Electric Power Systems Research 82 (2012) 18–26

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Harmonic disturbance identification in electrical systems with capacitor banks

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ARTICLE INFO

Article history:
Received 13 December 2010
Received in revised form 20 May 2011
Accepted 17 August 2011
Available online 21 September 2011

Keywords:
Power quality
Harmonic
Distortion source
Distortion assessment
Distribution networks
Non-linear loads

ABSTRACT

The identification of distortion sources in a power system is an unsolved topic. The problem is difficult to solve because there are elements in the system that do not produce harmonics but amplify those already present in the electrical network. The most common of these elements is the capacitor, which is widely used to compensate for the power factor at the fundamental frequency. The capacitor behaviour makes the indices proposed up until now to identify distortion sources fail in the presence of this element. This paper presents a new index: the load characterization index. Besides using an extended equivalent circuit to represent the load, this index calculates the distortion introduced by the load, evaluating, in addition to the current distortion at its input, the voltage distortion at its terminals. The introduction of voltage assessment makes the index suitable for identifying the linear and non-linear loads in the power system even in the presence of capacitors and from only the voltage and current measured at the point of common coupling.

1. Introduction

In a liberalized electricity market, the electric power quality, EPQ, in the grid can be a critical competitive parameter and may represent a key to supply contracts. Both measuring and assessing consumers' contribution to the EPQ are becoming increasingly important [1–6]. Harmonic distortion is one of the main aspects of power quality and it is the fastest growing in importance in recent years because of the proliferation of non-linear and time-varying loads in power systems, which absorb non-sinusoidal currents. Moreover, the definition of the different power components becomes a great deal more complicated within a distorted environment [7,8].

There are many proposals in technical papers to establish the responsibility of each agent for the harmonic distortion in power distribution networks [5–27]. One of the most noteworthy is that based on the sign of the harmonic active power using single-point [9–14], or distributed measurements [15–20]. If the analyzed load is linear, the harmonic active power flows from source to load. However, in the case of distorting loads, it may flow in the opposite direction. Therefore, by considering the sign of the harmonic active power, the load participation in the total distortion can be quantified.

Another procedure for locating distortion sources is that based on using a Norton model to represent the harmonic equivalent circuit. The analysis is carried out using the parameters and harmonic source currents of the Norton equivalent to find the relation between the harmonic impedance and harmonic voltage source from measurements taken at the PCC [21–23]. Another method is known as the principle of critical impedance method [24], whose principle is to compare two magnitudes of harmonic voltage sources in the Thevenin equivalent circuit and choose the larger one as the main harmonic source. Certainly, this kind of method can detect which side contributes a higher level to the PCC. However, these procedures require knowledge of network and consumer harmonic impedances.

A noteworthy group of proposals is based on current decomposition [25–27]. The first current component represents the part of the actual load that does not introduce distortion into the system and the second component represents the part of the load that produces distortion. In the case of a linear load, the first is the only component, whereas both components exist in the case of a non-linear load.

In addition, it is necessary to consider multi-point indices such as the toll-road model [17], which is based on some power or current parameters or the Global Power Quality Index [18,19], which is a combination of several single-point indices.

All those procedures have their advantages and disadvantages. However, none of them is able to identify the true distortion sources on systems in the presence of capacitors [28]. Indeed, it should be noted that while the loads that produce harmonics are undoubtedly non-linear loads which introduce distortion into the system, other elements may have an important role in the propagation of

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doi:10.1016/j.epsr.2011.08.013

harmonics in the networks, although they cannot be listed as distortion sources. The capacitor is the most important one. It is widely used in power systems to compensate for the low power factor of inductive loads. However, its performance is optimal only if the network operates in steady-state sinusoidal conditions. In another case, the capacitor may cause serious problems [28]. This is mainly due to its harmonic impedance, which decreases as the frequency increases, and in addition, it increases the distortion of the current that the load consumes.

In this sense, the theoretical criteria adopted to assign responsibility for harmonic distortion in the presence of capacitor banks is analyzed. The indices considered are, among others, the global harmonic index, based on the sign of the harmonic active power, and what is known as the non-linear current index [27]. The conclusions presented in [28] indicate that the capacitor plays an important role in the spread of harmonic distortion in a power distribution network. It does not introduce new harmonics into the network, but amplifies those already present. Thus, some of the techniques proposed in the literature to identify distortion sources penalize capacitors as such. This fact is in stark contrast to the standard that requires the use of capacitors for power factor correction at the fundamental frequency. Other techniques, based on the harmonic active power flow, are very sensitive to the uncertainty introduced by measuring devices. In fact, at high harmonic orders, capacitive impedances are very low and the current is almost completely non-active. So, in these conditions the determination of the active power sign is very difficult.

For this reason, this paper presents a new procedure that evaluates the distortion introduced by each load connected to a point of common connection, PCC, from only the voltage and current measured at the load input. Additionally, it takes into account the presence of capacitors to compensate for the power factor at the fundamental frequency and its behaviour at high frequency. This procedure, which results in the so-called load characterization index (LCI), could be implemented in commercial network analyzers to carry out the analysis of the responsibility of each load for the total power system distortion.

The behaviour of the index has been checked by simulation and experimental tests, based on industrial applications where problems have been detected.

2. The load characterization index

The problem presented in the previous section makes necessary a new procedure which allows linear loads to be identified in the presence of capacitors. A new method is presented in this section.

2.1. Load equivalent circuit

The background of this new method is all those developments based on current decomposition into two parts. Thus, the analyzed load can be represented by the circuit shown in Fig. 1, in which there are two parallel branches: the first is a linear load and the second is a non-linear current source, $\mathbf{I}_{nl}$. In [27], the linear part is represented by an inductive impedance (a resistor R_{L1} in series to an inductance L_1) as shown in Fig. 1. The component values are calculated as the ratio of the voltage and the fundamental current component. From this fundamental impedance, that corresponding to the other harmonic orders is calculated: the approximation of considering that the resistor remains the same regardless of the frequency is adopted; and on the other hand, reactance is considered proportional to the harmonic order. The ratio of each order of harmonic voltage and the corresponding impedance is that order of linear current. The set of all the harmonics is the linear component of the current flowing to the load, $\mathbf{I}_{lin}$. The non-linear component

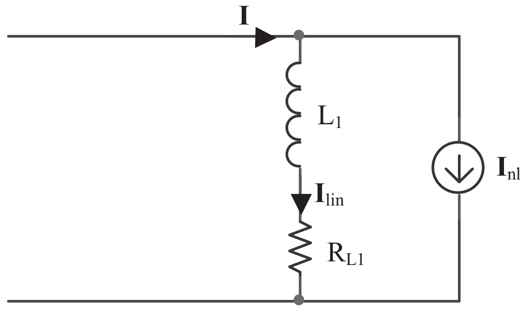

Fig. 1. Single-phase load equivalent circuit according to [27].

of the current, $\mathbf{I}_{nl}$, is calculated as the difference between the total, $\mathbf{I}$, and the linear component, $\mathbf{I}_{lin}$. The ratio of the rms values of non-linear and total current is called the non-linear current index and it is assigned to the load by [27] to assess its responsibility in the total system distortion.

This procedure provides good results when applied to inductive loads. On the other hand, it does not identify linear loads in the presence of capacitor banks. To solve this problem, a new procedure is proposed in this paper. It involves representing the load by an equivalent circuit with two parts: a linear load and a harmonic current source. However, in this case, the linear load is constituted by three parallel branches: the first is still an inductive impedance (a resistor R_{L1} in series to an inductance L_1), the second is a resistor, R_1, and the third is a capacitor, C_1, which represents the element used for power factor compensation. Thus, the load is represented in the new procedure by the circuit shown in Fig. 2. It takes into account, in addition to inductive loads, the pure capacitive or the inductive loads compensated by capacitors, in addition to the non-linear.

In this new procedure, the fundamental current is still flowing through the linear part of the load. However, in the new method, the determination of the value of each element is not as easy as above. As there are three parallel branches in the linear part, there are infinite possibilities of sharing fundamental current between them. This problem is solved in this procedure by testing different values for each element. That is, the proposed index is calculated (as described below) for a specific number of circuits, varying the values of the elements in the linear part of the model which represents the actual load. In this way, an array of index values is obtained: an index value for each set of values considered for the elements.

The objective of the method is to find out the circuit which best represents the actual load. The only constraint is that the linear current component flows through the linear part of the equivalent circuit. Thus, the lower the index value, the better the tested circuit represents the actual load. Therefore, the circuit that provides the smallest value for the index will be considered equivalent to the studied load.

The methodology followed to set the value of each element that constitutes the linear part of the load-equivalent circuit is presented below. To establish the capacitor values to be tested, the auxiliary system shown in Fig. 3 is considered. This is composed

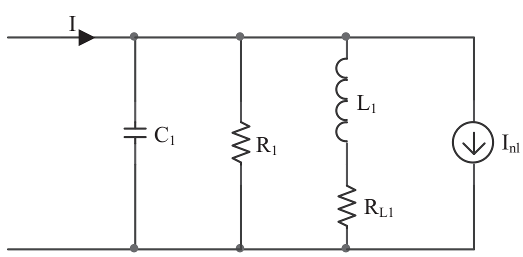

Fig. 2. Single-phase load equivalent circuit proposed in this paper.