Harmonic Models of Some Nonlinear Low Voltage Electric Devices and Their Applications

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Abstract – **In this paper the short overview of harmonic load models of some electric nonlinear lowvoltage devices is presented. Differently from the majority of the references based on aggregate models, this paper deals with the literature related to load models of the individual lowvoltage electric devices. The paper specifies advantages and disadvantages of the models, their applications, as well as future applications and need for new model development.**

Keywords – **Harmonic load model, Nonlinear devices, Lowvoltage devices.**

I. Introduction

Nowadays, the application of electric devices with nonlinear characteristics has increases. This is the consequence of the rapid development of electronics and semiconductor switching components. Their price decreases, the reliability and quality are good enough, so the manufacturers of electric appliancesuse themmassively. Many devices which were controlled by the mechanical control units, such as washing machine controllers, nowadays use electronic control units with a lot of semiconductor switches. The application of different power converters is also rising.

The most important consequences of the enlarged use of nonlinear devices and loads are deterioration of power quality and the increase of higher harmonics of the current injected intothe electric grid. Since the grid is designed to operate with sinusoidal current and voltage, the presence of higher harmonics in the network leads to numerous problems. The characteristic problems are: increased power losses, equipment overheating, error of electric meters, motor vibration, resonance, interference with communication systems, etc. [1]. One of the major problems in distribution networks caused by higher current harmonics is equipment overload. Therefore, it is very important to take into consideration the influence of the current distortion in terms of exploitation and planning of distribution systems.

Nonlinear devices that are commonly used are diverse. The most common nonlinear devices are: lighting sources (for example compact fluorescent lamps - CFLs), computers, laptops, air conditioners, television sets, battery chargers, electric vehicles, drive controlled induction motors. Thus, nonlinear low voltage electric devices are the components of each load sector: residential, commercial and industrial [2].

If it is necessary to perform any kind of electric power network analysis, the load model of aggregate load on higher voltage levels, or aggregate load and/or load model of individual electric devicesin distribution networks, should be known. One of the greatest problems of load modelling in distribution networks is the modelling of electric devices in particularload sector,and thereafter describing formulation of aggregate load models ([3] and [4]).

Aggregate load models in distribution networks are often based on the so called *ZIP* model.For examplethey provide overall power demandof household or overall power demand of household group. Such models can be used for demand-side management (DSM) and smart grid studies [3]. Nevertheless, data from the papers that deal with*ZIP* model cannot be used for harmonic flow analysis. For that kind of network analysis there is a need to use load models which take into account the existence of higher harmonicsin the current of devices or aggregate loads.

The scope of this paper is to givethe short overview of load models representing some most frequently used groups lowvoltage nonlinear devices that consider the existence of higher harmonic in devices' currents. Classification of the models is presented in the paper, and despite other published papers, critical analysis of the models is performed and models' nowadays and future applications are listed.

II. Classification of the Models

The classification of load models in general, used in different analyses of power networks,can be made by applied approach [5]:

- Component-based approach;
- Measurement-based approach.

Component-based load models are based on bottom-up modelling approach. Modelling starts from the lowest voltage level of the power grid (lowvoltage devices, i.e.load components) in order to build the aggregate model for theconsidered voltage level. The aggregate lowvoltage load model represents a group of the lowvoltage devices. Then, the modelling of the load on higher voltage level is based on aggregate load models on the previous voltage level. The levels of the grid can be divided on: device level (the aggregate load model of the group of devices is derived from this level), user level (the aggregate load model of the group of users is derived from this level), user group level (e.g. commercial, residential group; the aggregate user group load model is derived from this level), lowvoltage grid level, medium voltage distribution level and high voltage transmission level [3].

Measurement-based approach represents load modelling on a specific buses, i.e.grid level (for example individual user or user group level) based on measurements in the grid. According to the results of measurements on higher level of

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the grid, lower grid level can be modelled. For example, from the measurements performed in transformer substation load model of the individual users (supplied from this substation) can be derived [3]. It is also possible to create a model in the opposite direction- from measurements of the individual users the aggregate load model can be derived to represent the load model of the user group or the load of whole lowvoltage grid.

Mentioned load modelling approaches are usually used for the researches and analyses of transmission and distribution networks. In these applications the households, for example, are represented with the aggregate load models. Electric lowvoltage devices are not analysed individually, but these are essential parts of the equivalent household load model.

Since the number of electric devices using electronic switching components increases, analysis of the power flow and harmonic flow in lowvoltage networks becomes more important.It is necessary to develop harmonic load models of individual electric lowvoltage devices, which can be used in harmonic power flow and power quality analysis of lowvoltage distribution networks.

Harmonic load models of lowvoltage electric devices, developed by now, are categorized in this paper as:

- Analytical models;
- Measurement-based models.

III. Analytical Models

Analytical models of mentioned devices are usually based on equivalent electric circuits of these devices. Then, according to the equivalent electric circuit, harmonic load models are derived analytically.

The model of fluorescent lamp load is given in [5]. The corresponding equivalent electric circuit is shown in Fig. 1.

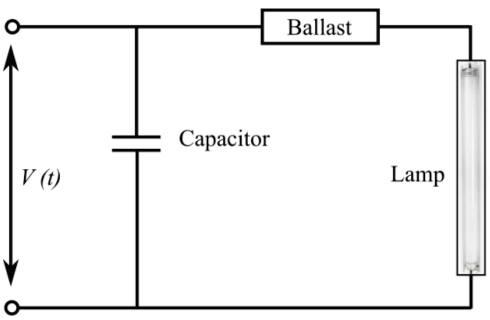

Fig. 1. Equivalent circuit of the fluorescent lamp

The load model is in the form of exponential static load model characteristics:

$$P = P_O \left(\frac{V}{V_O}\right)^{p_v} \left(\frac{F}{F_O}\right)^{p_f} , \quad (1)$$

$$Q = Q_O \left(\frac{V}{V_O}\right)^{q_v} \left(\frac{F}{F_O}\right)^{q_f} . \quad (2)$$

The assumption made in this model is: connected load voltage and frequency dependence on voltage and frequency can be modelled by exponential functions. The model of the fluorescent lamp is obtained according to the equations of real and reactive power of the lamp itself and its ballast. These equations are based on the current of the fluorescent lamp, comprising the presence of higher harmonic currents. The approximation of the hysteresis phenomenon of the fluorescent lamp is applied.Characteristic parameters of load model (p_v, p_f, q_v, q_f) are calculated for the lamps with and without shunt capacitor and presented in Table I [5]. The parameters of static load model characteristics are compared with the valuesobtained by measurements, and the results are also given in Table I.

Table I
Compared values of fluorescent lamp load characteristic parameters

Case	Parameter	Calculated values	Measured values
Without capacitor	p_v	1.8329	1.7 to 2
	p_f	-0.9804	-1.0
	q_v	2.7843	3.0
	q_f	-0.9722	-2.8
With capacitor	p_v	1.8329	1.7 to 2
	p_f	-0.9804	-1.0 to 1.0
	q_v	4.5	5.0
	q_f	-5.1	-5.53

The model of Switch-Mode Power Supply (SMPS) load is given in [6]. Modern electronic equipment connected to lowvoltage grid (computers, laptops, TV sets, etc.) are referred to as SMPS load. The equivalent electric circuit of the SMPS load is shown in Fig. 2.

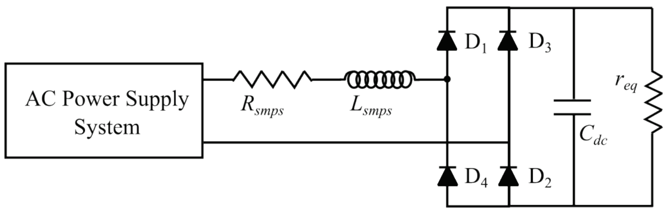

Fig. 2. Equivalent circuit of the SMPS load

The most important parameters of SMPS load are:R_{smps}– the sum of all resistances in SMPS conduction path, and L_{smps} – the sum of all inductances in SMPS conduction path (Fig. 2). The r_{eq}represents the equivalent load resistance. According to these parameters, the load model is obtained. Magnitudes and phase angles of current higher harmonics are calculated according to presented SMPS load model and given in [6]. The approximation applied insome calculations is that the impedance of lines/conductors connecting loads to the point of common coupling is negligible.Moreover, the results with different system impedance values are obtained and the comparison of the results is presented.

Analytical models of single-phase and three-phase adjustable speed drives, SASDs and ASDs, respectively, are presented in [7]. This comprehensive research also presents simulation results for: different drive controls - *U*/*f* open and closed-loop, field oriented control and direct torque control; different rms supply voltages; sinusoidal and non-sinusoidal supply voltage conditions; and four general types of mechanical loads - constant torque, linear torque, quadratic torque and constant mechanical power. Effect of dc link filter components and system impedance on ASD characteristics is also described in [7]. The measures of current distortion: individual and total harmonic distortion, are presented in the paper.

The main advantage of analytical models is that they are often represented with simple equivalent circuits, and that the model is derived by analytical equations. The disadvantages of these models are the facts that: it is very difficult to acquire all data of device components,inadequate data can yield wrong resultsand some approximations in circuit representation are usually adopted (for example hysteresis of the ballast of fluorescent lamp is simplified or not considered).

IV. Measurement-Based Models

The form of measurement-based electric load models of the nonlinear lowvoltage devicesare similar to measurement-based models used in transmission and distribution grids. The major difference is that measurements are not performedat different buses of the grid, butatelectric device connections, and they refer to a single, individual device.

One representative paper that describes measurement-based approach applied to the low voltage devices is [8]. In this reference the results of laboratory experiments performed on closed-loop speed controlled DC and AC electric drives are presented. The measurements of higher harmonic currents for different rms supply voltages and for different types of motor loads, are performed. The mathematic polynomial expressions that describe relationships between the voltage and total and individual harmonic distortions of current are presented for examined drives. It is found that the increase of the voltage causes the increase of harmonic distortion, with the reaching of saturation zone at the higher bound of the voltage range.

According to some otheravailable literature, the individual device model is derived by different advanced methods (stochastic, numerical). The principle which can be used in such methods is presented in [9]. It enables to calculate the magnitude and phase angle of the specific higher harmonic of current. Although the paper focuses on aggregate model at user level (household level) the used method can be applied on measurements of individual lowvoltage electric devices. Therefore, the model of certain device can be derived in the same way as in [9]. According to this reference, it will be necessary to know the model that represents the variation of harmonic emission of concerned type of device during the day (qualitative specification of the model) and distribution functionsfor magnitude and phase angle of the considered harmonics for each hour (quantification of the models). Afterwards, the model can be applied in performance simulation of the group of devices that belongs to the same type. As emphasized in the paper, the model can be extended in future by taking into account the influence of different days of the week and seasonson load class behaviour (or electric device usage).In combination with daily variations, better qualitative specification of the model will be obtained.The on/off operation of the specific devices can also be used in combination with measurement-based approach. These functions can be obtained from researches and surveys of the device users that analyseusers' habits, lifestyle, etc. The on/off functions canbe derived fromthe procedure given in [10].

When measurements are available in some characteristic points of the lowvoltage networks (for example point of common coupling), it is possible to identify which loads are turned on according to the measured real power and harmonic spectrum of the current [11]. It is important to mention that proposed method in [11] does not require measurements performed on any individual device.

The main advantage of the models based on measurements is that they are obtained by real measurement results, and they represent them well. A drawback of some of the presented measurement-based models is their complexity. Moreover, there are distribution functions, on/off functions and usage time functions of the devices, which may affect the accuracy of the model if they are not properly chosen. For accurate modes numerous measurements with precise equipment are needed.

V. Applications of the Load Models

Application of the load model of lowvoltage electric device can be different and it depends on the model itself – its form and the parameters, as well as on the data used for modelling. There are numerous possible applications ofharmonic load models:

- harmonic power flow analysis,
- network protection and fault analysis,
- analysis of resonance phenomenon in the networks,
- planning and design of the networks,
- analysis of networks with distributed energy sources,
- smart grid issues, etc.

This Section discusses the main characteristics of models described in this paper and opportunities for their applications. The load model of fluorescent lamp, proposed in [5], includes the presence of higher harmonics in total load current, but only static load characteristics and their parameters are obtained as the result of the model. Therefore, this model cannot be used for any harmonic analysis. This model can be applied in power system exploitation and planning, analysis of the system stability, or other types of analyses which include static load characteristics (characteristics of real and reactive power).

The load model of SMPS load is given in[6]. Magnitudes and phase angles of higher harmonic currents are calculated according to this model. The applications of the model are in power quality and especially in harmonic analysis. Despite this, the proposed SMPS load model can also be used for representation of aggregate SMPS loads and calculation of their real and reactive power demands.

In [7], individual and total harmonic distortions of SASDs and ADSs currents are presented. Besides, the angles of harmonic currents can be calculated from current waveforms obtained by simulations. Therefore, the models from [7] can be used for harmonic analysis of low voltage networks and for power flow analysis after real and reactive power calculation.

The measurement-based modelsfrom [8] are shown the trends of the influence of voltage change on current harmonic spectra that are not revealed by the usage of analytical models. The results of the paper can be applied as the basis for electric drive modelling and for harmonic power flow analysis.

Measurement-based model introduced in [9], takes into account the higher harmonics of the current (3rd and 5th current harmonicsare given in the paper). Aggregated model of the certain type of devices can be obtained by applying this method to the measurements which included single, individual devices of the same type. This resulting model can be applied in harmonic analysis of the lowvoltage network which includes modelling of current higher harmonic injections into the grid.

The on/off functions of electric devices, related to measurement-based models ([10], [11]), can be applied inthe identification of connected load from the results of the measurements. This enablesthe decomposition of the aggregate load (for example measured at the point of common coupling), so the load of the individual electric device can be specified.

VI. Conclusion

Despite many references that deals with aggregate load models used in the transmission and distribution systems, there are relatively small number of papers that consider the load models of individual low voltage electric devices. This paper makes an overview of representative papers regarding lowvoltage devices.It is emphasized that the models can be classified in two categories: analytical and measurement-based. The former can be represented with simple equivalent circuits, and derived by analytical methodsthat are their main advantages. The disadvantages of these models are that they usually have some approximations in circuit representation of the device and frequent lack of circuit data. The advantage of measurement-based models is that they are modelled on the bases of real measurement results and the main drawback is that numerous measurements are needed.

The main characteristics of models described in the paper are listed, and their possible applications are mentioned: harmonic and power quality analysis of low voltage network, power flow calculation and decomposition of the aggregate load. Furthermore, other possible, future applications are listed in the paper like: network protection and fault analysis, analysis of resonance phenomenon, planning and design of the network, smart grid issues and analysis of networks with distributed energy sources.

Although there are numerous nonlinear electric devices used in lowvoltage networks, the harmonic load models are not investigated for all of them.For example, battery and electric vehicle chargers are becoming more significant lowvoltage electricity consumers, especially in smart grids. Thus, developing their models is of importance for including them in future lowvoltage grid analyses in order to obtain more accurate results.

Acknowledgement

This paper is a part of the research done within the projects III44004 and III44006 at the University of Niš, Faculty of Electronic Engineering and was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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