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Power flow analysis with easy modelling of interline power flow controller

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ABSTRACT

This paper proposes an easy modelling of interline power flow controller (IPFC) into Revised Newton Raphson current injection load flow method. In this model, the IPFC is represented as series impedances with shunt injected currents at its terminal buses. The target of control for active and reactive power flow can be achieved by calculating these currents as a function of the desired power flow and the buses voltage at the terminals of IPFC. In case of controlling the active power flow only, these currents are calculated with the same method. But the reactive power flow is released and calculated according to the system. The injected currents are updated and added into the original current mismatches vector of load flow algorithm. By using this model, the symmetry of the admittance and Jacobian matrices can still be kept and incorporating of IPFC becomes easy without changing the basic load flow computational program. Consequently, the complexities of the computer program codes are reduced. Numerical results based on the literature 5-bus, IEEE 57-bus and IEEE 118-bus systems are used to demonstrate the effectiveness and performance of the proposed IPFC model.

1. Introduction

Flexible AC transmission system controllers are playing a leading role in efficiently controlling the line power flow and improving voltage profiles of the power system network. These FACTS controllers can be used to increase the reliability and efficiency of transmission and distribution systems [1–7].

In general, there are two generations of these developed control devices; the first generation is based on the conventional thyristor switched capacitors and reactors, and tap changing transformers, while, the second generation uses the GTO thyristor switched converters as voltage source converters (VSCs).

The first generation has resulted in the SVC, TCSC and the TCPS. The second generation has produced the STATCOM, the SSSC, the UPFC and the IPFC. The two groups of FACTS controllers have distinctly different operating and performance characteristics [4].

The IPFC is considered a new generation of FACTS controllers. The combinations of two or more series compensators are coupled via a common dc link to give the structure of IPFC.

The main advantage of IPFC is the ability to control both real and reactive power flow at a multi-line substation. Hence, the power can be transferred from the over loaded line to the under loaded line [7].

In general, the modelling of FACTS in power flow calculations with improving the reusability of computer program codes and avoiding the Jacobian modifications become important and challenging research problem. In contrast to the modelling of the UPFC and SSSC, research work on the modelling of IPFC for power system analysis is limited.

However, the following modifications are required in load flow analysis in order to incorporate FACTS controllers: firstly, the incorporation of FACTS into a transmission line requires adding auxiliary buses in the system. Secondly, the FACTS impedances have to be included into the admittance. Thirdly, the powers contributed by FACTS have to be included into power flow mismatch equations. Finally, the system Jacobian matrix contains entirely new Jacobian sub-blocks exclusively related to the FACTS controllers [4].

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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
SSSC static series synchronous compensator
TCSC thyristor controlled series capacitor
SVC static var compensator
GTO gate turn-off
VSCs voltage source converters
TCPS thyristor-controlled phase shifter
N total number of buses
P, Q active and reactive complex powers
$\Delta I_{rf}+j\Delta I_{mf}$ complex current mismatch at bus f
$\Delta V_{rf}+j\Delta V_{mf}$ complex voltage mismatch at bus f
r, m subscripts refer to real and imaginary parts
i, j, k subscripts refer to nodes
sp superscript refers to specified values
Z_{se1} the series transformer impedance of main converter
Z_{se2} the series transformer impedance of slave converter
V_i, V_j, V_k the complex voltages at sending and auxiliary buses
V_{se1} the complex series injected voltage source for main converter
V_{se2} the complex series injected voltage source for slave converter
$G_{km}+jB_{km}$ the element of nodal admittance matrix between buses (k, m)
$P_{G(f)}+jQ_{G(f)}$ generated complex power at bus f
$P_{L(f)}+jQ_{L(f)}$ complex power consumed by load at bus f
∂ refers to partial derivatives

Due to the above requirements, many excellent research works have been carried to incorporate some famous FACTS with minimum modifications in original load flow algorithm [7–23]. However, these developed techniques can be applied for modelling IPFC controller in load flow analysis.

Ref. [8] has presented simple modelling of FACTS based on decoupled approach. In this technique, the sending and receiving buses of FACTS are separated. Then, active and reactive loads are injected at the terminal buses with desired line flow. To control the voltage at particular bus, this bus has to be converted into PV-type with required voltage value. Then, after load flow convergence is achieved, an additional set of non-linear equations related to various FACTS parameters has to be solved. However, this technique faced some shortcomings such as; the FACTS parameters are computed after the load flow converge, so, the method has not the ability to known whether these parameters are within Limits or not, the method discussed only the situations when the FACTS device is used to control the active power flow, reactive power flow and voltage simultaneously, also, the problem of selecting suitable initial value of FACTS parameters still exists. Finally, what is the solution when the FACTS device is the only link between two sub-networks.

Ref. [12] has presented the FACTS control parameters as independent variables and their values are calculated during the iterative process of load flow program. This technique increases the size of the Jacobian matrix in order to accommodate the additional independent state variables of FACTS devices. However, the convergence manner is very sensitive to the initial value of the FACTS parameters [13]. Also the Jacobian matrix should be changed related to contribution of FACTS device.

Modelling of FACTS controllers based on indirect approach to reduce the complexity of programming codes have been presented in Refs. [16–18]. In this technique, the FACTS device is presented by an augmented equivalent network. Then, without any FACTS, the standard NR load flow can be carried out to calculate the steady state operating point of the original system containing FACTS. In this technique, the size of the Jacobian matrix has to be increased in order to accommodate the additional state variables of FACTS.

Modelling of FACTS controllers based on power injection approach has been presented in Refs. [14,15]. In these models, the Jacobian matrix can keep the block-diagonal properties; the FACTS state variables are adjusted simultaneously with the network state variables in order to achieve the specified control targets. In these two above methods, the elements of Jacobian matrix contain entirely new Jacobian sub-blocks exclusively related to the FACTS controllers have to be updated during the iterative process.

Ref. [19] presents an elegant approach based on power injection formulation to model UPFC in load flow algorithm to avoid the modification in Jacobian matrix.

With respect to load flow problem, NR method is considered as the state of the art load flow technique and widely used in the industry. The main disadvantage of this technique is the necessity for factorizing and updating the Jacobian matrix during the iterative process. However, the FD load flow method was proposed to speed up the NR load flow method and decreases the required minimum memory storage [24]. The main disadvantage of this method is affecting of convergence rate with high R/X ratios [25].