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EVALUATION OF A NEW MODEL FOR UPFC OPERATING AS IMPEDANCE COMPENSATION APPLIED TO MULTI-MACHINE SYSTEMS WITH NONLINEAR LOAD

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Abstract

In this paper, a new developed steady-state model of the UPFC is proposed. The proposed model consists of one shunt compensation block and two series compensation blocks. In this case, the UPFC with the new model will be investigated when it is installed in multi-machine systems with non-linear load model. In addition, the steady–state performance of the new model operating as impedance compensation will be presented and compared with that obtained from the original Gyugyi model.

Keywords: UPFC, FACTS, PWM, Multi-machine systems, Nonlinear load.

1. Introduction

The rapid development of power electronics technology provides exciting opportunities to design new power system equipment for better utilization of existing systems. During the last decade, a number of control devices under the term "Flexible AC Transmission Systems (FACTS)" technology have been proposed and implemented [1-6]. FACTS devices can be effectively used for power flow control, loop-flow control, load sharing among parallel corridors, voltage regulation, enhancement of transient stability, and mitigation of system oscillations. In 1991, a unified power flow controller (UPFC) concept was proposed by Gyugyi [1]. It is a multi-functional FACTS controller with the primary function of power flow control plus possible secondary duties of voltage support, transient stability improvement and oscillation damping, etc. [1, 2]. The installation of the UPFC in power systems has recently come under intensive investigation into its modeling and various control functions, including damping control for single-machine infinite-bus power systems. Many papers have been published related to modeling the UPFC into

Nomenclatures

I_n	Current in *n* transmission line, Amp
M_{pq}	Modulation index of the series compensation block of UPFC.
M_{sh}	Modulation index of the shunt compensation block of UPFC
P_{nm}	Active power flow in the line from point *n* to *m*, watt
Q_{nm}	Reactive power flow in the line from point *n* to *m*, Var.
V_n	Voltage at *n* point of the transmission line, Volt
V_{pq}	Injection voltage from the UPFC, Volt

Greek Symbols

α	Angle of the shunt compensation block of UPFC, deg.
$\delta_{1,2}$	Angles of V_3 and V_2 with respect to the slack bus voltage V_1, deg.
θ	Angle of the transmission line current I_1, deg.
ρ	Angle of the series compensation block of UPFC, deg.

multi-machine power systems in steady-state mode of operation for studying power flow control [7-12]. However, most of the work done used the original Gyugyi model of the UPFC (series compensation block (Converter 1) and shunt compensation block (Converter 2) as illustrated in Fig. 1 [7-22].

In this paper, a new steady-state model of a UPFC is proposed. The model consists of one shunt compensation block and two series compensation blocks. A UPFC with the new construction model installed in multi-machine systems with non-linear load model will be investigated. In addition, the steady–state performance of the new model operating as an impedance compensation will be presented and compared with that obtained from the Gyugyi model.

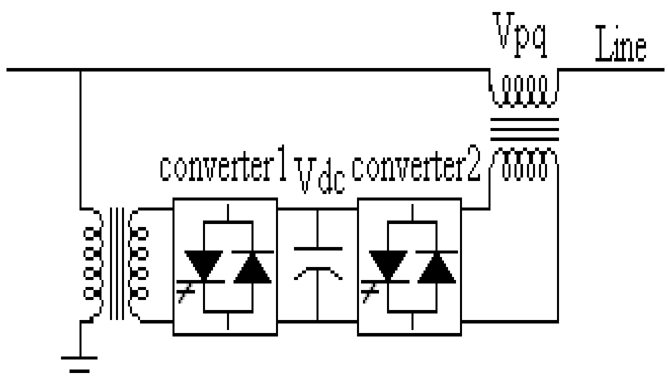


Fig. 1. A Block Diagram of UPFC.

2. Multi-machine Systems with UPFC as Impedance Compensation (Model 1)

The block diagram and the steady-state model of a Pulse-Width Modulation (PWM) based UPFC operating as impedance compensation installed in the multi-machine systems are shown in Figs. 2 and 3, respectively.

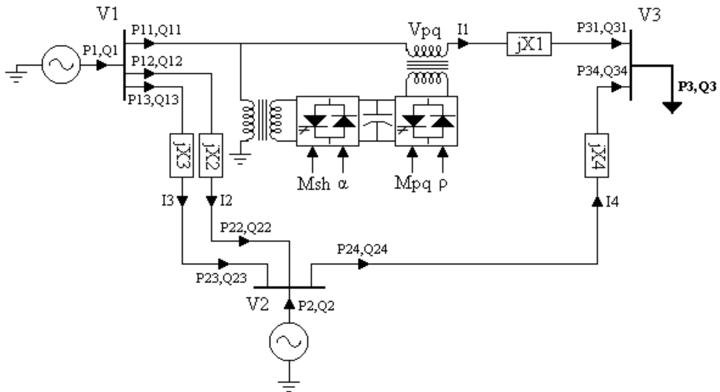


Fig. 2. Multi-machine Systems with UPFC (Model 1).

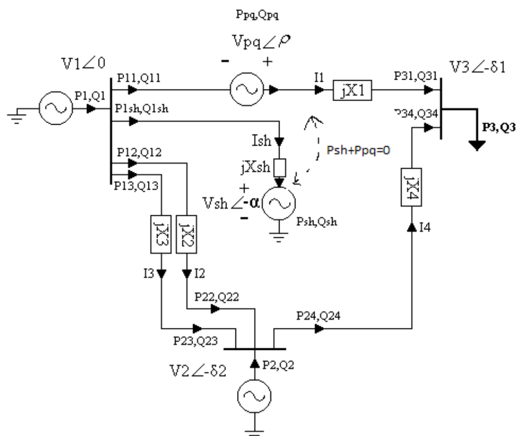


Fig. 3. The Steady State Model of the Multi Machine Systems with UPFC (Model 1).

If the system has a nonlinear load that depends on the terminal voltage V_3, then the active and reactive power could be characterized as follows [23]:

$$P_3 = P_0\left(\frac{V_3}{V_{30}}\right)^a \tag{1}$$

$$Q_3 = Q_0\left(\frac{V_3}{V_{30}}\right)^b \tag{2}$$

where, a and b are constant values and P_0, Q_0 and V_{30} are equal to the initial values of P_3, Q_3 and V_3, respictively.

In order to operate the UPFC as an impedance compensator, the voltage V_{pq} should be injected into the transmission line in quadrature with the transmission line current I_1, and thus the angle of V_{pq} must be:

$$\rho = -\theta - 90^{\circ} \tag{3}$$

where θ is the angle of the current I_1 with respect to the reference voltage V_1.

From the complex powers of the system, all active and reactive powers can be calculated for the system as follows:

$$P_{11} = -\frac{V_1 V_{pq}}{X_1} Cos(\theta) + \frac{V_1 V_3}{X_1} Sin(\delta_1) \tag{4}$$

$$P_{31} = \frac{V_1 V_3}{X_1} Sin(\delta_1) - \frac{V_3 V_{pq}}{X_1} Cos(\theta - \delta_1) \tag{5}$$

$$Q_{11} = -\frac{V_1 V_{pq}}{X_1} Sin(\theta) - \frac{V_1 V_3}{X_1} Cos(\delta_1) + \frac{V_1^2}{X_1} \tag{6}$$

$$Q_{31} = \frac{V_1 V_3}{X_1} Cos(\delta_1) - \frac{V_3 V_{pq}}{X_1} Sin(\theta - \delta_1) - \frac{V_3^2}{X_1} \tag{7}$$

$$P_{pq} = \frac{V_1 V_{pq}}{X_1} Cos(\theta) - \frac{V_3 V_{pq}}{X_1} Cos(\delta_1 - \theta) \tag{8}$$

$$P_{1sh} = \frac{V_1 V_{sh}}{X_{sh}} Sin(\alpha) \tag{9}$$

$$Q_{pq} = -\frac{V_1 V_{pq}}{X_1} Sin(\theta) + \frac{V_{pq}^2}{X_1} - \frac{V_3 V_{pq}}{X_1} Sin(\delta_1 - \theta) \tag{10}$$

$$Q_{1sh} = -\frac{V_1 V_{sh}}{X_{sh}} Cos(\alpha) + \frac{V_1^2}{X_{sh}} \tag{11}$$

$$P_{sh} = \frac{V_1 V_{sh}}{X_{sh}} Sin(\alpha) \tag{12}$$

$$Q_{sh} = \frac{V_1 V_{sh}}{X_{sh}} Cos(\alpha) - \frac{V_{sh}^2}{X_{sh}} \tag{13}$$

All the other active and reactive powers in the other lines can be found in a similar manner. Since the operation of the converters of the UPFC is based on PWM method, the magnitude of the output voltage (*Vpq*) from the series compensation block can be calculated as [24]:

$$\left|V_{pq}\right| = K_1 M_{pq} V_{dc} \tag{14}$$

where, K_1 is equal to 0.612 [24] and M_{pq} is the modulation index of the converter (2) that can be varied from (10% to 100%). On the other hand, the magnitude of the voltage in the shunt compensation block is:

$$\left|V_{sh}\right| = K_2 M_{sh} V_{dc} \tag{15}$$

where, K_2 is equal to 0.612 [24] and M_{sh} is the modulation index of converter (1) which will be set to 100%.

Therefore, from Eqs. (14) and (15), the magnitude of the injection voltage can be written as:

$$\left|V_{pq}\right| = M_{pq}\left|V_{sh}\right| \tag{16}$$

The voltage V_{sh} has an angle α with respect to the transmission line voltage V_1. This angle will determine the amount of power transfer needed from converter (1) to converter (2).

For the sake of simplicity, it is assumed that the active power consumed by this FACTS device is zero. Therefore,

$$P_{sh} + P_{pq} = 0 \tag{17}$$

3. Multi-machine Systems with the New UPFC as Impedance Compensation and Voltage Regulator (Model 2)

The new proposed UPFC steady-state model with three converters that are all connected to the DC link is shown in Fig. 4. Operation of the three converters is based on PWM method. The first converter is the shunt converter and its modulation index is selected to be 100%. The second converter (series injection) is installed between the Bus 1 and Bus 3. This converter is operated as an impedance compensator with an amplitude V_{pq1} and a phase angle of ($\rho = -\theta-90$) degrees so that its output voltage is in quadrature with the line current I_1. The magnitude of the output voltage of this converter can be controlled by varying its modulation index M_{pq1} from 10% to 100%. The third converter is installed at the line between Bus 1 and Bus 2. This converter is operated as a voltage regulator of amplitude of V_{pq2} and at an angle in phase with the terminal voltage at Bus 1 (angle of 0 degrees). The magnitude of the output voltage of this converter can be controlled by varying its modulation index M_{pq2} from 10% to 100%. Therefore, the advantage of this model is that only one FACTS device is required to control two lines in the transmission system rather than installing two different FACTS devices. The steady-state model of the multi machine systems with the new developed UPFC is shown in Fig. 5.

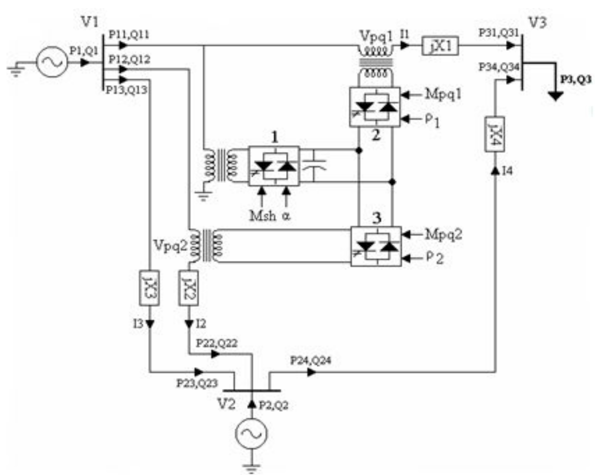


Fig. 4. Multi-machine Systems with the New Developed UPFC (Model 2).

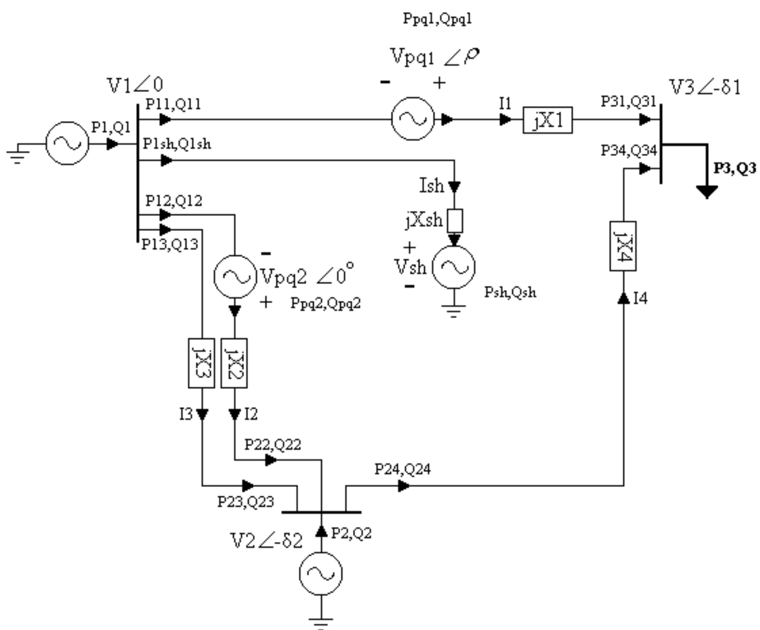


Fig. 5. The Steady State Model of the Multi Machine Systems with New Developed UPFC (Model 2).

In this case, the same nonlinear load is considered as was presented in Eqs. (1) and (2). From the complex powers of the system, all active and reactive powers can be calculated for the system as follows:

$$P_{11} = -\frac{V_1 V_{pq1}}{X_1} Cos(\theta) + \frac{V_1 V_3}{X_1} Sin(\delta_1) \tag{18}$$

$$Q_{11} = -\frac{V_1 V_{pq1}}{X_1} Sin(\theta) - \frac{V_1 V_3}{X_1} Cos(\delta_1) + \frac{V_1^2}{X_1} \tag{19}$$

$$P_{31} = \frac{V_1 V_3}{X_1} Sin(\delta_1) - \frac{V_3 V_{pq1}}{X_1} Cos(\theta - \delta_1) \tag{20}$$

$$Q_{31} = \frac{V_1 V_3}{X_1} Cos(\delta_1) - \frac{V_3 V_{pq1}}{X_1} Sin(\theta - \delta_1) - \frac{V_3^2}{X_1} \tag{21}$$

$$P_{pq1} = \frac{V_1 V_{pq1}}{X_1} Cos(\theta) - \frac{V_3 V_{pq1}}{X_1} Cos(\delta_1 - \theta) \tag{22}$$

$$Q_{pq1} = -\frac{V_1 V_{pq1}}{X_1} Sin(\theta) + \frac{V_{pq1}^2}{X_1} - \frac{V_3 V_{pq1}}{X_1} Sin(\delta_1 - \theta) \tag{23}$$

$$P_{12} = \frac{V_1 V_2}{X_2} Sin(\delta_2) \tag{24}$$

$$Q_{12} = \frac{V_1^2}{X_2} - \frac{V_1 V_{pq2}}{X_2} - \frac{V_1 V_2}{X_2} Cos(\delta_2) \tag{25}$$

$$P_{22} = \frac{V_1 V_2}{X_2} Sin(\delta_2) - \frac{V_2 V_{pq2}}{X_2} Sin(\delta_2) \tag{26}$$

$$Q_{22} = \frac{V_1 V_2}{X_2} Cos(\delta_2) - \frac{V_2 V_{pq2}}{X_2} Cos(\delta_2) - \frac{V_2^2}{X_2} \tag{27}$$

$$P_{pq2} = \frac{V_2 V_{pq2}}{X_2} Sin(\delta_2) \tag{28}$$

$$Q_{pq2} = \frac{V_1 V_{pq2}}{X_2} - \frac{V_{pq2}^2}{X_2} - \frac{V_2 V_{pq2}}{X_2} Cos(\delta_2) \tag{29}$$

All the other active and reactive powers in other lines can be found in a similar way.

As explained earlier, the relation between the magnitude of the voltages of V_{pq1} and V_{pq2} with the magnitude of voltage of V_{sh} as a function of the modulation index can be written as:

$$\left|V_{pq1}\right| = K_1 \cdot M_{pq1} \cdot \left|V_{sh}\right| \tag{30}$$

$$\left|V_{pq2}\right| = K_2 \cdot M_{pq2} \cdot \left|V_{sh}\right| \tag{31}$$

For simplicity, it is again assumed that the active power consumed by the converters is zero (No losses). Therefore,

$$P_{sh} + P_{pq1} + P_{pq2} = 0 \tag{32}$$

4. Simulation Results

The two systems shown in Figs. 3 and 5 have been modelled and simulated using Matlab. In both systems, an active power (P_2) supplied to the grid by the synchronous machine (2) is selected to be 2.479 p.u. and the active power (P_1) is considered as variable power demanded by the load. The impedance of the reactance of the transmission lines are selected to be: X_1=0.04 p.u., X_2=X_3=0.22 p.u. and X_4= 0.047 p.u. [25]. The constants *a* and *b* of the non-linear load given in Eqs. (1) and (2) are considered to be 1.38 and 3.22, respectively [24]. These values represent the residential load model. The other parameters are V_{30}=1 p.u., P_0=6.381 p.u., Q_0=0.2458 p.u., V_1=1.018 p.u., and V_2=1.011 p.u.

For the system shown in Fig. 3, the steady state performance of the UPFC is investegated for different values of the modulation index. The flow of active and reactive powers in all the lines is recorded. It is found that, by varying the modulation index (M_{pq}) of converter 2, both the active and reactive powers in all transmission lines can be varied. The most important result found is that the active power (P_{31}) can be controlled by the modulation index and this power can be raised from 3.7034 p.u. (without compensated system) to approximately 4.9

p.u. as can be seen in Fig. 6. In addition, it was found that the direction of the flow of power in the parallel lines can be reversed at approximately 0.8 modulation index as shown in Fig. 7.

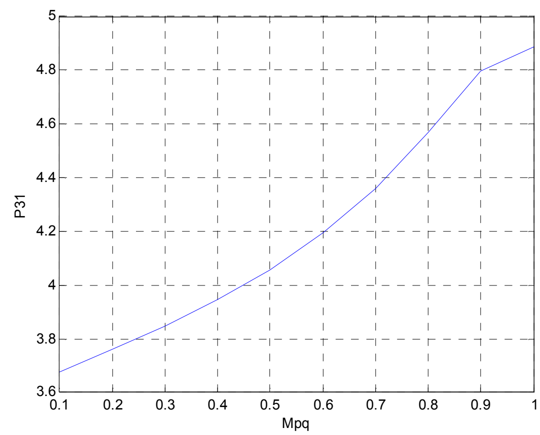


Fig. 6. The Flow of Active Power (P_{31}) as Modulation Index is Varying.

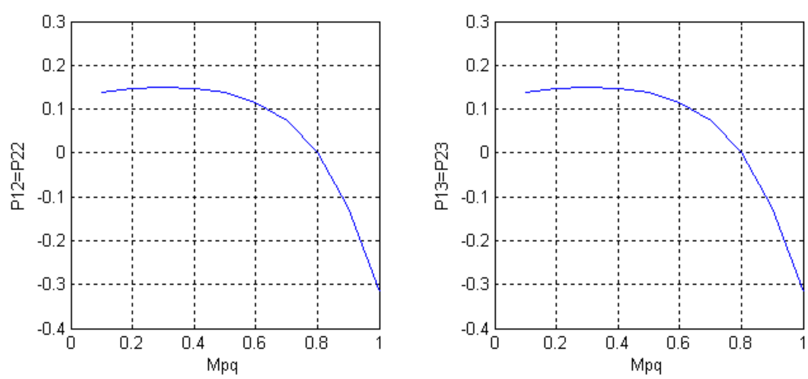


Fig. 7. The Flow of Active Powers in Parallel Lines as Modulation Index is Varying.

On the other hand, for the system shown in Fig. 5, the steady state performance of UPFC was investegated for two different values of the modulation index. The flow of active and reactive powers in all the lines is also recorded. In this case, the modulation index of converter 3 (M_{pq2}) has very little affect on the power flow in all lines as shown in Fig. 8. However, the most changes in active power flow come from changing the modulation index of converter 2 (M_{pq1}). Therefore, converter 3 has much less sensitivity than converter 2 on controlling the active power flow between Bus 1 and Bus 3. But, it can be seen that converter 3 has much higher sensitivity effect on the reactive power flow on some transmission lines as shown in Fig. 9.

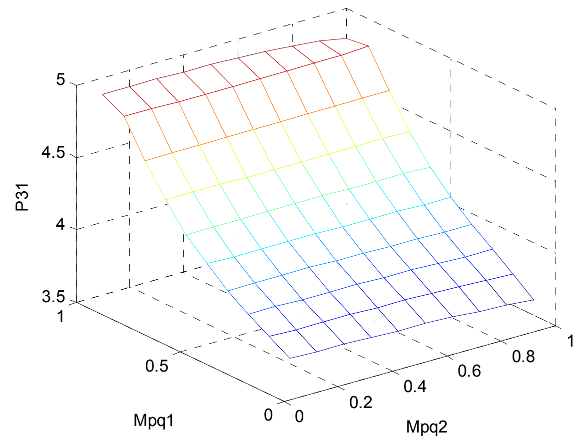


Fig. 8. The Flow of Active Power (P_{31}) as Modulation Index of Converters 2 and 3 are Varying.

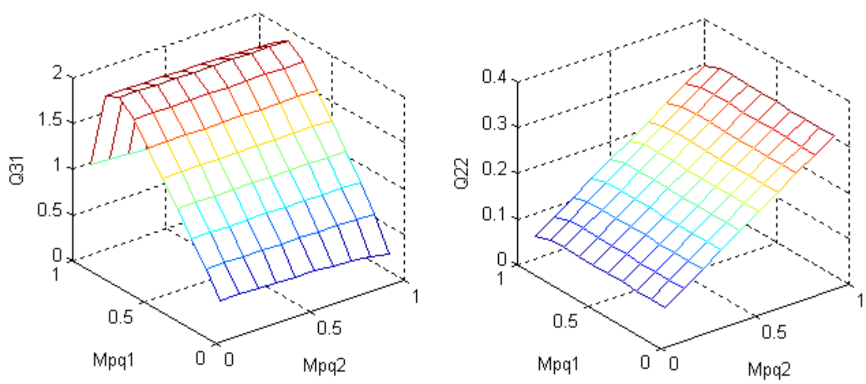
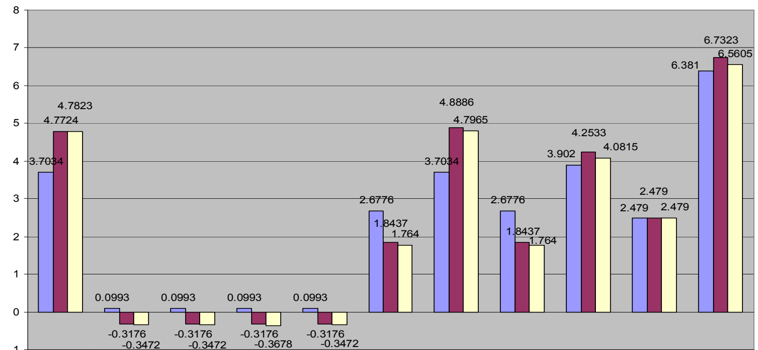


Fig. 9. The Flow of Reactive Power (Q_{31} and Q_{22}) as Modulation Index of Converters 2 and 3 are Varying.

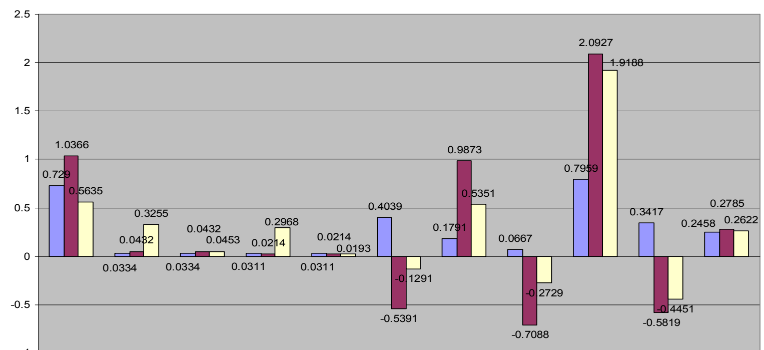
In addition, Figs. 10 and 11 compare the active and reactive power flows in the lines before compensation and after the compensation with Model (1) and Model (2) at 100% modulation index. These two figures show that both Models can be used when controlling the flow of the active and reactive power in the transmission lines. However, both figures also show that the amount of compensation of active and reactive powers in the transmission lines in case of Model (1) is slightly better than that of Model (2). Moreover, Model (2) can be used to control two transmission lines at the same time and therefore the range of controlling the power flow in this case will be larger and more flexible.

In addition, Fig. 11 shows that, there is improvement in reactive power control as a result of modelling the series controller (V_{pq2}) as a voltage regulator. Furthermore, an investigation should be done in order to see the effect of such controller (V_{pq2}) if it is modelled as impedance compensator.



	P11	P12	P13	P22	P23	P24	P31	P34	P1	P2	P3
Before compensation	3.7034	0.0993	0.0993	0.0993	0.0993	2.6776	3.7034	2.6776	3.902	2.479	6.381
mode 1	4.7724	-0.3176	-0.3176	-0.3176	-0.3176	1.8437	4.8886	1.8437	4.2533	2.479	6.7323
mode 2	4.7823	-0.3472	-0.3472	-0.3678	-0.3472	1.764	4.7965	1.764	4.0815	2.479	6.5605

Fig. 10. The Flow of Active Power in the Transmission Line without the Compensation and with the Compensation Using Model (1) and (2).



	Q11	Q12	Q13	Q22	Q23	Q24	Q31	Q34	Q1	Q2	Q3
Before compensation	0.729	0.0334	0.0334	0.0311	0.0311	0.4039	0.1791	0.0667	0.7959	0.3417	0.2458
mode 1	1.0366	0.0432	0.0432	0.0214	0.0214	-0.5391	0.9873	-0.7088	2.0927	-0.5819	0.2785
mode 2	0.5635	0.3255	0.0453	0.2968	0.0193	-0.1291	0.5351	-0.2729	1.9188	-0.4451	0.2622

Fig. 11. The Flow of Reactive Power in the Transmission Line without the Compensation and with the Compensation Using Model (1) and (2).

5. Conclusions

A new steady-state model of UPFC was proposed. This model consists of one shunt compensation block and two series compensation blocks. The UPFC with the new proposed model is investigated when installed in multi-machine systems with non-linear load model. The steady–state performance of the new model operating as impedance compensation and voltage regulator is presented and compared with that obtained from the original Gyugyi model. The results found in this paper would be very useful in selecting the highest possible amount of compensation of active or reactive power flow in transmission lines.

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