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Assessment of the harmonic currents generated by single-phase nonlinear loads

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ABSTRACT

The problem of computing the harmonic currents produced by nonlinear loads has been constantly raised in the field of power quality. Such a problem becomes even more difficult when the voltage supply has already been polluted with harmonics. This context is further investigated in this work by presenting measurement results showing how the harmonic currents generated by a nonlinear load can depend on the distortion parameters of the voltage supply. When dealing with the representation of a nonlinear load through admittances, whose magnitude and angle depend on the harmonic content of the supply voltage, the tensor based procedures are accurate enough when the load admittance loci yields to a circle, which is usually the case for simulations. However, this modeling approach does not fit all types of loads. To account for the admittance variation due to the dependency on the supply voltage angle, this work introduces a special procedure involving a collection of admittance matrices, which is suitable for any load modeling, as it can use data even from measurement. The method is based on the iterative calculation using an updated Norton admittance, which takes into account the magnitude and angle voltage dependency behavior of the nonlinear load. Once the parameters from the electrical system and loads are gathered, the method provides a deterministic way of assessment the line current produced by a single load or a group of these specific loads. Besides the mentioned measurements, numerical calculations comparing results from time-domain simulation and the proposed methodology are presented for validation purposes.

1. Introduction

In general, to improve the power quality in any industrial or commercial plant, time and resources are spent in both mitigation actions and staff training in power quality management and monitoring. These procedures promote energy cost reduction, increase installation availability and, as an overall result, improvement in the productivity and profitability is achieved [1–6]. For many applications, it is quite enough to conduct power quality measurement campaigns and adjust the circuits accordingly. An even better approach is to foresee problems during the installation conception, leading to a design with a better compliance in terms of power quality. One question that arises in the design is how to determine the proper size for power cabling, fuses, transformers and other parts, as they will carry harmonic polluted currents. The commonplace solution, albeit incorrect, is to rate all the equipment using the fundamental voltages and currents.

There is a vast literature dealing with the effects of the harmonic currents in electrical components and systems [1,7–11] and there are many methods on harmonic currents assessment and aggregation [12–27]. Some of them use approximations for the actual currents in their studies, since the main idea is to provide a rough and easy estimate of the parameters to be determined. For the prior determination of the current spectrum, data are originated from a fixed set of harmonic components obtained from a table or direct laboratory measurement. The problem is that, quite frequently, the tabled current frequency spectrum does not correspond to the actual values for the equipment when in normal operation. Furthermore, there are only approximate methods to calculate the current spectrum for a group of nonlinear loads and, therefore, it is difficult to determine accurately the current through the feeder.

Methods for harmonic analysis in the frequency domain, hybrid frequency-time domain and time domain, are summarized in [28]. Most of them use a harmonically coupled admittance matrix whose

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components are estimated from the network solution in two operation points, which are defined by changing the supply voltage, as in [29]. In [30] and [31], the authors developed an accurate analytical solution for finding the matrix elements for an ac-dc converter and ballast, respectively. Such network solution can account only for a particular combination of voltage angles, resulting in a single matrix. According to their work, the off-diagonal elements exist, since there are couplings between current and voltage of different frequencies, but they are small. Thus, the results presented in [29–31] are obtained considering a predefined set of voltage angles for the harmonics in the supply voltage, leading to a single matrix. Therefore, the resulting harmonic current are accurate only when the harmonic voltage composition is similar to that used when calculating the harmonically couple admittance matrix. The authors of [32] investigate the sensitivity of this method, which uses a single admittance matrix, compared to the fixed-current source model and Norton model, which use a single element (similar to diagonal elements in the single admittance matrix), by changing the supply system. For the condition used in their work, the authors conclude that the less accurate results were obtained using the single matrix approach. This may indicate the need for improvements in the latter. The above results based on single matrices do not account for all possible voltage angles, since it is not possible to group the voltage and phase dependency in a single complex number. When the context demands that the phase dependency of harmonic currents on the phase of harmonic components in a polluted voltage source should be considered, a special arrangement based on tensor theory and iterative analysis must be used [28,33]. Smith [33] showed that a converter admittance and its voltage phase dependency can be described by four real values as a tensor at any frequency. These procedures are accurate enough when the load admittance loci yield to a circle, which is usually the case for simulations. When data are obtained from measurements, the admittance loci may not be a circle. Thus, each level of perturbation regarding the harmonic pollution of the voltage source may produce a different shape, and the required linearization to fit it to a circle may not lead to good results. If the admittance loci cannot be represented by a circle, the tensor representation, as shown in [34,35], is not accurate. Another example of this behavior is presented in [36], which studied LED lamps and in [37] for households.

In this context, this work proposes a method to evaluate the current spectrum in each branch due to the presence of a set of single-phase nonlinear loads, which voltage supply is harmonic polluted, without the use of tensors or time-domain simulations, which could lead to large computational costs and therefore rendering it unfeasible. The proposed method uses the admittance matrix modeling, extensively accepted in the literature for the harmonic impedance assessment in time-variant devices as FACTs and HVdc [1,38] and for the relationship between the generated current and the bus voltages in power electronics [39]. To account for the admittance variation due to voltage phase dependency, a special procedure involving a collection of pre-determined admittance matrices is developed and produces one iteratively updated matrix that may be used to study the load behavior. Once this matrix is built, it will be used for assessing the steady-state current for a set of loads and will be phase and voltage dependent and does not require additional linearization, since its original elements are properly determined. Thus, the methodology depicted in this work provides a way of evaluating the steady-state current drawn by a single non-linear load, or by a group of non-linear loads, facilitating the proper design of the electrical system components.

The remainder of the paper is organized as follows. In Section 2, current summation methods, using current sources without adjustment for terminal voltage conditions, are briefly reviewed. As an example of the need to take into account the effect of harmonic pollution in voltage supply, experimental results consisting of measured harmonic currents due to an electronic ballast, which exhibits strong voltage phase dependency, is shown in Section 3. The proposed Norton admittance modeling is given in Section 4. In Section 5, the Y_{Norton} matrix that incorporates all the referred individual Norton admittance matrices into one single matrix is presented. In Section 6, the interaction load-network, according to the proposed model, is discussed and the methodology to find the current summation due to a group of nonlinear is presented in Section 7. Section 8 shows computer simulations for a study case dealing with this load-network interaction and comparisons with time-domain simulations to validate the proposed modeling and methodology. Conclusions are stated in Section 9.

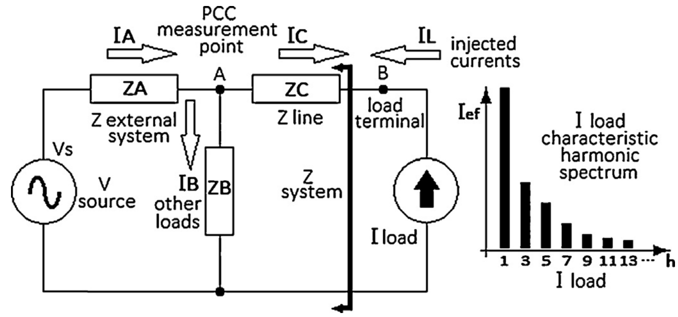

Fig. 1. Fixed current source model.

2. The harmonic current summation methods

Starting from the characteristic spectrum (Fig. 1) for a given load, weighting equations are established in an attempt to reproduce the actual current harmonic amplitudes in PCC (Point of Common Coupling), which are usually smaller than the simple harmonic amplitude summation. Some works deal with electrical currents as stochastic quantities and try to evaluate their behavior in the network by using different probability distributions [40–42]. Despite most of them being perfectly mathematically sound, the practical application of such methods is not straightforward and difficult in some cases. The displacement angles of the harmonic components are not taken in consideration and, therefore, it is not possible to accurately estimate the effects of the harmonic current injection in the system.

The desired effect of grouping several loads is to summarize them into a single load that produces the same current spectrum as the group. As each load, when switched on or off, changes the voltage spectrum at PCC, thus affecting all other loads, a simple evaluation using the original or the characteristic spectrum will give wrong results. This is the reason why the summation must be done using updated line currents, which takes into account the modified voltage spectrum, instead of using the pre-defined load spectrum, since they are often different. The fixed current source model statement suggests that the load currents are the same for all terminal voltages, which is not correct, and requires an additional treatment to compensate the current mismatches for the actual currents. This can be done through the iterative procedure depicted in this work, as shown in the remainder of the paper.

3. The voltage angle dependency

To evaluate the voltage angle dependency, an experimental setup is used to show that the generated current is much more dependent on the harmonic angle than on the harmonic amplitude. The measurements were carried out using the diagram displayed in Fig. 2, for an electronic ballast for fluorescent lamps fed by a single harmonic voltage component V_j superimposed to the fundamental