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Analyzing the Effect of Power Injection Model of Generalized Unified Power Flow Controller

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Abstract: Now a day, because of the technological developments in power electronics industry, it is easy and more secure to operate the power system to enhance the performance. The power electronic based controllers are used to improve the power transfer capability, voltage control and the system active power losses, simply known as Flexible AC Transmission System (FACTS) Controllers. Based on the type of connection of the voltage source converters in a given system, it has been proved that, multi-line controllers are more powerful than that of the single line controllers. In this paper, detailed power injection model of Generalized Unified Power Flow Controller (GUPFC) is presented. The effect of this device on system parameters is analyzed by incorporating this device in NR load flow. The proposed methodology is tested on standard 9-bus and IEEE-23 bus test systems with supporting numerical and graphical results.

Keywords: Generalized Unified Power Flow Controller, PIM of UPFC, NR-load flow, Incorporation procedure.

I. INTRODUCTION

In the present day electricity market, due to continuous increase in the demand for the electricity day by day, it is necessary to cope up with the latest technology to solve this type of problems. This technology is developed based on the developments in the power electronics technology. Thus technology in turn uses the voltage source converters developed using solid state devices.

The only possible alternative to increase the power transfer capability of the transmission system is using Flexible AC Transmission System (FACTS) controllers. The capability of these controllers can control the voltage magnitude at system buses and power flow in the transmission lines individually or simultaneously. There are basically, two different types of FACTS controllers, such as variable impedance type and voltage source converter type. Out of which, based on the various modes of operations obtained with voltage source converter type FACTS controllers, these are popularly used to control the power system parameters.

Based on the type of connection of the converters in a system, these FACTS controllers can be classified as series, shunt, combined series-shunt and combined series-series controllers. Similarly, based on the controlling purposes, these are classified as single line power flow controllers and multi-line power flow controllers. The latest convertible static compensators such as interline power flow controllers, generalized unified power flow controllers, etc., are developed to control multiple transmission lines simultaneously [1, 2].

The Unified Power Flow Controller (UPFC) can be used for simultaneous control of the power system parameters (voltage, impedance, phase angle), or any of the above combinations [3, 4] as it is a versatile and effective device. This device consist one series converter coordinated with one shunt converter.

A comprehensive load flow model for UPFC, to incorporate into existing Newton-Raphson (NR) Load flow is presented in [5].

An algorithm is proposed for determining the optimum flow and size of UPFC for power flow applications [6]. The UPFC operation, control, sequencing, and protection methodologies under practical constraints are discussed in [7]. An effective modeling of UPFC and its performance has been presented in [8, 9].

The complete working procedure and fundamental frequency model of GUPFC is described in [10]. In [11], a mathematical model of the GUPFC suitable for power flow is proposed. Voltage source based mathematical models of the GUPFC and its implementation in Newton power flow is presented in [12].

In [13], the application of GUPFC in a real power grid for power flow as well as voltage control by applying a four converter GUPFC in Sichuan power system of China is analyzed. Steady state mathematical model of GUPFC, based on d-q axis reference frame decomposition has been derived in [14]. Robust modeling of the GUPFC with small impedances in power flow analysis is given in [15].

From the careful review of the literature, it is identified that, most of the literature is concentrated in modeling UPFC using voltage source based model. It is also identified that, this type of modeling is easy and simple to incorporate the FACTS controllers in load flow analysis to study the impact of the same. In this paper, voltage source based power injection model is presented for generalized unified power flow controller, to analyze the effect of this device on system parameters such as bus voltages, line active and reactive power flows and total system power losses. The proposed methodology is implemented on standard test systems such as IEEE-6 bus and IEEE-23 bus systems with supporting numerical results.

II. MATHEMATICAL MODELING OF GUPFC

In general, GUPFC consist three voltage source converters and using this basic configuration, it can control power flow in two transmission lines simultaneously by varying device control parameters. For the sake of explanation, the complete voltage source based mathematical modeling of GUPFC is presented in this section. The principle configuration of GUPFC connected between buses i, j and k is shown in Fig.1.

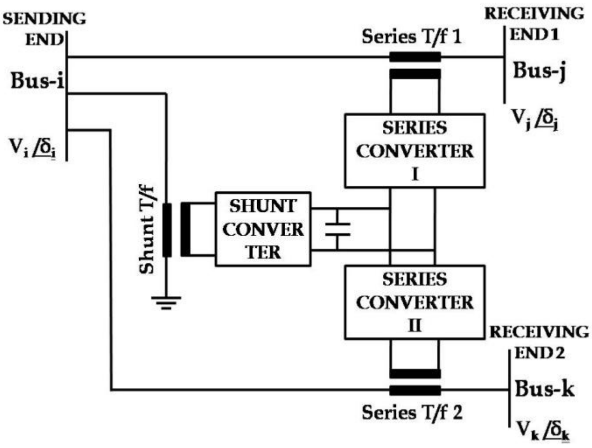

Fig 1. Schematic diagram of GUPFC

In this configuration, two voltage source converters are connected in two different transmission lines having a common bus. The third converter is connected at this common bus and acts as a shunt connected voltage source converter. This shunt converter supplies the power that is supplied by the series converters. All these converters are connected through a common DC link to exchange the power flow.

For the sake of simplification, it is assumed that, the voltage injected by the series converters is sinusoidal and the reactance of the coupling transformer is neglected. With these assumptions, the final voltage source model of GUPFC is shown in Fig.2. The voltages at GUPFC connected buses can be expressed as

$$\overline{V}_m = |V_m|\angle\delta_m \quad \forall \quad m = i, j, k$$

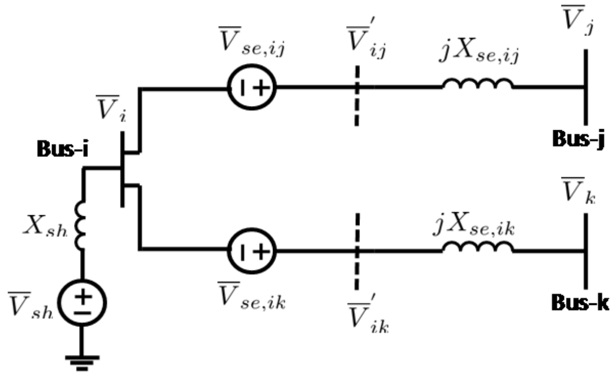

Fig.2. Voltage source model of GUPFC

The voltage injected by the series converters can be expressed as

$$\overline{V}_{se,im} = |V_{se,im}|\angle\delta_{se,im} \quad \forall \quad m = j, k$$

In Fig.2, the voltage behind the series voltage source can be expressed for both converters as

$$\overline{V}'_{im} = \overline{V}_i + \overline{V}_{se,im} \quad \forall \quad m = j, k$$

To develop the power injection model, the voltage source model is converted into an equivalent current source model using Norton's theorem and is shown in Fig.3.

$$\overline{I}_{se,im} = -jB_{se,im}\overline{V}_{se,im}$$

Where, $B_{se,im} = \frac{1}{jX_{se,im}}$ is the admittance of the coupling transformer.

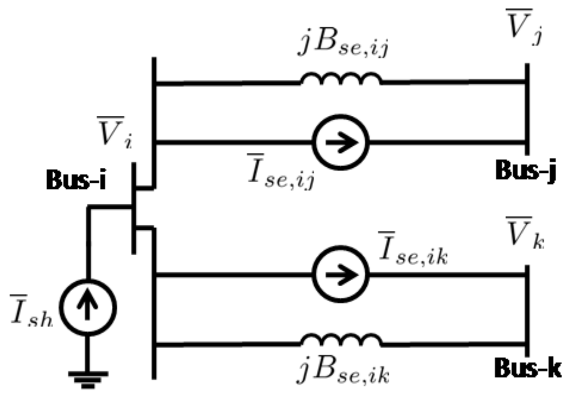

Fig.3. Equivalent current source model GUPFC

Using this, the power injected by these sources at the device connected buses can be expressed as

$$\overline{S}_{i,se} = \overline{V}_i(-\overline{I}_{se,ij} - \overline{I}_{se,ik})^*$$
$$\overline{S}_{m,se} = \overline{V}_m\overline{I}^*_{se,im}$$

Using Eqn. (6), Eqns (7) and (8) can be simplified as

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$$\overline{S}_{i,se} = \sum_{m=j,k} (-jV_iV_{se,im}B_{se,im}\angle(\delta_i - \theta_{se,im}))$$
$$\overline{S}_{m,se} = jV_mV_{se,im}B_{se,im}\angle(\delta_m - \theta_{se,im}) \quad \forall \quad m = j,k$$

Finally, the real and reactive powers injected at GUPFC connected buses can be expressed as

$$\begin{aligned} P_{i,se} &= V_iV_{se,ij}B_{se,ij}\sin(\delta_i - \theta_{se,ij}) \\ &\quad + V_iV_{se,ik}B_{se,ik}\sin(\delta_i - \theta_{se,ik}) \\ Q_{i,se} &= -V_iV_{se,ij}B_{se,ij}\cos(\delta_i - \theta_{se,ij}) \\ &\quad - V_iV_{se,ik}B_{se,ik}\cos(\delta_i - \theta_{se,ik}) \\ P_{j,se} &= -V_jV_{se,ij}B_{se,ij}\sin(\delta_j - \theta_{se,ij}) \\ Q_{j,se} &= V_jV_{se,ij}B_{se,ij}\cos(\delta_j - \theta_{se,ij}) \\ P_{k,se} &= -V_kV_{se,ik}B_{se,ik}\sin(\delta_k - \theta_{se,ik}) \\ Q_{k,se} &= V_kV_{se,ik}B_{se,ik}\cos(\delta_k - \theta_{se,ik}) \end{aligned}$$

The final series voltage source with the respective power injections is shown in Fig.4.

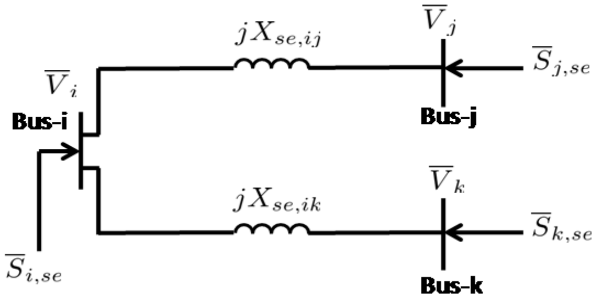

Fig.4. Equivalent series voltage source model of GUPFC

Similarly, the shunt connected voltage source converter can be modeled as an equivalent power injection at the respective bus. In this modeling, it is assumed that, the reactive power injected by the shunt converter is zero, because the purpose of this reactive power is to maintain the voltage magnitude at the converter connected bus. The equivalent shunt voltage source model of GUPFC is shown in Fig.5. The net active power injected at shunt converter connected bus can be expressed as

$$P_{sh} = -P_{series,ij} - P_{series,ik}$$

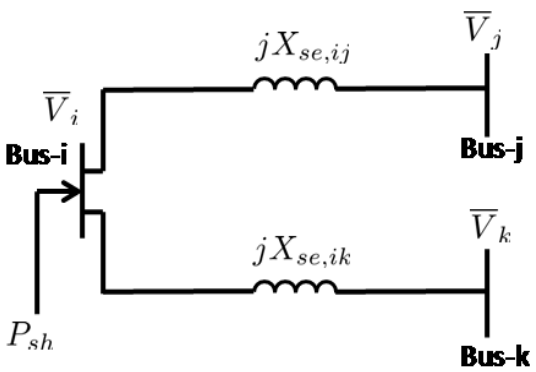

Fig.5. Equivalent shunt voltage source model

The amount of apparent power supplied the series converters can be calculated as

$$\overline{S}_{series,im} = \overline{V}_{se,im}\overline{I}_{ij}^{*} = j\overline{V}_{se,im}B_{se,im}(\overline{V}_{ij}^{'} - \overline{V}_m)^{*} \quad \forall \quad m = j,k$$

Using Eqn (2), after simplifying, the expressions for active and reactive powers supplied by the series converters derived are

$$\begin{aligned} P_{series,im} &= V_iV_{se,im}B_{se,im}\sin(\theta_{se,im} - \delta_i) \\ &\quad - V_mV_{se,im}B_{se,im}\sin(\theta_{se,im} - \delta_j) \quad \forall \quad m = j,k \\ Q_{series,im} &= -V_iV_{se,im}B_{se,im}\cos(\theta_{se,im} - \delta_i) \\ &+ V_mV_{se,im}B_{se,im}\cos(\theta_{se,im} - \delta_j) - V_{se,ij}^2B_{se,ij} \quad \forall \quad m = j,k \end{aligned}$$

The final power injection model is obtained by combining series voltage source model and shunt voltage source model. The combined model is shown in Fig.6. The respective power injections at GUPFC connected buses can be obtained as

$$\begin{aligned} P_i^{gupfc} &= 2V_iV_{se,ij}B_{se,ij}\sin(\delta_i - \theta_{se,ij}) + 2V_iV_{se,ik}B_{se,ik}\sin(\delta_i - \theta_{se,ik}) \\ &\quad - V_jV_{se,ij}B_{se,ij}\sin(\delta_j - \theta_{se,ij}) - V_kV_{se,ik}B_{se,ik}\sin(\delta_i - \theta_{se,ik}) \\ Q_i^{gupfc} &= -V_iV_{se,ij}B_{se,ij}\cos(\delta_i - \theta_{se,ij}) - V_iV_{se,ik}B_{se,ik}\cos(\delta_i - \theta_{se,ik}) \\ P_j^{gupfc} &= -V_jV_{se,ij}B_{se,ij}\sin(\delta_j - \theta_{se,ij}) \\ Q_j^{gupfc} &= V_jV_{se,ij}B_{se,ij}\cos(\delta_j - \theta_{se,ij}) \\ P_k^{gupfc} &= -V_kV_{se,ik}B_{se,ik}\sin(\delta_k - \theta_{se,ik}) \\ Q_k^{gupfc} &= V_kV_{se,ik}B_{se,ik}\cos(\delta_k - \theta_{se,ik}) \end{aligned}$$

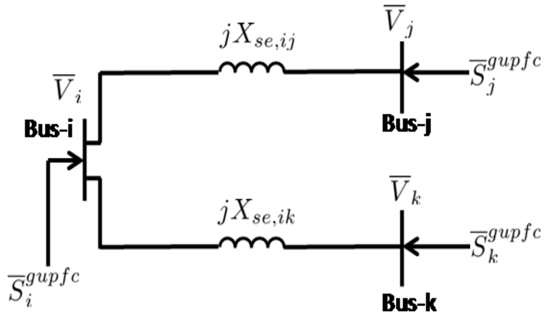

Fig.6. Equivalent power injection model of GUPFC

III. INCORPORATION OF GUPFC MODEL IN NEWTON RAPHSON ALGORITHM

To incorporate GUPFC in a given network, the conventional system equation in Newton Raphson load solution should modify to show the impact of the device.

The developed power injection model is very to incorporate in a given power system by modifying the Jacobian and power mismatch equations at the IPFC connected buses. The final steady state network equation in the presence of this device can be expressed as

$$\left(\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} + \begin{bmatrix}P^{gupfc}\\ Q^{gupfc}\end{bmatrix}\right) = \left(\begin{bmatrix}H & N\\ J & L\end{bmatrix} + \begin{bmatrix}H^{gupfc} & N^{gupfc}\\ J^{gupfc} & L^{gupfc}\end{bmatrix}\right)\begin{bmatrix}\Delta\delta\\ \frac{\Delta V}{V}\end{bmatrix}$$

Where, $\Delta P,\ \Delta Q$ are the respective power mismatch vectors, $\Delta\delta,\ \Delta V$ are the vector increments with respect to voltage magnitude and angles, H, N, J, and, L are the partial derivatives with respect to δ and V respectively.
The respective power mismatch equations and Jacobian elements corresponds to GUPFC connected buses can be represented as

A. Modifications in power mismatch equations
The power mismatch equations at the GUPFC connected buses can be modified by adding the GUPFC injected powers to the power mismatch equations without device. These power mismatch equations can be expressed as

$$\Delta P_m^{gupfc} = \Delta P_m^0 + P_m^{gupfc} \quad \forall \quad m = i, j, k$$
$$\Delta Q_m^{gupfc} = \Delta Q_m^0 + Q_m^{gupfc} \quad \forall \quad m = i, j, k$$

B. Modifications in Jacobian elements
The diagonal and off-diagonal elements of 'H^{gupfc}' are

$$H_{ii}^{gupfc} = \frac{\partial P_i^{gupfc}}{\partial \delta_i} = -Q_j^{gupfc} - Q_k^{gupfc}$$
$$H_{jj}^{gupfc} = \frac{\partial P_j^{gupfc}}{\partial \delta_j} = -Q_j^{gupfc}$$
$$H_{kk}^{gupfc} = \frac{\partial P_k^{gupfc}}{\partial \delta_k} = -Q_k^{gupfc}$$
$$H_{ij}^{gupfc} = \frac{\partial P_i^{gupfc}}{\partial \delta_j} = Q_j^{gupfc}$$
$$H_{ji}^{gupfc} = \frac{\partial P_j^{gupfc}}{\partial \delta_i} = Q_j^{gupfc}$$
$$H_{ik}^{gupfc} = \frac{\partial P_i^{gupfc}}{\partial \delta_k} = Q_k^{gupfc}$$
$$H_{ki}^{gupfc} = \frac{\partial P_k^{gupfc}}{\partial \delta_i} = Q_k^{gupfc}$$

Similarly, the diagonal and off-diagonal elements of 'N^{gupfc}' are

$$N_{ii}^{gupfc} = |V_i| \frac{\partial P_i^{gupfc}}{\partial V_i} = -P_j^{gupfc} - P_k^{gupfc}$$
$$N_{jj}^{gupfc} = |V_j| \frac{\partial P_j^{gupfc}}{\partial V_j} = P_j^{gupfc}$$
$$N_{kk}^{gupfc} = |V_k| \frac{\partial P_k^{gupfc}}{\partial V_k} = P_k^{gupfc}$$
$$N_{ij}^{gupfc} = |V_j| \frac{\partial P_i^{gupfc}}{\partial V_j} = -P_j^{gupfc}$$
$$N_{ji}^{gupfc} = |V_i| \frac{\partial P_j^{gupfc}}{\partial V_i} = P_j^{gupfc}$$
$$N_{ik}^{gupfc} = |V_k| \frac{\partial P_i^{gupfc}}{\partial V_k} = -P_k^{gupfc}$$
$$N_{ki}^{gupfc} = |V_i| \frac{\partial P_k^{gupfc}}{\partial V_i} = P_k^{gupfc}$$

The diagonal and off-diagonal elements of 'J^{gupfc}' are

$$J_{ii}^{gupfc} = \frac{\partial Q_i^{gupfc}}{\partial \delta_i} = 0$$
$$J_{jj}^{gupfc} = \frac{\partial Q_j^{gupfc}}{\partial \delta_j} = P_j^{gupfc}$$
$$J_{kk}^{gupfc} = \frac{\partial Q_k^{gupfc}}{\partial \delta_k} = P_k^{gupfc}$$
$$J_{ij}^{gupfc} = \frac{\partial Q_i^{gupfc}}{\partial \delta_j} = 0$$
$$J_{ji}^{gupfc} = \frac{\partial Q_j^{gupfc}}{\partial \delta_i} = -P_j^{gupfc}$$
$$J_{ik}^{gupfc} = \frac{\partial Q_i^{gupfc}}{\partial \delta_k} = 0$$
$$J_{ki}^{gupfc} = \frac{\partial Q_k^{gupfc}}{\partial \delta_i} = -P_k^{gupfc}$$

Similarly, the diagonal and off-diagonal elements of 'L^{gupfc}' are

$$L_{ii}^{gupfc} = |V_i| \frac{\partial Q_i^{gupfc}}{\partial V_i} = 2Q_i^{gupfc}$$
$$L_{jj}^{gupfc} = |V_j| \frac{\partial Q_j^{gupfc}}{\partial V_j} = Q_j^{gupfc}$$
$$L_{kk}^{gupfc} = |V_k| \frac{\partial Q_k^{gupfc}}{\partial V_k} = Q_k^{gupfc}$$
$$L_{ij}^{gupfc} = |V_j| \frac{\partial Q_i^{gupfc}}{\partial V_j} = 0$$
$$L_{ji}^{gupfc} = |V_i| \frac{\partial Q_j^{gupfc}}{\partial V_i} = Q_j^{gupfc}$$
$$L_{ik}^{gupfc} = |V_k| \frac{\partial Q_i^{gupfc}}{\partial V_k} = 0$$
$$L_{ki}^{gupfc} = |V_i| \frac{\partial Q_k^{gupfc}}{\partial V_i} = Q_k^{gupfc}$$

IV. RESULTS AND ANALYSIS

In this section, the proposed voltage source based power injection model of GUPFC is incorporated in a given power system using the procedure given in section-3.

A. Example-1
WSCC-9 bus test system with 9 buses and 9 transmission lines is considered. To demonstrate the effect of GUPFC on this system, this device is placed in lines 4 and 6, i.e. between buses 5, 4, and 7 with bus-5 as common. One series converter is connected in line-4 and another converter is connected in line-6, the shunt converter is connected at bus-5.

For this system, the device control variables, V_{se} is varied from 0 p.u. to 0.04 p.u. in steps of 0.02 p.u. and θ_{se} is varied from 0 deg to 360 deg in steps of 20 deg. The effect of this device is analyzed on system bus voltage magnitudes, line apparent power flows and system active power losses.

The consolidated variation of bus voltage magnitudes is shown in Fig.7. From this figure, it is identified that, maximum variation of voltage is varied at bus-5, because it is shunt converter connected bus. The variation of voltage magnitude at buses 4, 5, 6 and 7 is shown in Fig.7. From this figure, it is very clear that, major variation is

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obtained when Vse is operating at 0.04 p.u. At this condition, the maximum voltage at bus-5 is obtained when θse is at 0 deg and 360 deg, on the other hand, minimum voltage is obtained when θse is at 200 deg.

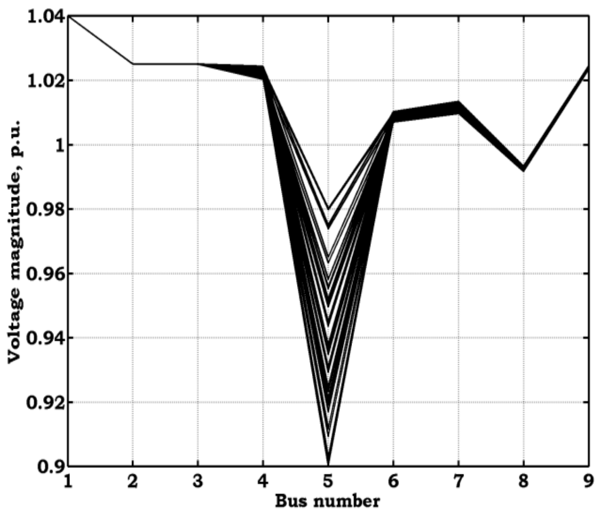

Fig.7. Consolidated bus voltage variation of WSCC-9 bus system

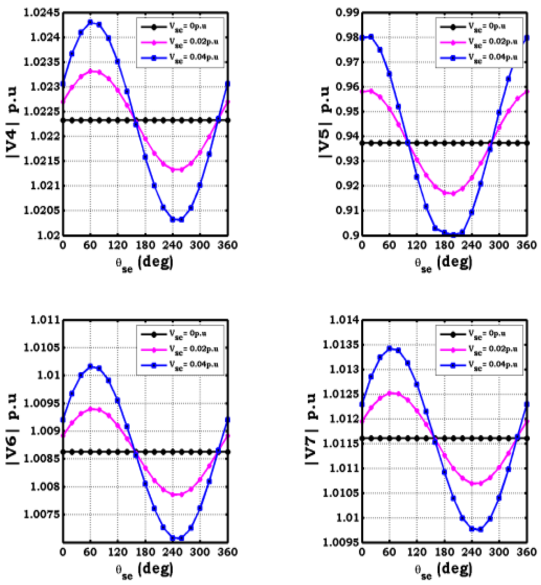

Fig.8. Variation voltage magnitude at system buses of WSCC-9 bus system

Similarly, the consolidated variation of apparent power flow in transmission lines is shown in Fig.9. From this figure, it is observed that, major variation in power flow is in line-4. This is because of one of the series converter is connected in this line.

The individual variation of the power flow in line-4 is shown in Fig.10. From this figure, it is observed that, major variation in power flow is when Vse is at 0.04 p.u. At this condition, maximum power flow is obtained when θse is at 260 deg and minimum power flow is obtained when θse is at 60 deg.

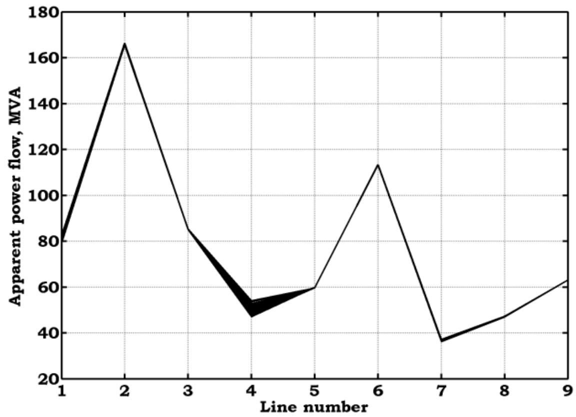

Fig.9. Consolidated power flow variation in lines of WSCC-9 bus system

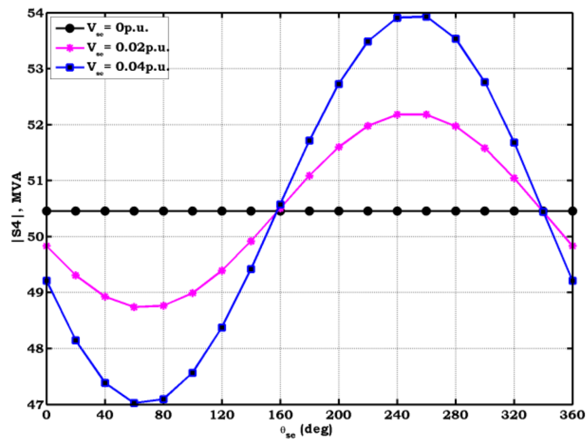

Fig.10. Variation of power flow in line-4 of WSCC-9 bus system

The variation of system active power losses by varying device control parameters is shown in Fig.11. From this figure, it is observed that, maximum variation is obtained when Vse is at 0.04 p.u. At this condition, maximum losses are obtained when θse is at 260 deg and minimum losses are obtained when θse is at 60 deg.

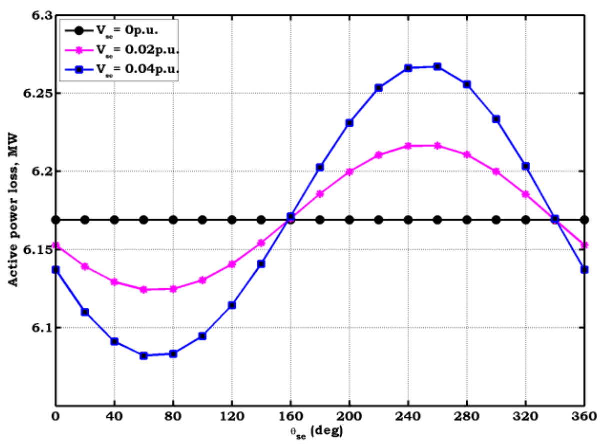

Fig.11. Variation of system active power losses of WSCC-9 bus system

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B. Example-2

To extend the effect of the proposed modeling of GUPFC, IEEE-23 bus system with 28 transmission lines is considered. For this system, GUPFC is placed in lines 12 and 18 i.e. between buses 12, 11 and 23 with bus-12 as common bus. Precisely, one of the GUPFC converters is placed in line between buses 12, 11 and another converter is placed in line between buses 12, 23 and shunt converter is connected at bus-12. For this system, the device control parameters Vse is varied from 0 p.u. to 0.09 p.u. in steps of 0.03 p.u. and θse is varied from 0 deg to 360 deg in steps of 20 deg. The effect of device control parameters on system parameters is analyzed as follows.

The consolidated variation of voltage magnitude at system buses is shown in Fig.12. From this figure, it is observed that, major variation in voltage magnitude is at buses 8, 10 and GUPFC connected buses (11, 12, 23) when compared to other buses. The individual variation of voltage magnitude at buses 8, 11, 12 and 23 is shown in Fig.13. From this figure, it is observed that, major variation in power flow is obtained when Vse is at 0.09 p.u. At this condition, it is also observed that, maximum voltage at buses 11 and 23 is obtained when θse is at 180 deg and at buses 8 and 12 is obtained when θse is at 0 deg or 360 deg.

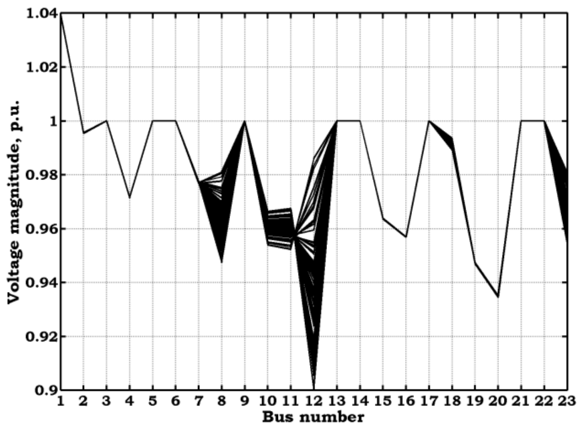

Fig.12. Consolidated bus voltage variation of IEEE-23 bus system

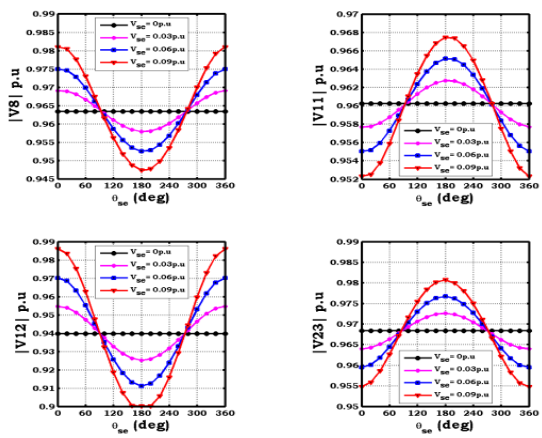

Fig.13. Variation voltage magnitude at system buses of IEEE-23 bus system

Similarly, the consolidated variation of line apparent power flow is shown in Fig.14. From this figure, it is observed that, maximum variation is obtained in line-11 and GUPFC connected lines (lines 12, 18) when compared to other lines. The individual variation of apparent power flow in device connected lines is shown in Fig.15. From this figure, it is observed that, major variation in power flow is observed when Vse is at 0.09 p.u.

At this condition, maximum power flow in these lines is obtained when θse is at 0 deg and 360 deg. Similarly, minimum power flow is obtained when θse is at 220 deg in line-12 and 140 deg in line-18.

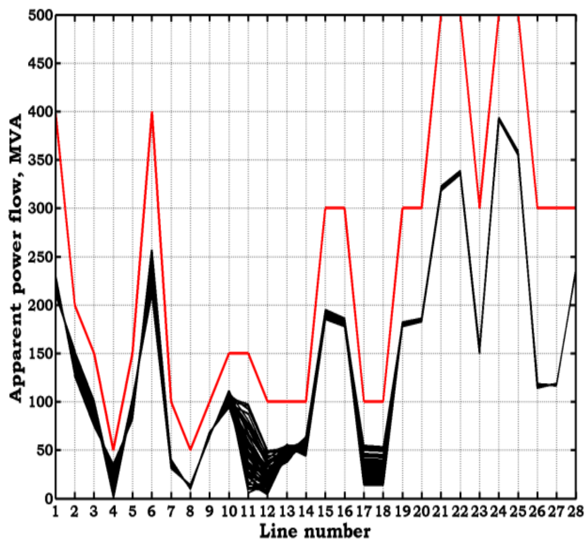

Fig.14. Consolidated power flow variation in lines of IEEE-23 bus system

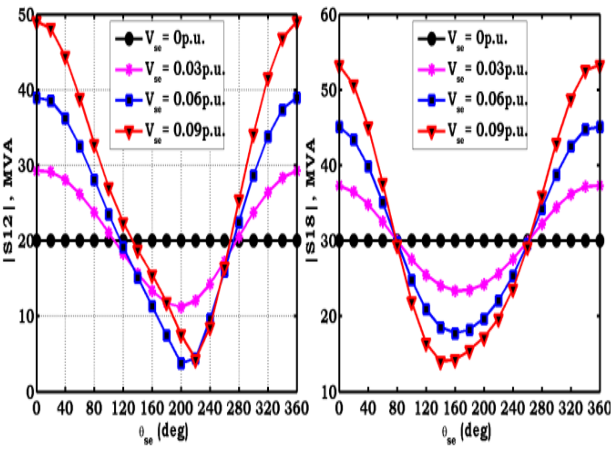

Fig.15. Variation of power flow in GUPFC connected lines of IEEE-23 bus system

The variation of system active power losses by varying device control parameters is shown in Fig.16. From this figure, it is observed that, maximum losses are obtained when Vse is at 0.09 p.u. and θse is at 340 deg, similarly, minimum losses are obtained when Vse is at 0.06 and θse is at 100 deg.

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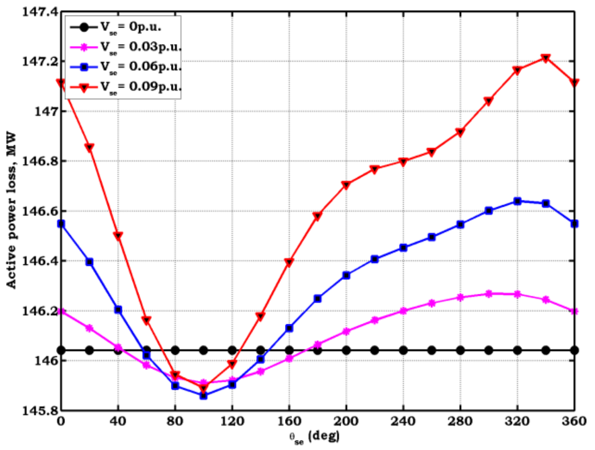

Fig.16. Variation of system active power losses of IEEE-23 bus system

V. CONCLUSION

In this paper, a detailed power injection modeling of GUPFC is presented with supporting mathematical derivations. This modeling procedure is used to incorporate GUPFC is a given system. The effect of this device on system parameters is analyzed by varying the device control parameters, the system parameters such as bus voltage magnitudes, line apparent power flows and system active power losses are analyzed on standard test systems with supporting graphical and numerical results.

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