Electric Power Systems Research 106 (2014) 151–159

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Harmonic analysis of power systems including thyristor-controlled series capacitor (TCSC) and its interaction with the transmission line

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ARTICLE INFO

Article history:
Received 25 June 2013
Received in revised form 21 August 2013
Accepted 21 August 2013
Available online 19 September 2013

Keywords:
Harmonic propagation
Companion harmonic circuit modeling
Series compensation
TCSC

ABSTRACT

The increase of nonlinear devices in power systems leads us to consider their adverse effects on the waveform distortion, and consequently, the effects and propagation of this harmonic distortion over the whole power system. This paper presents the analysis of the adverse impact caused by the harmonic distortion generated by the thyristor-controlled series capacitor (TCSC) and its interaction with the transmission line. The analysis is carried out on the frequency domain, where total harmonic distortion, apparent power, active power, reactive power, distortion power and power losses are presented under different TCSC operation condition. The analysis of a four-node radial power system exhibiting harmonic distortion because of the TCSC operation is presented.

1. Introduction

Because of the use of nonlinear devices in power systems the problem of harmonic distortion becomes an important issue to address. This harmonic distortion has several and sometimes critical power quality problems such as interference in communication systems, protection system misoperations, overheating of the electrical equipment and conductors, reduction of the equipment life span, and additional losses in the power systems [1]. Consequently, an analysis of harmonic propagation in the power system is important.

In general, the power systems contain a variety of nonlinearities, each of them constituting a potential harmonic source. Complete information of the harmonics generated by the nonlinearities is useful for the analysis of the harmonic propagation [2].

In the last years, there has been a growing interest for obtaining the steady-state network voltages at harmonic frequencies because of the increase of nonlinear devices in the electric power network. Several procedures in the frequency and time domains have been used to analyze the harmonic problems [3]. An important issue is the consideration of the nonlinearities; for example, the simplest approaches assume no interaction between network and nonlinear devices [3,4]. Other methods such as iterative harmonic analysis contemplate the effect of the harmonic voltage on the representation of the nonlinear devices but with the limitation that the fundamental voltages are assumed to be unaffected by harmonic voltages [5,6]. Some reformulations of the conventional load flow exist in order to include nonlinear devices; the fundamental and harmonic voltages can be assumed to produce power consumption [7–9]. An extensive review of these methods is presented in [3,10].

Note that the representation of harmonic sources is a key problem, and exist different ways to represent them; for example in commercially available software these are presented as current sources, which may come from measurements, from experiences with similar systems or from calculations under specified system conditions. These values, however, only represent the system at the time of the test [4]. Several algorithms have been proposed with more advanced representations of the critical harmonic sources focusing on their interaction with the rest of the power system components [2–4]. Furthermore, the accuracy of the obtained steady-state solution with any of the harmonic power flow approaches depends on the type of nonlinear components connected to the system and the models used to represent them [1–12]. Another point to consider is the fact that the exclusive use of measurement and analysis at discrete points (nodes) of the system provides no information of the harmonic voltages and currents along the transmission lines, and yet this information is essential to determine effects on the equipment near the lines and in the lines themselves [1–3].

Previous contributions indicate that the harmonic analysis can be performed in the frequency, the time or the hybrid domain. In particular, for power systems with nonlinear components and transmission lines with frequency dependent parameters, the harmonic analysis in the frequency domain presents some advantages; for instance, the frequency dependent transmission line model is very simple as compared with the equivalent model in the time

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0378-7796/$ – see front matter
http://dx.doi.org/10.1016/j.epsr.2013.08.013

domain; for steady-state, the frequency domain model is purely algebraic. On the other hand, the time domain models of nonlinear components are in general simpler than those in the frequency domain; however, the frequency domain model of the TCSC has been widely studied and currently has a detailed and computationally efficient model. In [13] the time and frequency methods for harmonic analysis in power systems is presented in detail. Under this scenario, the harmonic domain is the natural frame of reference for analysis of harmonic propagation in power systems with TCSC and transmission lines with frequency dependent parameters.

1.1. Power electronics based devices

The rapid development of power electronics technology at transmission and distribution levels has been developing a number of control devices under the concept of flexible AC transmission systems (FACTS). FACTS devices can be effectively used for power flow control, voltage regulation and enhancement stability problems and more. One of the adverse problems related with the implementation of FACTS devices is their harmonic generation and their effect over the transmission system [14–16].

The wide spread presence of power electronic devices in power systems demands the accurate and detailed representation of such equipment in power system studies and simulations. The availability of specific and accurate models is important when the periodic steady-state is required, either to initialize a transient simulation or to study the harmonic content of currents and voltages in the system under analysis [17]. Note that the steady-state of power electronic devices is usually based on their time domain characteristic considering idealized terminal conditions. Nevertheless, the harmonic distortion caused by these devices is affected by interactions with the network components and topology and also varies as the operating conditions change [15,17].

A large amount of research effort has gone into designing these devices and studying their impact on the performance of the power system. The operation of individual switching elements and control systems in the FACTS devices is also fully represented. This level of modeling is useful for confirming their proper operation [15–21].

This paper presents an approach for a complete and unified harmonic propagation analysis in power systems including a TCSC, the adverse impacts caused by the harmonics generated and its interaction with the transmission line. This approach includes linear and nonlinear components to be represented by a set of algebraic equations that describes the whole system, which allows harmonic coupling interactions between them. The behavior of each harmonic component along the transmission line is also presented. On the other hand, the companion harmonic circuit modeling (CHCM) of the static compensator presented in [22] is employed to obtain a detailed model of the TCSC and the consequent analysis of the harmonic propagation response of an electrical system in steady-state conditions.

2. Transmission line model

The basic elements required to represent a power system are resistors, inductors and capacitors, which are used to represent different components: i.e., loads, filters, compensators, etc. Nevertheless, a key element in power systems is the transmission line; therefore, a representation that provides a full description of the performance of transmission lines is mandatory.

The proposed analysis is based on the use of CHCM. As is well reported in Refs. [22,23] the steady-state CHCMs are represented for a simple complex admittance matrix **Y**. According to [22] the harmonic complex admittance matrix for an inductance L is then given by

$$\mathbf{Y}_L = [L\mathbf{D}]^{-1} \tag{1}$$

In addition, the harmonic complex admittance matrix for a capacitance C is given by

$$\mathbf{Y}_C = C\mathbf{D} \tag{2}$$

where the matrix **D** is a differential operator [23].

For proper harmonic propagation analysis in power systems, the transmission line model has to consider the inclusion of frequency dependent parameters [24,25]. Fig. 1 shows the equivalent π model of the transmission line with frequency dependent parameters.

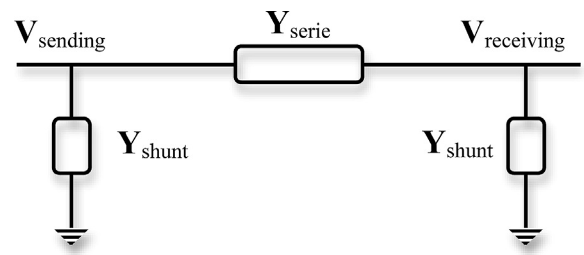

Fig. 1. Equivalent π model of the transmission line with frequency-dependent.

The harmonic complex admittance matrix for the series branch of the transmission line is given by

$$\mathbf{Y}_s = [\mathbf{Z}_C \sinh(\gamma l)]^{-1} \tag{3}$$

The model of the line is completed by the shunt capacitance given by

$$\mathbf{Y}_{sh} = 2\mathbf{Z}_C^{-1} \tanh\left(\frac{\gamma l}{2}\right) \tag{4}$$

where the matrices $\mathbf{Z}_C$ and γ are the characteristic harmonic impedance matrix and the harmonic propagation constant matrix, respectively. Additionally,

$$\mathbf{Z}_C = \sqrt{\frac{\mathbf{Z}'}{\mathbf{Y}'}}$$

$$\gamma = \sqrt{\mathbf{Z}'\mathbf{Y}'} \tag{5}$$

The series impedance matrix $\mathbf{Z}'$ and the shunt admittance matrix $\mathbf{Y}'$ are the per-unit-length parameters. For any transmission line configuration, $\mathbf{Z}'$ is calculated according to Eq. (1) using the per-unit-length inductance plus the per-unit-length resistance of the conductors, and $\mathbf{Y}'$ is calculated using Eq. (2) with the per-unit-length capacitance. It is important to remark that the CHCM is able to represent transmission line models with distributed and frequency dependent parameters in an easy and straightforward way.

Finally, one must consider that for any network of arbitrary configuration with n nodes, a system of n equations are derived from their CHCM. The representation of the network is given by the nodal equation

$$\mathbf{I} = \mathbf{Y}\mathbf{V} \tag{6}$$

where **Y** is a symmetric nodal admittance matrix of dimension $n \times n$, **V** is a vector of n node voltages, and **I** is a vector of n current sources.

3. Harmonic propagation in transmission lines

The equivalent π model provides information at the ends of the transmission line, but no information along the transmission line is given. Nevertheless, for harmonic propagation analysis the