Electrical Power and Energy Systems 57 (2014) 304–310

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A duality-based model of the controlled shunt compensator of transformer type (CSCT)

Mohammad Tavakoli Bina *, Hosein Samsami, Hamed Valizadeh Haghi

Faculty of Electrical and Computer Engineering, K.N. Toosi University of Technology, P.O. Box: 16315-1355, Tehran, Iran

A R T I C L E I N F O

Article history:
Received 24 March 2012
Received in revised form 29 July 2013
Accepted 25 November 2013

Keywords:
CSCT
Duality based model
Parameter estimation
Simulation

A B S T R A C T

This paper discusses the structure of controlled shunt compensator of transformer type (CSCT) based on its operating principles. The modeling procedure of CSCT is further explored from a duality-based modeling viewpoint. Then, an experimental prototype is implemented and the results are measured up to the theory and simulation. Finally, the proposed model is used to simulate the interchanged reactive power between network and CSCT in order to demonstrate the capabilities of this compensator in both capacitive and inductive modes of operation.

1. Introduction

Transmission lines are bulky reactive power sources and often operate with surplus reactive power. This gives rise to several problems [1]; as a result, using reactive power compensation is indispensable. There is a variety of compensation techniques, controllers and devices, such as synchronous condensers, conventional shunt reactors, static VAR compensators (SVCs) and controllable reactors are developed to cater for such demand. By now, synchronous condensers nearly have been abandoned. Conventional shunt reactors cannot provide smooth power regulation, hence, cannot satisfy the requirements of excessively-high voltage long-distance networks. Owing to their complicated techniques, high manufacture cost and difficult maintenance, SVC are inapplicable for some countries which has lower semiconductor technique and economy level [2]. Hence, experts put up with some new kinds of controllable reactors such as thyristor controlled reactor (TCR), also called the controllable reactors of transformer type (CRT) [3], and the magnetic controllable reactor (MCR) [4].

A MCR is developed on the principle of a magnetic magnifier. By controlling the angle of thyristor opening, the dc flux component in the core is regulated and thus the saturation of the core. By this means the purpose of automatic control of reactive power is realized. Unfortunately, there are two shortages inherent in MCRs [3]. First, due to the iron saturation, there is a high level of harmonics in the working currents. Then, the existence of the dc bias magnetization gives rise to large electromagnetic Inertia, which results in low response. To get around the main defect of the MCRs, researchers proposed CRTs in the late 20th century [3].

A CRT is equivalent to a multi-winding transformer with a network winding (NW) which is connected to the network high voltage bus, and several control windings (CWs), in which a thyristor valve (TV) in parallel with a voltage circuit breaker, are connected across each of them. By controlling the TVs properly, CRT can realize the function of smooth stepwise power regulation from no load to nominal conditions, satisfying the current harmonic content constraints. In addition to those advantages of ordinary reactors, a CRT possesses other virtues such as low current harmonic content, fast response, and small losses. Therefore, a CRT can be employed to control reactive power of transmission networks [3]. However, in case there is strong inductive coupling among CWs, such negligence cannot render satisfactory results. It is noticed that the voltage of the network winding is the high voltage of the grid. Hence, when the short-circuited impedance between the NW and CW is less than 100%, current-limiting reactors (CLRs) are needed to limit the currents within the rated. When the regulation step number is more than two, the number of the windings for a CRT is larger than three. In this case, a precise calculation is very hard to obtain.

This paper presents a controlled shunt compensator of transformer type (CSCT) as a new kind of the CRTs, with only one control winding and too high short circuit reactance to solve the above problems. It provides sufficient response rate, very low total harmonic distortion (THD) and independently bidirectional reactive power injection.

The controlled shunt compensator of transformer type (CSCT) is a new compensator which can be installed in high voltage

* Corresponding author. Tel.: +98 21 8406 2280; fax: +98 21 8846 2066.
E-mail address: tavakoli_bina@ieee.org (M. Tavakoli Bina).

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.11.041

transmission lines. As a controlled reactor, it provides sufficient response rate, very low total harmonic distortion (THD) and independently bidirectional reactive power injection.

The general structure of this compensator is presented in Fig. 1. The transformer consists of three windings; the network winding (NW), the control winding (CW) and the compensating winding (ComW). The NW is the main winding of the compensator and connected to the high voltage bus of the network. The CW is the second winding in which thyristor valves (TV) in parallel with a voltage circuit breaker (VCB) are connected across the secondary. The ComW, indicated as the tertiary winding in Fig. 1, includes two tuned harmonic filters connected across it. It is important to note that the CSCT is a three phase compensator. Both the NW and CW is of star-connected type with the grounded neutral. However, the ComW can be of delta-connected type.

When the TV is open, the entire magnetic flux passes through the magnetic core, leading to a minimum reluctance and maximum capacitive current in NW. This eventually injects reactive power to the network. On the other hand, with the TV closed, the flux passes through the air gap as well as the windings. Hence, the reluctance and inductive current of NW is maximal. As the latter lead to a different direction of reactive power flow, the compensator can practically operates in both capacitive and inductive modes.

Employing thyristors results in higher harmonics in the current of CSCT. Hence, a tertiary winding connected to a filtering block is required to suppress the harmonics. This includes several parallel branches, each composed of an inductor and a capacitor in series, so that each branch can bypass a certain harmonic order. In this way, the harmonic cannot pass through the main winding which is connected to the network [4].

Like other new equipment, an accurate modeling of CSCT is required prior to analyzing its behavior. This paper presents a model based on a magnetic circuit modeling framework using the principle of duality [5,6]. The steps toward building such a model and determining its parameters are given in Sections 2 and 3, respectively. Section 4 discusses model verification and experiments followed by the simulation of CSCT behavior in Section 5. Finally, conclusions are presented in Section 6.

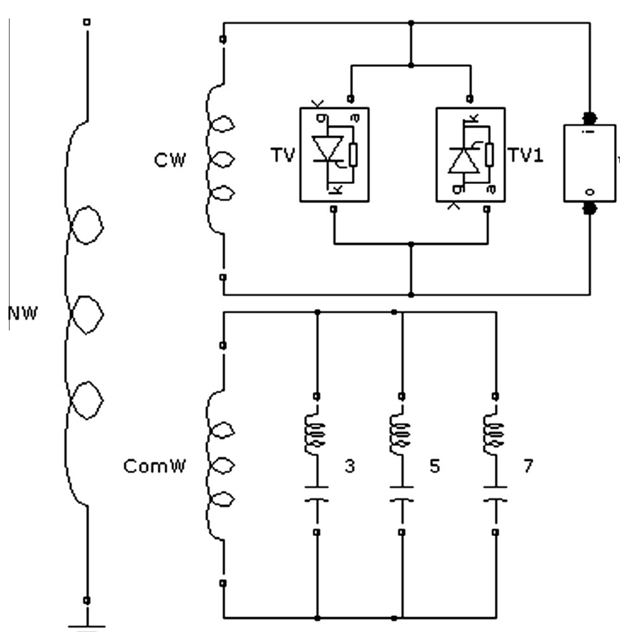

Fig. 1. General scheme of CSCT: TV-thyristor valve, VCB: vacuum circuit breaker, 3, 5 and 7: filter of third, fifth and seventh harmonics.

2. Modeling approach

There are a variety of approaches for transformer modeling, each of which has benefits of its own. Most of the common low-frequency models are usually based on the principle of duality [7]. Modeling CSCT based on this principle is presented in this section.

2.1. Equivalent magnetical circuit

In the equivalent magnetic circuit, windings appear as magnetomotive force (mmf) sources, leakage paths appear as linear reluctances and magnetic cores appear as saturable reluctances [8]. The magnetic equivalent circuit of CSCT is shown in Fig. 2.

The model of Fig. 2 consists of.

R_L: The reluctance of the core limb which the three windings of the phase are located on it.
R_Y: The reluctance of the yoke.
R_S: The reluctance of the magnetic shunt which covers three windings of the phase.
R_{LY}: The reluctance of lateral yokes.
R_{12}: The leakage reluctance of the air gap between the innermost winding and the middle winding of the phase.
R_{23}: The leakage reluctance of the air gap between the outmost winding and the middle winding of the phase.
F_{NW}: Magneto motive force of the network winding.
F_{CW}: Magneto motive force of the control winding.
$F_{Com.W}$: Magneto motive force of the compensating winding.

2.2. Equivalent virtual circuit

In this step, the mmf of each winding is represented by an equivalent voltage source. Also, the permeance of each magnetic path should be modeled by a capacitance of the same value. The virtual equivalent circuit of the system of Fig. 2 is shown in Fig. 3. In this figure, the permeance of limbs and yokes are modeled with nonlinear capacitances. This represents the nonlinear nature of iron core. This figure also contains some linear capacitances which represent the air gap in parallel to each limb. This is necessary due to the five-legged structure of the magnetic core.

2.3. Equivalent electrical circuit

The equivalent electrical circuit is derived from the circuit shown in Fig. 3 by using the duality concept according to following rules:

– Dual of each mesh is a node. This is true about the outer loop as well.
– Dual of the each capacitance between two meshes is an inductance between their dual nodes by the same value.
– Dual of each voltage source is a current source by the same value.

2.4. Final model

The final model of the CSCT is obtained by adding/replacing the following elements as shown in Fig. 4 [8]:

– The duals of current sources are replaced with ideal transformers assuming only one turn on the secondary for which the primary turn is determined such that the turns ratio equals to in the related winding of CSCT.
– Add a resistance in parallel with each core inductance to represent the magnetic core losses in limb, yoke or lateral yoke.