Electric Power Systems Research 121 (2015) 176–182

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Advanced modeling of center-node unified power flow controller in NR load flow algorithm

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ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 8 November 2014
Accepted 14 December 2014

Keywords:
FACTS
C-UPFC
NR load flow
Power & current injection approach

ABSTRACT

A new and versatile member of flexible AC transmission systems (FACTS) controller is center-node unified power flow controller (C-UPFC). The C-UPFC is capable to control various system parameters independently, e.g., the active power through the line, the reactive powers at the ends of line and the magnitude of the voltage at the mid-point of the line. Applying C-UPFC device may increase the power transfer capability of a transmission corridor. This paper presents a proposed power and current injections model of C-UPFC. The developed model is incorporated in Newton–Raphson (NR) based on combined mismatches load flow algorithm. The shunt and series voltage control variables of C-UPFC are updated during the iterative process. This model contrary to some existing models of FACTS devices, keeps the original structure and symmetry of admittance and Jacobian matrices. The model presents a simple approach for implementation the C-UPFC in load flow code without any modification in Jacobian matrix. The approach is tested on the IEEE 30-bus and 57-bus systems using C++ load flow engine, proving its effectiveness in incorporating the C-UPFC in load flow algorithm.

1. Introduction

During the last decades, the flexible AC transmission Systems (FACTS) devices have been subjected intensive research and some of them are widely used for power system applications. In general, FACTS devices may be used to control the transfer power and voltage in this way enhancing the capacity of power network. This realized by controlling various parameters of transmission systems such as, shunt and series impedances, current, magnitude of voltage, phase angle [1–3].

In the late 1980s, the EPRI introduced the first vision of FACTS devices. In general, today the wide spectrums of power electronic devices are denoted with the acronym FACTS devices. The most common in application and research are; SVC, STATCOM, SSSC, TCSC, UPFC, GUPFC and IPFC, etc. As a basis for any study is the research of steady state situation, many researchers have focused their efforts on modeling such devices in load flow algorithms [2–15].

In [6,7] the shunt and series FACTS have modeled with a simple method based on decoupled approach. In this approach the FACTS parameters are updated after the convergence of load flow program. Based on that, it is difficult to determine whether the parameters of FACTS are within limits or not. The proposed models have been developed when the voltage, active and reactive line flows are controlled simultaneously. Also, the decoupled models faced the problem of selecting the suitable starting values of FACTS parameters and the problem when the FACTS devices are the only link between two sub-networks.

The comprehensive FACTS models have been developed in [2,3], to solve the drawbacks of decoupled technique. In this approach, the size of the Jacobian matrix is increased related to state variables of FACTS devices. The proposed approach needs suitable starting values of the FACTS parameters to improve the convergence characteristic of load flow algorithm.

Using the proposed approach in [8–10], the FACTS devices can be implemented in existing power flow algorithm with some modifications in Jacobian matrix. Based on this approach, a good modeling for UPFC has been presented to avoid any modifications in Jacobian matrix [11].

Ref. [12], presented good models for some FACTS devices based on matrix partitioning approach. However, this technique needs new codes related to the FACTS devices.

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http://dx.doi.org/10.1016/j.epsr.2014.12.013
0378-7796/

Nomenclature

p.u.	per unit
NR	Newton–Raphson method
PV	voltage controlled buses
PQ	load buses
FACTS	flexible AC transmission systems
IPFC	interline power flow controller
STATCOM	static synchronous compensator
UPFC	unified power-flow controller
C-UPFC	center-node unified power flow controller
GUPFC	generalized unified power flow controller
SSSC	static series synchronous compensator
TCSC	thyristor controlled series capacitor
SVC	static var compensator
EPRI	Electric Power Research Institute
N	total number of buses
P, Q	active and reactive complex powers
$\Delta I_r + j\Delta I_m$	complex current mismatch
$\Delta V_r + j\Delta V_m$	complex voltage mismatch
r,m	subscripts refer to real and imaginary parts
i, k, n, l	subscripts refer to nodes
Sp	superscript refers to specified values
sh	superscript refers to shunt values
se	superscript refers to series values
Vj, Vn, Vk	complex voltages at mid-point and two auxiliary buses
V_S	complex injected voltage source for first series converter
V_R	complex injected voltage source for second series converter
V_{sh}	complex injected voltage source for shunt converter
X_S	reactance of first series converter
X_R	reactance of second series converter
X_{sh}	reactance of second shunt converter
∂	refers to partial derivatives

A recent approach based on converting the controllers to augmented equivalent network has been proposed to model different types of FACTS devices [13–15]. The proposed approach reduces the complexities of load flow program with FACTS devices. But this approach needs to increase the size of Jacobian matrix in order to include the related state variables of FACTS devices.

The center-node unified power flow controller (C-UPFC) is one of FACTS devices which may have some advantages compared to other multi-parameters concepts [16,17]. Such device may be installed in series within transmission line. It basically consists of three voltage sources. One source is connected in shunt and the others in series. This device can be used to control four variables independently, e.g., the line real power, the reactive powers at both sides of a line and additionally the voltage magnitude at the midpoint of the transmission line.

Very few publications have been interested on the mathematical modeling of this new FACTS device in power system analysis. A transient model of C-UPFC device has been presented in [18]. However, the modeling of C-UPFC in load flow analysis has not been reported yet. Therefore, in this paper, a mathematical model of the C-UPFC suitable for power flow study is presented.

The developed C-UPFC model is incorporated in the new NR based on power and current mismatches load flow [19,20]. The proposed C-UPFC model is based on power and current injection approach. The implementation of C-UPFC model can be done easily without any modification in the original load flow code with keeping the same structure and symmetry of admittance and Jacobian matrices.

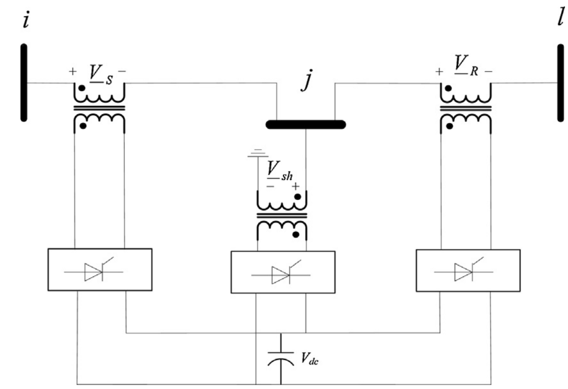

Fig. 1. Schematic diagram of C-UPFC.

The rest of paper is organized as follows: Section 2 establishes the operation principles and equivalent circuit of C-UPFC. Section 3 presents the formulation of C-UPFC model. In Section 4, two standard IEEE date systems are used to demonstrate the computational performance of the developed C-UPFC model in load flow algorithm. Brief conclusions are given in Section 5.

2. Operation principles and equivalent circuit of C-UPFC

In [16], the concept of a FACTS device positioned in the middle of a transmission line is presented. If voltage in middle of a line is controlled, virtually the transmission limitation due to transmission angle is extended by factor two. Based on that fact, B. T. Ooi and B. Lu have proposed a new device called C-UPFC which allows the range of series voltage compensation to be extended without exceeding the insulation voltage margin [17]. This new device may be positioned at any point in the transmission line. From operation point view, its optimal position is near from the mid-point. As already mentioned, the C-UPFC can independently control the active power in the line (P^{sp}), reactive powers of sending and receiving ends (Q_S^{sp}, Q_R^{sp}) and the mid-point voltage magnitude (V_J).

The C-UPFC consisting of three voltage source converters connected with common dc link provided by a dc storage capacitor is depicted in Fig. 1. One converter is a shunt at the mid-point of the transmission line and the others are series at the sides of the mid-point. The C-UPFC arrangement functions as an ideal ac-to-ac power converter in which the active power can freely flow in either direction among the ac terminals of the three converters, and each converter can independently generate or absorb reactive power at its own ac output terminal [17,18].

The basic function of shunt converter may be considered injecting or absorbing the active power demand by series converters at the common dc link to support the active power exchange resulting from the series voltage injection.

The equivalent circuit of C-UPFC consists of three voltage sources with series reactance representing the coupling transformers are presented in Fig. 2. For clarity in the presentation of this paper, the line resistances and converter losses are assumed to be negligible. The three voltage sources control the power flow of the line between nodes *i* and *l* and the voltage magnitude at mid-point (*j*). Buses *k* and *n* are reference points of the power flow direction. These buses are set as PQ-type [17,18].

The ideal C-UPFC voltage sources are:

$$\underline{V}_{sh} = V_{sh}(\cos\theta_{sh} + j\sin\theta_{sh}) \tag{1}$$

$$\underline{V}_S = V_S(\cos\theta_S + j\sin\theta_S) \tag{2}$$