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Power flow model/calculation for power systems with multiple FACTS controllers

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Abstract

This paper presents a new procedure for steady state power flow calculation of power systems with multiple flexible AC transmission system (FACTS) controllers. The focus of this paper is to show how the conventional power flow calculation method can systematically be modified to include multiple FACTS controllers. Newton–Raphson method of iterative solution is used for power flow equations in polar coordinate. The impacts of FACTS controllers on power flow is accommodated by adding new entries and modifying some existing entries in the linearized Jacobian equation of the same system with no FACTS controllers. Three major FACTS controllers (STATic synchronous COMpensator (STATCOM), static synchronous series compensator (SSSC), and unified power flow controller (UPFC)) are studied in this paper. STATCOM is modeled in voltage control mode. SSSC controls the active power of the link to which it is connected. The UPFC controls the active and the reactive power flow of the link while maintaining a constant voltage at one of the buses. The modeling approach presented in this paper is tested on the 9-bus western system coordinating council (WSCC) power system and implemented using MATLAB software package. The numerical results show the robust convergence of the presented procedure.

Keywords: Power flow; SSSC; STATCOM; UPFC; Modeling; Steady state analysis

1. Introduction

Power flow calculations are performed in power systems for planning, operational planning, and operation/control [1]. Power flow programs are the most frequently used computer routines for power systems calculations. Appropriate steady state model of power system is needed for writing the computer programs. The model includes nonlinear algebraic equations, which must be solved iteratively. Power flow calculation is needed for both steady state power flow analysis and initializations for different dynamic analyses.

Flexible AC transmission system (FACTS) controllers are able to change the network parameters in a fast and effective way in order to achieve better system performance [2]. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady state. Three advanced FACTS controllers are considered in this paper. These controllers are: STATic synchronous COMpensator (STATCOM), static synchronous series compensator (SSSC), and unified power flow controller (UPFC).

Most researchers and industries use Newton–Raphson method of iterative solution. This method is also used in present paper. Newton–Raphson method is superior to other methods because of its quadratic convergence properties. Traditional power flow programs do not include the newly developed FACTS controllers: STATCOM, SSSC and UPFC. This paper shows how easily and systematically an existing power flow program can be extended/modified to include these controllers.

Several researchers have reported the development of steady state models for FACTS controllers [3–12]. Reference [3] proposes a method to account the losses of STATCOM in power flow analysis. Reference [10] describes a multi-functional model of the SSSC for power flow analysis, which can be used for steady state control of one of the several parameters including: the transmission line active (or reactive) power flow, voltage magnitude at the bus, and line reactance. Reference [11] presents a power

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flow model for UPFC that can be set to control one or more of three variables (active power, reactive power, and voltage magnitude) simultaneously.

The objective of the present paper is to develop a power flow model for a power system with multiple FACTS–controllers and a procedure using which the conventional power flow calculation is systematically extended to include these controllers. Newton–Raphson method of power flow solution in polar coordinate as described in [13] is used in this study. The steady state power flow models for the FACTS–controllers, used in this study, have been validated by other authors [8].

2. Modeling of power systems with multiple FACTS controllers

The block diagram given in Fig. 1 shows a symbolic representation of a power system that includes several generators, several loads, a STATCOM, an SSSC, and a UPFC. The different components are interconnected through the transmission network modeled by its *Y*-matrix. It should be noted that, this *Y*-matrix does not include the admittances of the loads and the FACTS controllers. The steady state (or power flow model) of the system includes, primarily, the equality constrained imposed by the transmission network for supplying the demands at different buses. These equations relate the net injected active/reactive power at each bus to all other bus voltages (both magnitudes and angles).

The power flow equations for a generic bus (Bus *i*) of the power system with no FACTS controller is given below:

$$P_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (1)$$

$$Q_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

where $|V_i| \angle \delta_i$ represents the complex voltage of a generic Bus *i* and $|Y_{ij}| \angle \theta_{ij}$ represents the (*i*, *j*)-entry of the *Y*-matrix. The above set of power flow equations are iteratively solved using

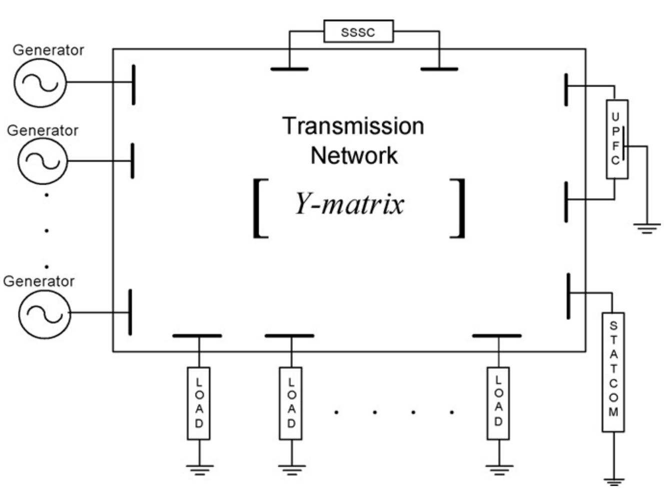

Fig. 1. Symbolic representation of a power system.

the linearized Jacobian equation given by [13]. This equation is given in (3), next page, where the sub-Jacobian matrices are defined as $J^1 = \partial P/\partial\delta$, $J^2 = \partial P/\partial|V|$, $J^3 = \partial Q/\partial\delta$ and $J^4 = \partial Q/\partial|V|$:

$$\begin{bmatrix} J^1 & J^2 \\ J^3 & J^4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (3)$$

The objective of this paper is to solve the power flow problem for the system with the FACTS controllers (STATCOM, SSSC, and UPFC). The presence of FACTS controllers is accommodated and accounted for by adding new equations to the set of the power flow equations and modifying some of the existing power flow equations as needed. The Jacobean equation is extended/modified accordingly.

2.1. Power system with STATCOM

Fig. 2 shows the circuit model of a STATCOM connected to Bus *k* of an *N*-Bus power system; the subscript ‘p’ means the STATCOM is connected in parallel with the power system. The STATCOM is modeled as a controllable voltage source (E_p) in series with an impedance [8]. The real part of this impedance represents the ohmic losses of the power electronic devices and the coupling transformer, while the imaginary part of this impedance represents the leakage reactance of the coupling transformer. Assume that the STATCOM is operating in voltage control mode. This means that the STATCOM absorbs proper amount of reactive power from the power system to keep $|V_k|$ constant for all power system loading within reasonable range. The ohmic loss of the STATCOM (identified by P_p in Fig. 2) is accounted for by considering the real part of Y_p in power flow calculations. The net active/reactive power injection at Bus *k* including

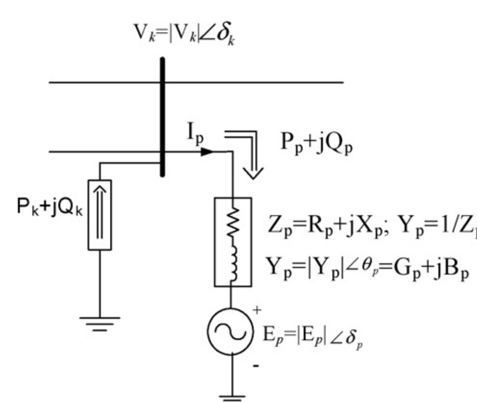

Fig. 2. Steady state model of STATCOM.