		2	1	1/5	3.66	366	
		3	1	1.5	3.66	366	
		4	0.96	1/5	3.66	366	
		51	0.38	1/5	3.66	366	
10. HID	1	1	0.94	1	1	100	100
11. CFL	10.8	1	0.95	1/9	1.2	120	1080
		2	1.03	1/9	1.2	120	
		3	2.07	1/9	1.2	120	
		4	0.89	1/9	1.2	120	
		5	1	1/9	1.2	120	
		6	1.69	1/9	1.2	120	
		7	0.94	1/9	1.2	120	
		8	1.09	1/9	1.2	120	
		9	0.95	1/9	1.2	120	
12. LED	5.3	1	1.32	1/5	1.06	106	530
		2	2.4	1/5	1.06	106	
		3	-0.01	1/5	1.06	106	
		4	1.07	1/5	1.06	106	
		5	0.1	1/5	1.06	106	

The method is also applied using only the average values of the parameter sets, instead of the multiple equally-weighted sets. As in the case of residential load model, mean parameter values of aggregate loads remain the same, while narrower and less realistic ranges are obtained for both k_{pv} and k_{qv}: 0.06÷1.60 and -0.01; 3.67, respectively.

Furthermore, it is found that both k_{pv} and k_{qv} of aggregate commercial load are very sensitive to parameter weights. Assuming that maximum k_{pv} values for each load component from Table XI have weight 1, while weights for other parameters are set to 0, a value of 0.60 is obtained for mean k_{pv} value of aggregate load. When 1 is assigned to the weights of the minimum load component parameter values, k_{pv}=1.19 is obtained. The same analysis is performed for parameter k_{qv}, when 0.31 and 3.88 are obtained for using only the minimum and only the maximum parameter values from Table XII, respectively. The main reasons for such large deviations are differences between k_{pv} parameter values, especially for lighting loads (LFL, CFL and LED) and significant differences of k_{qv} parameters for SMPS with no_PFC, 3PIM_CT, LFL, CFL and LED load components. Therefore, the example of commercial load class demonstrates even more clearly that inappropriate weighting of the parameters might result in unacceptably high errors during the estimation of aggregate load parameters.

TABLE XII
VALUES OF K_{QV} FOR DIFFERENT LOAD COMPONENTS AND OTHER VARIABLES USED IN THE PRESENTED METHOD APPLIED TO COMMERCIAL LOAD MODEL

i^{th} Load Component	p_{i_Q} [%]	j	$k_{qv,ij}$	w_{ij_Q}	$w_{ij\_Q} \cdot p_{i\_Q}$ [%]	N_{i_Q}	P_{i_Q}
2. SMPS p_PFC	8.6	1	-0.5	1/2	4.3	430	860
		2	-0.52	1/2	4.3	430	
3. SMPS no_PFC	4.3	1	-1.21	1/2	2.15	215	430
		2	2.36	1/2	2.15	215	
4. SPIM RSIR_CT	3.9	1	1.92	1	3.9	390	390
5. SPIM CSR_CT	5.7	1	1.68	1	5.7	570	570
6. 3PIM_CT	1.7	1	1.44	1/4	0.43	43	172
		2	2.4	1/4	0.43	43	
		3	1.84	1/4	0.43	43	
		4	1.4	1/4	0.43	43	
7. 3PIM drive	15.1	1	-0.88	1/6	2.52	252	1512
		2	-0.71	1/6	2.52	252	
		3	-0.57	1/6	2.52	252	
		4	-1.11	1/6	2.52	252	
		5	-1.11	1/6	2.52	252	
		6	-0.73	1/6	2.52	252	
9. LFL	31.4	1	3.9	1/5	6.28	628	3140
		2	3	1/5	6.28	628	
		3	4.6	1.5	6.28	628	
		4	7.38	1/5	6.28	628	
		5	1.43	1/5	6.28	628	
10. HID	1.7	1	-1.47	1	1.7	170	170
11. CFL	18.5	1	0.31	1/9	2.06	206	1854
		2	0.46	1/9	2.06	206	
		3	3.21	1/9	2.06	206	
		4	1.21	1/9	2.06	206	
		5	5.84	1/9	2.06	206	
		6	4.67	1/9	2.06	206	
		7	0.52	1/9	2.06	206	
		8	0.72	1/9	2.06	206	
		9	1.76	1/9	2.06	206	
12. LED	9.1	1	2.06	1/5	1.82	182	910
		2	3.59	1/5	1.82	182	
		3	-1.14	1/5	1.82	182	
		4	0.83	1/5	1.82	182	
		5	0.91	1/5	1.82	182	

The presented results indicate that in a likely case when parameters of individual load types participating in the aggregate demand are not specified, these can be taken from a wider search of load models in available literature and provide reasonably accurate results. An important distinctive feature of the presented aggregation methodology is that it also produces the expected ranges of k_{pv} and k_{qv} values.

VI. CONCLUSIONS

The analysis and statistical processing of static exponential load model parameters for different low voltage devices reported in existing literature showed that if different low voltage devices are grouped into the same general load category, quite different model parameter values/ranges could be identified. However, resistive loads can be modelled as a constant impedance load type, real power of CFLs as constant current load type, while real power of SMPS loads and fully loaded directly connected IMs can be modelled as constant power load type. For other electrical devices and/or loading conditions, the paper provides a detailed discussion of reported parameter values and, whenever possible, recommends use of their ranges of values for the correct load modelling in component-based load modelling approaches.

The results in the paper confirm significant variations in reported parameter values of static load models of residential, commercial, industrial and mixed load classes, for different regions and for different seasons. The corresponding information from the statistical analysis of the responses to a survey from [10] showed that CP static load model is used for steady state analysis by 84 % of surveyed utilities and TSOs. Processing of the reported parameters of static exponential load models used in dynamic power system studies worldwide resulted in mean values of k_{pv}=0.67 and k_{qv}=1.35, with typical ranges from 0.01 to 1.33 for k_{pv}, and from 0.23 to 2.47 for k_{qv}. Further details are given in the paper for different continents, which can be also used in the power system studies by the utilities and TSOs that have not identified actual and network-specific load model parameters.

For modelling aggregate load at buses with known or assumed load composition (i.e. for large-scale power system analysis), a novel aggregation method is introduced in the paper. This method uses all available parameter values of individual load types (electrical devices). In essence, this method allows to adopt the values reported in the literature or to assign appropriate weights to these load model parameter values that are identified as appropriate. The applicability and accuracy of the method is demonstrated on the two examples of residential and commercial load class models. Importantly, the outputs of the presented method are not only the most probable (mean) values of the model parameters (standard method application), but also their ranges of values. This allows to use the results presented in this paper in the studies in which both typical/mean parameter values and their ranges should be varied (e.g. probabilistic power system studies and analysis based on interval arithmetic), as well as when it is required to perform sensitivity analysis of power system operation with respect to present or anticipated changes in load model parameters (e.g. deployment of EVs).

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