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Modeling of loads dependent on harmonic voltages

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Electrical system models are important to allow the accomplishment of several studies aiming at reducing losses, and improving power quality, among others. In the current context, carrying out harmonic analysis becomes necessary due to the increasing insertion of nonlinear loads in the system. Since the networks voltage and current profiles are strongly affected by the load behavior, their modeling is essential to perform such analyses. Different from the other harmonic models found in the literature, this paper presents a new proposal of load modeling, combining the ZIP model and a cross admittance matrix. This combination brings together the benefits of load characterization with the traditional ZIP model, which provides some physical knowledge about the load, as well as the frequency crossing given by an admittance matrix. In this way, it is possible to accurately determine the harmonic power injection in the load bus, by knowing its harmonic voltage. The present proposal still considers a limitation for the ZIP coefficients, in order to identify the power ratio in terms of constant impedance, constant current and constant power. In addition to discussing the method for determining the load model parameters, using exhaustive search and multiple linear regression, a real case study with data obtained with a power quality meter exemplifies the model application in an electronic load. The results show that the proposed harmonic model was able to represent the load with high accuracy, and the parameters found provide information about the type of the modeled load.

1. Introduction

Several factors have made the electric power system planning and control increasingly challenging to increase its robustness and compliance with normative criteria. Among these factors, we can mention: unbalance between generated and demanded power; distributed generation intensification with renewable energy resources using static power converters; nonlinear loads quantity increase with switched devices and saturated magnetic devices. Static converters are the largest nonlinear loads used in the industry for different purposes, such as adjustable speed drives and uninterrupted power supplies. Therefore, in order to maintain the electric power system with reduced energy losses and with the desired voltage and current profile, providing acceptable levels of quality, safety, availability, reliability, and economic viability, various studies and analyses about the system are needed [1–4].

In this context, considering that the loads have a great influence on the busbar voltage profile and circulating network current, the load representation has a significant impact on the power system analysis and control functions [2,5]. However, the load models are the least known models among the various components of the system [6]. The different and more complex characteristics of modern loads in relation to older loads require detailed studies of their actual behavior in power flow studies and in harmonic analyzes. Many problems of power system analysis consider constant value loads ignoring its dependence on voltage, current and frequency. Thus, in the absence of appropriate models for the representation of actual loads, power system analyses may produce erroneous results [6,7]. All of these factors make it challenging to model the load for applications in the power system.

Due to the increase in the use of nonlinear loads and electronic devices in the power system, the harmonic currents injection in the distribution networks has increased significantly, causing distortion in the voltage drops along the network. Consequently, this change in the sinusoidal voltage profile causes distortions even in the current of linear loads connected to the bus [1,4,6,8]. Currently, in addition to the nonlinear loads, the distribution systems are submitted to harmonic currents and voltages due to the presence of power inverters to interface solar and wind power plants [9]. The

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existence of harmonic voltages and currents in the system causes serious problems such as transformers and conductors heating, electronic equipment malfunction and power demand increase. Consequently, harmonic monitoring has become an important task to ensure the power quality [1,6,8]. Therefore, it is fundamental to perform electric system harmonic analysis, adopting harmonic models of loads, aiming to increase the system efficiency through the application of techniques for the reduction of harmonic distortion [6,8,10,11].

Static models are widely used for the representation of loads in various analyses of the power system. The characterization of static loads may be done by the ZIP model, which represents the active and reactive powers of the load by components of constant impedance, constant current and constant power, considering voltage variations [6], and thus providing some physical significance on the load [12]. This model is widely used to represent modern residential and industrial loads in several studies on the power system as in stability analyses [5], power flow studies and power system planning [6], voltage and reactive power control [13], Conservation Voltage Reduction (CVR) [14], evaluation of the Available Transfer Capability (ATC) [15], islanding detection for inverter-based Distributed Generation (DG) [5] and fault location [16]. In Ref. [17], a time variant ZIP model was applied in the allocation of DGs in a mesh distribution system. A quasi real-time ZIP model was proposed in Ref. [18] in a CVR study. A history of load modeling including the ZIP model can be seen in Ref. [14].

On the other hand, models that consider harmonic voltage and current components are used to estimate the nonlinear loads impact on the system. Among the harmonic load modeling we mention: fixed current source model, where each harmonic current component of the load is represented by a constant current source [10,19]; Norton model, in which each load harmonic current component is represented by the Norton equivalent circuit, containing an admittance in parallel with a current source [20–22]; coupled Norton model, whose equation considers a constant current for each harmonic order of load current and an admittance matrix responsible for the harmonic coupling between components of several harmonic orders of voltage and current of the load [19,23]; and harmonically coupled admittance matrix model, which contains an array of admittances that relates voltages and currents of several harmonic orders [19].

This paper focuses on the proposition and parameters determination of a novel model for harmonic loads considering voltage variations. Thus, after determining the load model parameters, following the methodology proposed in this article, it is possible to accurately determine the active and reactive power harmonic injection in the load bus as its voltage function.

This proposal associates elements widely used in load modeling, which is the ZIP model and a cross-admittance matrix. Unlike the other harmonic models presented previously, this combination associates the benefits of the characterization of loads by the model ZIP, as well as the frequency crossing given by the admittance matrix, necessary in nonlinear loads. The ZIP model provides some physical knowledge about the load, besides flexibility in the representation of different types of loads, considering voltage variations. Thus, the proposed model may represent the load in a widely diffused form in studies on the system through the components of constant impedance, constant current and constant power. The cross-admittance matrix provides the cross-interaction between several harmonic voltage components in the composition of the power and current of the modeled load, providing the representation of nonlinear loads. Some characteristics of the coupled Norton model are also incorporated since in this proposal there is a constant current component, but with a constant power factor, in addition to the cross coupling of frequencies given by the admittance matrix. This model can subsidize several harmonic analyses in systems with the presence of numerous nonlinear loads. Such analyses can be used to detect loads that contribute significantly to the system voltages distortion through the injection of harmonic currents, as well as to the application of measures to mitigate unwanted harmonic components.

The parameters of the ZIP portion of the fundamental component of the model are determined by exhaustive search, while the other parameters are obtained by multiple linear regression. All parameters are found from measured voltage and current data of the load. Such data should consider different operating points, covering the whole range of values in which the system is to be modeled. This study also proposes the use of the coefficients of the ZIP model in a predetermined range, and it can help in the interpretation of the type of load modeled in terms of the proportions of constant impedance, constant current and constant power. A case study, using actual data, is presented in this paper showing the results of this approach for a three-phase full-bridge diode rectifier. The proposed model was able to represent the tested nonlinear load with high accuracy, although it contains a lower number of parameters than the coupled Norton model for analyses that consider more than three harmonic orders.

2. Load modeling

Load models must be compatible with the intended analysis. Thus, several models are proposed in the literature. Static models are widely used in load steady state studies, whereas dynamic models are typically used in load transient studies. However, in order to consider the load harmonic components, it is necessary to use harmonic modeling.

This section shows the load models considered in the proposed modeling.

2.1. Polynomial model or ZIP model

Static models express the characteristics of the load, at any instant of time, as a function of the load bus voltage, where the active and reactive power components are considered separately. This model is only indicated for situations in which the voltage and frequency variations are small or slow, where the steady state is reached quickly. The static model can also be applied when the interest is focused only on steady state analyses. Most composite loads have this behavior and static modeling can be employed [15,24]. The static model is usually represented in the literature as an exponential and polynomial model [25–27].

It is possible to represent loads with constant power, constant current or constant impedance characteristics, with exponents equal to 0, 1 or 2, respectively. The ZIP denomination can be used due to the model composition by constant impedance, constant current and constant power components. This representation is described in (1) and (2).

$$P = P_0[p_Z(\frac{|V|}{|V_0|})^2 + p_I(\frac{|V|}{|V_0|}) + p_P] \quad (1)$$

$$Q = Q_0[q_Z(\frac{|V|}{|V_0|})^2 + q_I(\frac{|V|}{|V_0|}) + q_P] \quad (2)$$

where subscript 0 represents the initial operation condition of the respective variable and the coefficients p_Z, p_I and p_P, whose sum is equal to 1, define the proportion of each component in the load active power characterization. The same reasoning can be applied to the reactive power coefficients [6,18,25].

In Ref. [3], the substation load modeling of the electric power distribution system is performed using the exponential and ZIP model with dynamic estimation of its parameters by the weighed least squares method in the recursive form. In Ref. [13], however,