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Power Flow Analysis Using Unified Power Flow Controller

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ABSTRACT
This paper presents the power flow control in electric power systems by use of an improved steady state mathematical model of unified power flow controller embedded in a power system. The main characteristic of the approach is that an equivalent mathematical model is developed based on the concept of injected powers in which the operational losses can be taken into account. The model is is quite suitable in load flow studies, since it accepts employing conventional techniques such as Newton Raphson method. The model is validated by embedding it in IEEE 14 bus system and then carrying out the load flow studies using MATLAB.The results of load flow analysis show the effectiveness of the model.
Key words - FACTS, UPFC, Power flow analysis

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I. INTRODUCTION

The power transmitted over an AC transmission line is a function of the line impedance, the magnitude of sending-end and receiving-end voltages, and the phase angle between these two voltages. There is a need for new power flow controllers capable of increasing transmission capability and controlling the parameters affecting the power flow in the transmission line [1].Flexible ac transmission system (FACTS) devices give more flexibility of control for secure and economic operation of power systems. Among FACTS devices, the unified power flow controller (UPFC) is emerging as a promising solution for improving power system characteristics for its high degree of controllability of many power system variables. UPFC can control simultaneously or selectively, all parameters affecting power flow in the transmission line i.e., voltage, impedance and phase angle. It can also independently control both real and reactive power flow in the transmission line, besides that it has the capabilities of improving transient stability, mitigating system oscillations and providing voltage support. Performance analysis of UPFC in load flow studies requires its steady state modeling[4, 5]. In [6],UPFC is represented by two ideal voltage sources with series source impedances, connected in series and parallel with the transmission line, representing the output voltages of series and shunt branches of UPFC. BecauseUPFC employs two voltage source converters and two coupling transformers; the mathematical model proposed here is based on the true representation of them in a computational environment. Converters are modeled as controllable voltage sources, while the effects of the transformers are modelled as pure inductances connected to the lines and real power loses in UPFC.

II. STEADY-STATE UPFC REPRESENTATION

The conceptual hardware configuration of UPFC is shown in Fig. 1.Converters labeled as “series converter” and “shunt converter” are operated from a common dc link voltage provided by dc storage capacitor. Two coupling power transformers are also required to isolate UPFC and the transmission line, and to match the voltage levels between the power network and voltage produced by the converters. This arrangement can be functionally treated as an ideal ac to ac power converter in which the magnitude and phase shift of the ac output voltages of both converters can be controlled at any desired value, assuming that the controlled voltage source in series with the transmission line can be controlled without restriction. This means that the phase angle of the series injected voltage can be chosen independently of the line current. Eventually as seen in Fig. 1, the real power can freely flow in either direction between ac terminals of the two converters and each converter can also generate or absorb reactive power independently at its own ac output terminals. The series converter performs the main functions of UPFC, while the shunt converter is used to provide real power demanded by the series converter and the losses in UPFC.

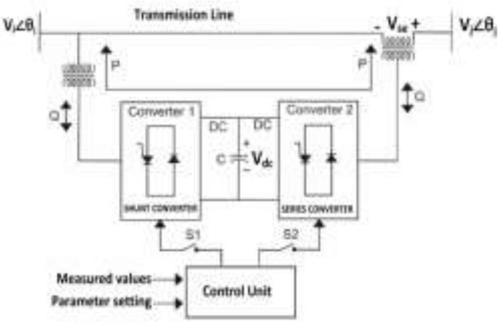


Fig. 1. Schematic diagram of an UPFC

The UPFC can be represented in steady state by the two voltage sources with appropriate impedances as shown in Fig. 2.The voltage sources can then be represented by the relationship between the voltages and amplitude modulation ratios, and phase shifts of UPFC. In this model, the shunt transformer impedance and the transmission line impedance including the series transformer impedance are assumed to be constant. Themathematical model is constructed by representing the ac output terminals of the two converters with two ideal voltage sources,V_{se}andV_{sh}respectively in series with the reactance's X_{se}, and X_{sh}, denoting the leakage reactance of the two coupling transformers respectively in Fig. 2. I_L represents transmission line current having a phase angle of Φ_{IL}

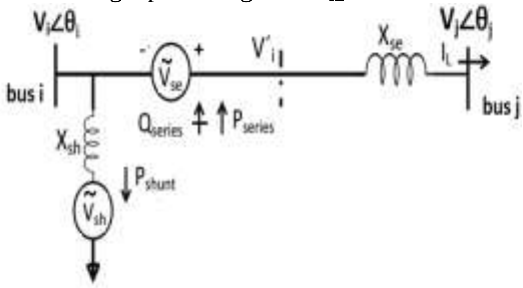


Fig. 2. Equivalent circuit of UPFC

A. Series Connected Voltage Source Converter

As seen in Fig. 2, $\tilde{V}_i$ represents an imaginary voltage behind the series reactance X_{se}

$$\tilde{V}_i = \tilde{V}_{se} + \tilde{V}_i \quad (1)$$

Series voltage source, V_{se} is controllable both in magnitude and phase angle

$$\tilde{V}_{se} = r\tilde{V}_i e^{i\theta}$$

(2)

Where, $0 \le r \le r_{max}$ and $0 \le$□≤ 2□

The related phasor diagram of the concerned parameters in (1) and (2) is drawn in Fig. 3.

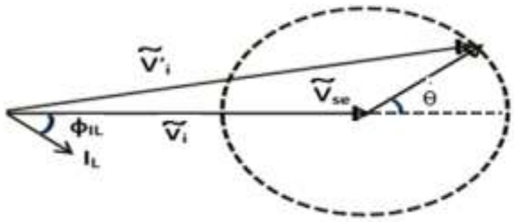


Fig. 3. Phasor diagram

In Fig. 3, voltage of bus i, V_i is assumed to be reference vector i.e $v_i = v_i < 0^0$. The power injection model can be obtained by replacing the voltage source V_{se} by a current source I_{se} in parallel with the transmission line as shown in Fig. 4.

$$\tilde{I}_{se} = -jb_{se}\tilde{V}_{se}$$

(3)

Where $b_{se} = 1/X_{se}$

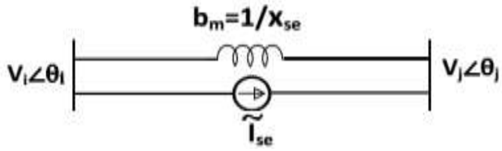


Fig**. 4.** Replacement of series voltage source by current source

The effects of the current source I_{se} and susceptanceb_{se} can be modeled by the injection powers at buses i and j.

$$S_{is} = \tilde{V}_i(-\tilde{I}_{se})^* \quad (4)$$

$$\tilde{S}_{js} = \tilde{V}_j(-\tilde{I})^* \quad (5)$$

$$\tilde{S}_{is} = P_{is} + jQ_{is} = -rb_{se}v_i^2 \sin\theta - jrb_{se}v_i^2 \cos\theta$$

(6)

$$\tilde{S}_{js} = P_{js} + jQ_{js} = v_i v_j b_{se} r \sin\left(\phi_i - \phi_j + \theta\right) + jv_i v_j b_{se} \cos\left(\phi_i - \phi_j + \theta\right) \quad (7)$$

Based on (6) and (7), power injection model of series connected voltage source can be seen as two dependent power injections at buses i and jshown in fig. .5.

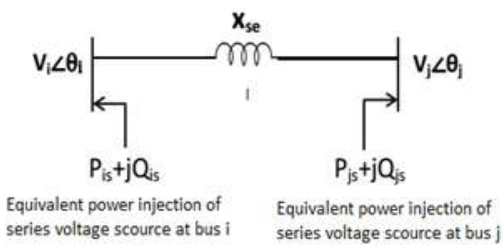


Fig. 5. Equivalent power injections of series voltage source.

B. Shunt Connected Voltage Source Converter

In UPFC, shunt connected voltage source is used mainly to provide both real power, P_{series}, which is injected to the system through the series connected voltage source, and the total losses within the UPFC. The total switching losses of the two converters is estimated to be about 2 % of the power transferred for thyristor based PWM converters [7]. If the losses are to be included in the real power injection of the shunt connected voltage source at bus i, $P_{shunt}$is equal to 1.02 times the injected series real power P_{series}through the series connected voltage source to the system.

$$P_{shunt} = -1.02 P_{series} \quad (8)$$

The complex power supplied by the series voltage source converter is given as

$$\begin{aligned} \tilde{S}_{series} &= \tilde{V}_{se} \tilde{I}_L^{\,*} = P_{series} + jQ_{series} \\ &= v_i v_j b_{se} r \sin(\phi_i - \phi_j + \theta) - r b_{se} V_i^2 \sin\theta \\ &\quad - jrv_i v_j b_{se} \cos(\phi_i - \phi_j + \theta) + \\ &\quad jrV_i^2 b_{se} \cos\theta + jr^2 b_{se} V_i^2 \end{aligned} \quad (9)$$

The reactive power delivered or absorbed by shunt converter is not considered in this model, but its effect can be calculated and modeled as a separate controllable shunt reactive source, The main function of this reactive power is to maintain the voltage level at bus i within acceptable limits, in this case shunt converter functions as a static var compensator. In view of the above explanations, we assume that Q_{shunt}=0**.** Consequently, the UPFC power injection model is constructed from the series connected voltage source model with the addition of a power injection equivalent to P_{Shunt} + j0to bus i as shown in Fig. 6.

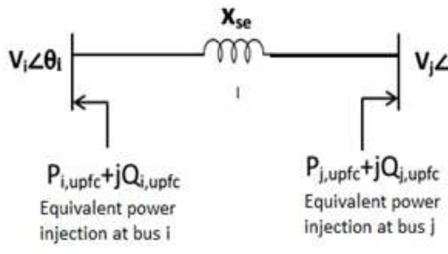


Fig. 6. Complete power injection model

$$\begin{aligned} P_{i,upfc} &= P_{is} + P_{shunt} = 0.02 r b_{se} V_i^2 \sin\theta \\ &\quad -1.02 r v_i v_j b_{se} \sin(\phi_i - \phi_j + \theta) \end{aligned} \quad (10)$$

$$Q_{i,upfc} = Q_{is} = -r b_{se} V_i^2 \cos\theta \quad (11)$$

$$P_{j,upfc} = P_{js} = r v_i v_j b_{se} \sin(\phi_i - \phi_j + \theta) \quad (12)$$

$$Q_{j,upfc} = Q_{js} = r v_i v_j b_{se} \cos(\phi_i - \phi_j + \theta) \quad (13)$$

III. IMPLEMENTATION OF UPFC MODEL IN POWER FLOW STUDIES

Two imaginary PQ buses (bus i and bus j) are created on line where UPFC is consideredto be located. In order to represent the model correctly, seriesreactance Xse, is positioned between these two buses. When the position of UPFC on the transmission line is changed, the line data, Z, should be modified, depending on the location of the UPFC. Here the UPFC is considered to positionin the middle of line as illustrated in Fig. 7.

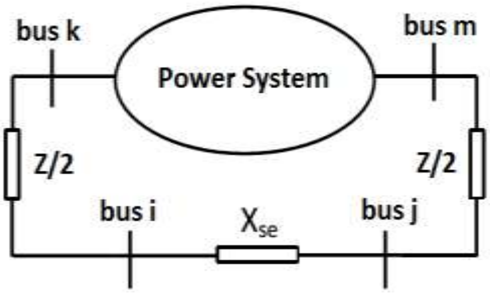


Fig. 7. Modification of line data due to UPFC position

IV. SIMULATION

The performance of the UPFC injection model is tested by carrying load flow studies on IEEE 14-bus system [3] embedded with UPFC by using Newton Raphson method in MATLAB. The injection model isplaced near bus 2 on line 5, near to power generation sections as shown in Fig.8.

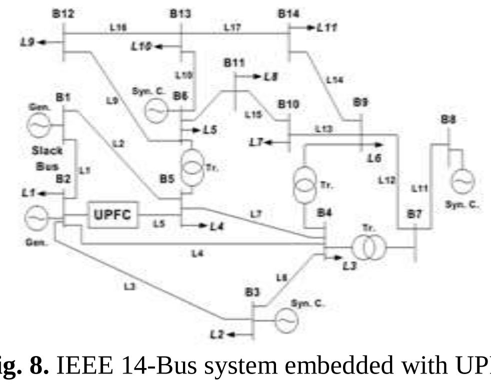


Fig. 8. IEEE 14-Bus system embedded with UPFC

The UPFC has two control parameters r and θ, the magnitude and phase of the injected voltage respectively. Allowed iteration tolerance is taken as IE-5.Firstofall without any compensation, the electrical system is studied in order to determine the load flow in each of the transmission line, then after introducing the UPFC in the system and with different UPFC parameters the voltage profile of all buses, the transmitted active and reactive power of all lines are studied. All the results indicate good convergence and high accuracy achieved by the proposed method. TABLE 1 shows the selected results of the load flow analysis. Fig.8 and Fig. 9 shows the graphical results related with simulation. Comparing load flow solutions without and with UPFC, power flows can be flexibly controlled by UPFC. The simulations show that UPFC provides independent control of active and reactive power and improvement of voltage profile at the busses.

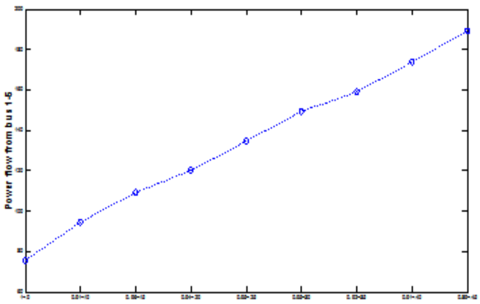
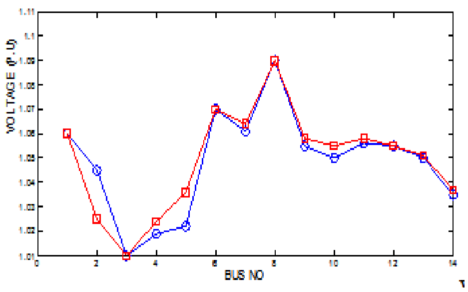


Fig.8. Active power flows



Without UPFC with UPFC

Fig. 9. Voltage profile of 14 bus system

V. CONCLUSIONS

An injection modeling approach for power flow analysis of power system with UPFC is studied. A steady state mathematical model for the UPFC was proposed. The proposed model can easily be incorporated in existing power flow programs. In this paper the performance of UPFC was investigated in controlling the flow of power over the transmission line. Numerical results verify the effectiveness of the model in terms of computational speed, accuracy and computing resources requirement. It was found that the UPFC regulates the voltage of the buses as well as regulates the active and reactive power of the buses.

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TABLE 1: LOAD FLOW RESULTS OF IEEE 14-BUS SYSTEM WITHOUT AND WITH UPFC

Bus no	Line power flow in p.u			
	without UPFC	With UPFC		
	r=0, θ=0°	r=0.95, θ =25°	r=0.91, θ =40°	r=0.89, θ =45°
1-2	1.568-i0.2335	0.84439-i0.0482	0.3860-i0.6252	0.3679-i0.6198
1-5	0.7556-i0.2806	1.348-i0.0271	1.740+i0.0048	0.1893+i 0.0621
2-3	0.7280+i0.0121	1.071-i0.0104	1.315+i0.1920	1.396+i10.9231
2-4	0.5586-i0.6517	1.273-i0.1497	1.814+i0.0301	1.972 +i0.0680
4-5	-0.61914-i0.1629	0.2879-i0.2688	0.9279-i0.4219	1.111-i0.4530
Total active power loss	0.1334	0.0187	0.0839	0.2221
Total reactive power loss	0.0534	0.3265	0.1560	0.2118

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