

POWER FLOW ANALYSIS OF POWER SYSTEM EMBEDDED WITH UPFC USING PSASP PROGRAM

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ABSTRACT

Unified Power Flow Controller (UPFC) is a very superior high power compensator in which solid-state power electronic-based converters are employed, able to control simultaneously or selectively all three network parameters (voltage, impedance, transmission angle) determining power transmission. This paper shows that it is possible to use currently available commercial software, Power System Analysis Software Package (PSASP), to easily simulate a UPFC embedded within a power network. Computer simulation of UPFC is conveniently obtained from a power injection model, which is suitable for steady-state studies. On the basis of computer modeling, case studies would be useful to investigate potential capabilities of an UPFC on active and reactive power flows.

I. INTRODUCTION

The development of power electronic-based Flexible AC Transmission Systems (FACTS) has been initiated by Electric Power Research Institute (EPRI), in which power flow is dynamically controlled by various power electronic devices [1]. And because of the fast progress in power electronics technology [2], it becomes as a promising subject. Along with advanced control techniques on FACTS devices, transmission grid is getting more controllable and flexible [3,4]. Among a variety of FACTS members, UPFC is the most compete and versatile, capable of acting over basic electrical system parameters; line voltage, line impedance, and phase angle which determine transmitted power [5,6,7]. Therefore it is chosen as the focus of investigation. It allows to force power transmit in prescribed routes in which the power flow is solely governed by classical network laws. Power flow in individual lines of the transmission grid is determined by their impedance and it often cannot be restricted to the desired power

corridors. As a consequence, power flow loops develop and certain lines become overload, while some of them are underloaded below their thermal limit, all the situations lead to inefficient use of transmission system and also with the overall effect of deteriorating voltage profiles and decreased system stability. [8]. Besides acting on power flow control, the most important characteristics of UPFC are its multiple control functions including, dynamic voltage regulation, transient stability enhancement and oscillation damping [9,10]. Comparison of UPFC, with more conventional compensation method of employing thyristor switched/controlled reactors (TSC/TCR) and pure reactors shows its superior performance including the unmatched capability of using both reactive and real power compensation to counteract dynamic disturbances, and being uniform in applicability. Based on IEEE 14-bus test system [11], a simulation study of UPFC is carried out in this paper. Firstly a mathematical representation of UPFC is developed based upon power injection model; secondly a method embedded in PSASP is applied to adopt the model for location of UPFC on a transmission line in IEEE 14-bus test system. The static characteristics of the system with UPFC under normal operating conditions, including the control effects of UPFC on various operational parameters and the steady-state response of the system when UPFC input parameters are being changed, is investigated.

II. A BRIEF REVIEW OF UPFC

Figure 1 shows the schematic diagram of the basic structure of an UPFC. It consists of shunt and series connected power electronic-based voltage sourced converters, two coupling transformers, Tr_{sh} and Tr_{se} , and a dc link capacitor, C . Power converters are constructed by GTO thyristor valves and diodes. The principal function of the converters is to emulate

symmetrical ac output voltages with controllable magnitude and phase angle at their ac output terminals. The formation of ac voltages might be implemented principally by two approaches. Firstly, the outputs of multiple converter units giving symmetrical square waveform are shifted in phase and summed to give multi-pulse nearly sinusoidal waveform by means of a magnetic structure. This method requires low pulse number design for each unit, but multi-level structure introduces complexity into the magnetic structure and its related controls. Another approach is that using sinusoidal pulse width modulation technique (SPWM), which can be an alternative to improve the shortcomings mentioned above. In case of SPWM technique, the magnetic structure is even simpler and since high number of pulses is aimed, the harmonic injection into the power system would not be too large. Generally the more number of pulses are achieved, the fewer amounts of adverse effects of harmonics are introduced into the power system. Operating losses of the converters should also be taken into account in terms of efficiency.

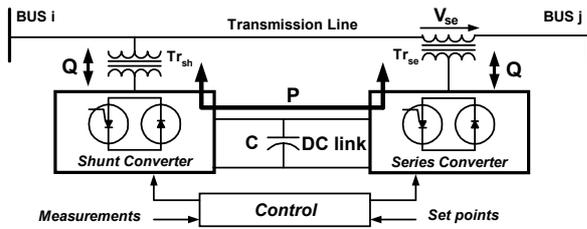


Figure 1 Basic schematic diagram of UPFC

In Figure 1 also the directions of both real power flow P , and reactive power flow Q in UPFC may be observed. The dc link provides a path for active power exchange between the two converters, while each converter can either deliver or consume reactive power at their output terminals. In a UPFC, the series connected converter can perform the main function of power flow control by inserting a controllable voltage, V_{sc} into the transmission line through transformer, Tr_{se} . Meanwhile shunt connected converter is used to balance the real power, which is injected into or absorbed from the transmission line by the series connected converter via the dc-linked capacitor. Since each converter unit is capable of performing reactive power compensation, shunt connected one may also be used for dynamic voltage control. Since the objective of this study is both to develop a sufficient steady-state model of UPFC for representing it in PSASP and to investigate the capabilities of UPFC on active and reactive power flow control, thereby the following assumptions are made.

- UPFC is simulated on a concept of power injection model based on the idea of representing the ac outputs of the two converters as ideal sinusoidal voltage sources of which the magnitude and phase angle are fully and

independently controllable. So the outputs of the converters are assumed to be harmonic free.

- The dynamics of switching behavior of the converters and the coupling transformers are neglected.
- At the same time, the voltage of the DC link capacitor is assumed to be constant, i.e., the dynamics of the DC link are ignored. Thereby the active power exchange between the series and shunt converter are assumed to be fully satisfied.

If a dynamic study were to be carried out, in order to obtain accurate simulation results, the factors listed above should be taken into account in order to reflect precisely and thoroughly the operational characteristics of the UPFC and its effects on power network.

III. UPFC POWER INJECTION MODEL

Power injected model of UPFC can be derived by referring Figure 2. Bus i and Bus j are added to system by incoming of UPFC. Sending-end and Receiving-end Buses are the two buses belonging to transmission line on which UPFC might be sited. The converters are realized as controllable voltage sources and transformers as leakage reactances. The transmission line is modelled by its nominal π -equivalent circuit and transmission line current is flowing through voltage source V_{sc} , causing an active power exchange, P_{series} between UPFC and power system through shunt branch.

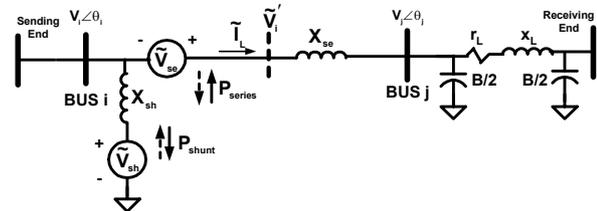


Figure 2 UPFC equivalent circuit in case of UPFC location near sending-end bus

By using the transformation from thevenin equivalent circuit into norton equivalent circuit, series connection of voltage sources and reactances can be transformed into shunt connection of current sources and susceptances. This transformation enables developing injected power model of UPFC. After a number of calculation steps [12], UPFC power injection model derived in polar form as injections of powers, $P_{i,upfc}$, $P_{j,upfc}$, $Q_{i,upfc}$, and $Q_{j,upfc}$ at Bus i and Bus j is obtained as shown in Figure 3. At the derivations the total efficiency of UPFC is taken as 98% [13].

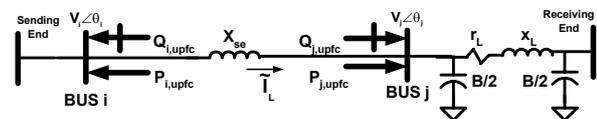


Figure 3 UPFC power injection model

Power injections, $P_{i,upfc}$, $P_{j,upfc}$, $Q_{i,upfc}$, and $Q_{j,upfc}$ are derived as follows:

$$\begin{aligned} P_{i,upfc} &= 0.02rb_{se} V_i^2 \text{Sin}\gamma \\ -1.02rb_{se} V_i V_j \text{Sin}(\theta_i - \theta_j + \gamma) \end{aligned} \quad (1)$$

$$Q_{i,upfc} = -rb_{se} V_i^2 \text{Cos}\gamma \quad (2)$$

$$P_{j,upfc} = rb_{se} V_i V_j \text{Sin}(\theta_i - \theta_j + \gamma) \quad (3)$$

$$Q_{j,upfc} = rb_{se} V_i V_j \text{Cos}(\theta_i - \theta_j + \gamma) \quad (4)$$

Where

r is per unit magnitude of V_{se} ,

γ is phase angle of V_{se} , with respect to θ_i ,

b_{se} is reciprocal of X_{se} , leakage susceptance of series coupling transformer.

IV. UPFC IMPLEMENTATION IN PSASP

PSASP is a newly developed power system analysis software package developed by EPRI China [14], has capability of creating user-defined models of many types of power system equipment. The block diagram of user-defined model of UPFC is drawn in Figure 4. Many blocks constitute the model and the functions of them are explained in Table 1. When constructing user-defined model, the following situations are realized.

- UPFC user-defined model is completely developed based upon power injection model derived in equations [1-4].
- Two P-Q buses (load buses) must be created on transmission line where UPFC is considered to be located.
- The transmission line data must be modified, depending on the location of UPFC, sending-end side, receiving-end side, or middle of line position.
- Series reactance X_{se} , leakage reactance of series coupling transformer of UPFC, must be considered in order to represent the model correctly.

Table 1 Blocks and their functions constituting user-defined model

Name of Block	Function
Y=A	Constant parameter block; input is equal to pre-defined constant A
AX1*X2	Multiplication block; multiplies the two inputs and outputs the result
AX1+BX2	Summing block; sums the two inputs and outputs the result
SIN	Sine block; take the sine of input and outputs the result
COS	Cosine block; take the cosine of input and outputs the result

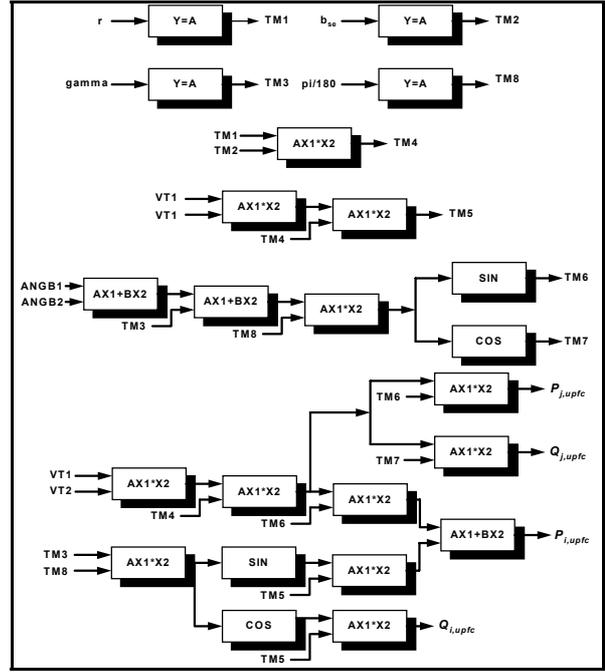


Figure 4 Block diagram of user-defined model of UPFC

V. SIMULATION SCENARIOS

Power flow case studies on IEEE 14-bus test system with embedded UPFC, shown in Figure 5 is carried out using PSASP. Newton (Power) calculation method is selected Allowed iteration tolerance is taken as $1E-6$ in all of the cases. Four different cases are considered in simulations. First of all and without any compensation, the electrical system is studied in order to determine the load flow in each of the transmission line. This allows to have a general idea about system steady-state operation. Then UPFC siting is chosen arbitrarily as near Bus 2 location on line (2-5), but thought to be near power generation sections. Different UPFC parameters are set to activate UPFC, the transmitted active and reactive power of all of the lines has remarkably changed. Table 2 shows the selected results of the load flow analysis as well as total transmission losses.

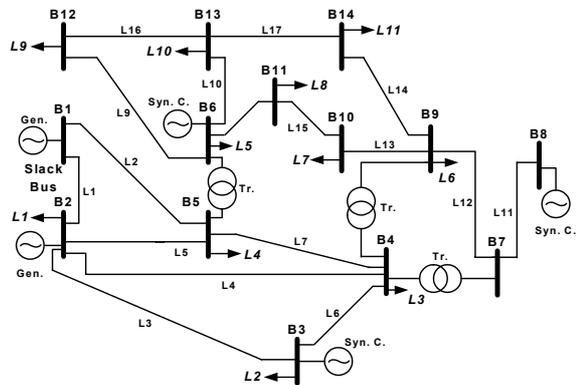


Figure 5 IEEE 14-bus test system

Comparing load flow solutions of the system without and with UPFC, it can easily be concluded that user-defined model for UPFC developed in this study is working properly that Table 2 shows a clear convergence of program in case of different UPFC parameters. Also the model is efficient on analysis of power flow and control parameters of UPFC. The simulation results regarding the system voltage profile can also be observed in Figure 5.

Table 2 Load flow results of the IEEE 14-Bus test system with and without UPFC

Without UPFC		Case 1	
UPFC parameters		UPFC parameters	
$r=0.0$	$\gamma=0.0^\circ$	$r=0.05$	$\gamma=45.0^\circ$
Power flow in (pu)		Power flow in (pu)	
Line	P+jQ	P+jQ	
L1	1.5512-j0.2296	1.2055-j0.1448	
L2	0.7774-j0.1363	0.7002-j0.1770	
L3	0.7176+j0.0132	0.7190+j0.0130	
L4	0.5564-j0.1648	0.5665-j0.2031	
L5	0.4183-j0.1927	0.0777-j0.04151	
L7	-0.6114-j0.055	-0.6052-j0.1587	
Transmission Losses		Transmission Losses	
Active (MW)		Reactive (MVAR)	
13.83	11.02	11.91	12.55
Case 2		Case 3	
UPFC Parameters		UPFC Parameters	
$r=0.1$	$\gamma=90.0^\circ$	$r=0.12$	$\gamma=15.0^\circ$
Power flow in (pu)		Power flow in (pu)	
Line	P+jQ	Line	P+jQ
L1	0.6586+j0.0045	L1	1.2375-j0.1529
L2	0.5223-j0.1303	L2	0.6898-j0.2461
L3	0.7129+j0.0136	L3	0.7009+j0.0149
L4	0.5496-j0.1791	L4	0.5383-j0.2507
L5	-0.4284-j0.1910	L5	0.1548+j0.02262
L7	-0.6234-j0.0944	L7	-0.6533-j0.2907
Transmission Losses		Transmission Losses	
Active (MW)		Active (MW)	
10.21	9.61	12.66	13.03

Table 2 PSASP calculation performance

Iteration number	Accuracy	UPFC parameters	
		r (pu)	γ° (degrees)
4	0.000000	0.0	0.0
8	0.000000	0.12	15.0
7	0.000000	0.1	90.0
6	0.000000	0.05	45.0

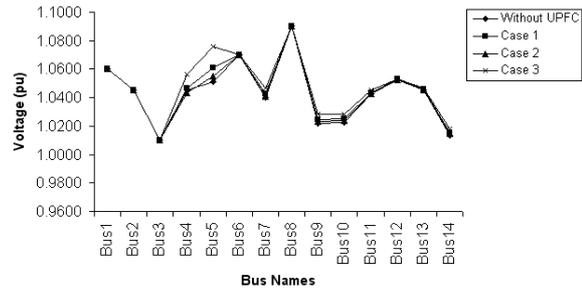


Figure 6 Voltage Profile of test system

VI. CONCLUSIONS

An injected power model for evaluating UPFC steady-state performance is developed and adopted into a user-defined model in PSASP in this study. The software used in this study is a very practical and useful software package that allows modeling of complex devices, such as UPFC. The application has been verified and tested on IEEE 14-bus test system in which UPFC is sited on a transmission line. Numerical computations have shown that the algorithm is effective in terms of computational speed and convergence. The case studies demonstrate that the UPFC is able to control both active and reactive power transmit on transmission lines. The studies on the IEEE 14-bus test system also show that the incoming of UPFC can disturb system voltage profile at the neighboring buses to UPFC located line significantly unless a voltage regulation support at those buses is provided.

VII. RECOMMENDATIONS FOR FUTURE WORK

The study may be expanded by using a closed-loop feedback control algorithm in order to regulate active and reactive power flows on transmission lines so as to keep them in pre-defined values. This situation is considered as a prospective study by the authors.

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