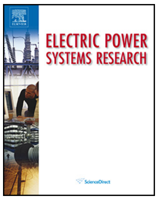
Electric Power Systems Research 129 (2015) 114–125

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Review

Applying conservative power theory for analyzing three-phase X-ray machine impact on distribution systems

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ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form 20 July 2015
Accepted 27 July 2015

Keywords:
Conservative power theory
Non-linear loads
Power quality
X-ray

ABSTRACT

This article proposes the use of the conservative power theory as an alternative tool to analyze and determine the possible impacts of noisy loads on electrical distribution systems. The orthogonal decomposition of current (or power) of the conservative power theory allows the definition of different performance factors, each factor represents a specific feature of the load (current lag behind the voltage, unbalance and harmonic distortion). Each factor is used to identify potential effects of the X-ray machine on the system. Furthermore, a computational model developed in PSCAD/EMTDC of the three-phase X-ray machine is presented. The analysis and discussions are based on simulations and actual measurements obtained on the terminals of an X-ray machine. The presented results helps to demonstrate the main advantage of the CPT compared to conventional approaches, which is related to its general application for single phase and poly-phase circuits, for asymmetrical and distorted supply voltages, for nonlinear and unbalanced loads and, for variable line frequency.

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http://dx.doi.org/10.1016/j.epsr.2015.07.019
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1. Introduction

Power Electronic (PE) is entering in a consolidated age, not only in the industrial sector but also in many other areas, bringing advantages in the processing of energy (more effective). On the other hand, due to this wide spread of PE, the level of harmonics and voltage and/or current asymmetries is increasing drastically, not only in industrial and commercial activities, but also for domestic use, causing disturbances in the distribution and consumption of electrical energy [1,2]. Thus, this subject has become extremely important especially regarding measurement issues, revenue metering and power quality (PQ) [3–6].

In this scenery, in recent decades, the use of X-ray machine has grown, mainly due to the development of portable appliances with lower cost and easy handling. Usually, no information is given to the power utility about their existence or utilization regime. Given their (nonlinear) constructive features, this type of device is considered as a potentially disturbing load [7,8]. It can bring many problems to the distribution system and PQ degradation.

This aspect has been reason of studies and discussions by the utilities and standards [3,6,9,10] that include, among other power quality indicators, the topic of harmonics distortions, load unbalance and power factor. In accordance to these orientations, and recognizing that the solutions to the adequacy of the performance indicators involve financial costs, appears the question of finding ways to determine the responsibilities for eventual violations of the pre-established limits for harmonic distortions, load unbalance and power factor. So, many researchers have been directing their efforts to propose new definitions and theories, able to be applied to non-sinusoidal and/or asymmetric conditions [3,5,11–16]. In practice, such a reassessment would produce impact on various applications such as compensation techniques, revenue metering, instrumentation, etc.

In this sense, the conservative power theory (CPT), presented in [5,11] is used to assess potential impacts caused by the X-ray machine on power systems, with focus on the PQ evaluation. The CPT proposes the orthogonal current/power decomposition in time domain, where each current/power component can be related to a specific load performance factors (PQ index), which allows to identify and to quantify the amount of resistive, reactive, unbalance and nonlinear characteristics of a particular load under different supply voltages condition [19]. In fact, as it will be discussed, this is quite different from using traditional PQ indexes, such as: displacement factor, negative and zero sequence factors or total harmonic distortion (THD). The load performance factors follow the same idea to traditional PQ indexes, however focusing on the identification and quantification of the load phenomena at the point of common coupling (PCC). Therefore, the CPT factors (load performance factors) represent the information of how the generic load circuits affect the current and power terms at the PCC. Besides, their information is related to the entire three-phase circuit, not to single phase variables. Furthermore, the developed model and its implementation in PSCAD^{TM}/EMTDC^{TM} software can be employed on power quality studies for exploring the load characteristic. The X-ray is modeled based on field measurement data obtained from a Brazilian university hospital [17,18]. Thus, this model and CPT PQ indices are used to discuss and analyze the possible impacts of the X-ray machine on distribution systems.

2. Description of X-ray current waveforms

The X-ray machine has two operation modes: continuous and momentary. During the operation in momentary mode at the time of radiography, the electrical power required is high and it can produce voltage sags or even damage the operation of other sensitive equipment connected to the circuit. Fig. 1a shows the load terminals instantaneous currents measured in an X-ray GE Yokogawa Medical System (Model 2137298) equipment during the execution of radiographies.

From Fig. 1b it is observed that the instantaneous current presents four different areas of operation:

- *Area A:* in this time zone the amplitudes of the instantaneous currents are minimal, showing that the device is energized, but there is no voltage being applied to the filament of X-ray tube;
- *Area B:* it is observed that the amplitude of the current increases, the equipment operator sends a command to perform an X-ray radiograph;
- *Area C:* in this time zone the execution of the radiography occurs, which causes a considerable increase in the amplitude of the instantaneous current (reaching maximum values), and thus originate a voltage sag;
- *Area D:* after execution of the radiography the device returns to its initial state, being just energized and waiting for the next execution command. The machine returns to the initial state (Area A) as an execution of one cycle.

For a better understanding of each operation area, in the following sections it will be presented all the circuits that compose the model of the X-ray machine.

3. Computational modeling of X-ray machine

As described in [7,18], the model of X-ray device (GE Yokogawa Medical System – Model 2137298) was implemented in PSCAD^{TM}/EMTDC^{TM} software and can be divided into three basic circuits:

- Filament supply circuit;
- Electronic control supply circuit;
- High-voltage supply circuit.

This configuration was adopted to enable the complete representation of the X-ray machine and shows in Fig. 2. Fig. 2a shows the supply circuit of the filament of the X-ray tube. This is the simplest circuit of the machine, consists of only an electrical resistance which is the filament of the X-ray tube.

The electronic control systems (Fig. 2b) generally require a low voltage DC (direct current) supply between 5 and 12 V [18]. Therefore the supply circuit was modeled by a three-phase 6-pulse rectifier followed by a LC filter (used to remove the voltage ripple) and a resistance representing the element which consumes electrical power.

Finally, Fig. 2c shows the circuit responsible for generating the necessary voltage to create the electric arc inside the tube. It is composed by a three-phase voltage transformer, 220 V to 100 kV and a 6-pulse bridge rectifier, used for rectifying the voltage. The parallel branch to the device's tube is responsible for loading the capacitor which will maintain a stable level of voltage in the tube during the electrical discharge. The consideration of this branch is essential for the correct representation of the device. It is worth highlighting that the electric model of GE Yokogawa Medical System (Model 2137298) is not available in the literature.

4. Impact evaluation of X-ray on electric power distribution systems

A typical configuration of the electrical network for a Brazilian university hospital was considered to analyze and quantify the impacts caused by X-ray machine. Fig. 3 shows the topology and its

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