The modeling of UPFC based on circuit elements in an exact transmission line model

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Abstract

UPFC is considered and known as one of the best FACTS devices. It is a combination of series and parallel quick compensation, and can therefore provide active and reactive control to achieve maximum power transfer, system stability and improve power quality and reliability. Therefore, presenting a suitable model for UPFC which enables studying the network and load flow in energy transmission lines, has gotten the experts' attention. This paper presents a new model of UPFC in steady state based on circuit elements in an exact transmission line model. Considering the fact that the elements like UJT and tunnel diode in negative resistance region cause power increase, the model determines the value of the active and reactive power injected by the series converter into the network, and then the series converter of UPFC is simulated by means of a negative resistor and an induction or capacitor reactance. Resistance and reactance are expressed as functions of voltage of buses, load angle, voltage injection and fire angle of series converter. The relations of this model have been achieved in a two-bus system and have been simulated in 14- and 30- bus standard.

Keywords: FACTS, UPFC, Load Flow, Reactive Power Control, Active Power Control.

1. INTRODUCTION

Unified power flow controller is a multi-functional inter-mediator in FACTs devices family. UPFC can act as a parallel or series compensator, voltage regulator, phase replacer or power controller in different conditions by simultaneous control of line parameters [1]. Different models of UPFC are presented in steady state, including:

UPFC model based on voltage sources and series impedance: in this model the series and parallel converters are replaced by a voltage source and series impedance [2],[3].

UPFC model based on ideal voltage and current sources: in this model the series converter is replaced by a voltage source and the parallel converter by an ideal current source [4].

UPFC injection mode: in this model the series and parallel converters are replaced by a voltage source and series impedance and are then combined with the π-line model [5].

UPFC hybrid model: in this model the series converter is replaced by a series voltage source and leakage impedance related to the series transformer, and the parallel converter is replaced by two ideal current sources; one expresses the shunt converter's active power and its loss, and the other indicates the reactive power of the shunt converter and its loss. [6]

This paper presents a new model of UPFC in steady state based on the circuit elements in the exact transmission line model in a way that the series converter injection active power can be simulated with a negative resistance and the series converter injection reactive power can be simulated with a capacitor or inductive reactance, and the parallel converter reactive power will be shown as a connected power to the bus. Equations of the resistance and reactance are computed in two–bus single machine power system in the approximate transmission line model. The model is then generalized to exact transmission line model and simulated in 14- and 30–bus power system.

2. UPFC model based on circuit elements

UPFC series converter injects active and reactive power to the network by injecting series voltage into the transmission line with controllable phase amplitude and angle. The series converter provides the required active power through the capacitor link and the parallel converter through the network. Also, each converter can inject reactive power to the network or receive from it independently (see figure 1).

In the existing UPFC models, converters are replaced by voltage or current sources and the controller final model is shown as the injection power to the bus which causes changes in the Jacobean matrix and the load flow program structure. The goal of this paper is to model the UPFC series converter with a resistance -which expresses the injected active power of series converter to the line- in steady state, and also to model the injected reactive power with a reactance so that the reactive power of parallel converter can be shown as connected power to the bus .

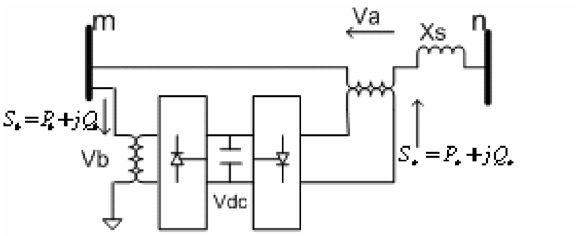

FIGURE 1: UPFC is placed in two- bus power system

In this model, we assume that the active and reactive power exchanged between the series converter and the network is known. Therefore, knowing the amplitude of buses' voltages and series converter injection voltage, we can compute the resistance and reactance values to replace the series converter.

Modelling of the Series Converter

For modelling of the UPFC series converter in steady state, the following assumptions are considered:

1- First, we consider the UPFC voltage source model in a two-bus one-machine system as depicted in figure 2 and by calculating the line current, we will obtain the active and reactive power injected by the series converter.

2- Then, we model the active power injected by a series converter with a negative resistance. The series converter reactive power is also modelled with a capacitive or inductive reactance, considering the type of the series converter.

Calculation of injected active and reactive power of the series converter

First, we obtain the electrical equations for figure 2 and calculate the series converter injection power.

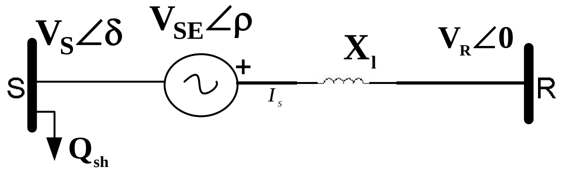

FIGURE 2: UPFC in a two–bus network

Flowing current in the line is calculated as follows:

$$I = \frac{V_S\angle\delta + V_{SE}\angle\rho - V_R\angle 0}{jX_L} \tag{1}$$

The active and reactive power injected by the series converter is expressed by the following equation:

$$S_{SE} = V_{SE} * \overset{*}{I} \tag{2}$$

Replacing the first equation in the second one and expanding it, the active and reactive power injected by the series converter is achieved:

$$P_{SE} = \frac{V_S * V_{SE}}{X_L}\sin(\delta-\rho) + \frac{V_R * V_{SE}}{X_L}\sin(\rho) \tag{3}$$

$$Q_{SE} = \frac{V_S * V_{SE}}{X_L}\cos(\delta-\rho) - \frac{V_R * V_{SE}}{X_L}\cos(\rho) + \frac{V_{SE}^2}{X_L} \tag{4}$$

The active and reactive power of the series converter can be modelled with a resistance and a reactance, respectively.

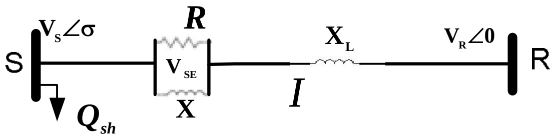

FIGURE 3: Modeling of the series converter with parallel

$$R = \frac{V_{SE}^2}{P_{SE}} \tag{5}$$

$$X = \frac{V_{SE}^2}{Q_{SE}} \tag{6}$$

To prove our assumptions, we calculate the R bus absorbed power for the both systems shown in figures 2 and 3 and show that the value of absorbed power by the R bus in the series converter voltage model and our own model are the same.

Calculation of the active and reactive power absorbed by the R bus in the UPFC voltage source model

The power of the R bus in the two–bus system of figure 2 is calculated using the following equation:

$$S_R = V_R * \overset{*}{I} \tag{7}$$

Replacing equation 1 in the above equation we have:

$$S_R = V_R * \left(\frac{V_S\angle\delta + V_{SE}\angle\rho - V_R\angle 0}{jX_L}\right)^* \tag{8}$$

Expanding this equation yields the following equation:

$$S_R = P_R + jQ_R \tag{9}$$

So, the active and reactive power absorbed by the R bus can be expressed by these equations:

$$P_R = \frac{V_S * V_R}{X_L}\sin(\delta) + \frac{V_R * V_{SE}}{X_L}\sin(\rho) \tag{10}$$

$$Q_R = \frac{V_S * V_R}{X_L}\cos(\delta) - \frac{V_R * V_{SE}}{X_L}\cos(\rho) - \frac{V_R^2}{X_L} \tag{11}$$

In the next section, the active and reactive power absorbed by the R bus will be calculated with the new UPFC model and we will show that the results are the same.

Calculating the active and reactive power absorbed by the R bus in the UPFC circuitry elements model

The flowing current in the two-bus system of figure 3 are as follows:

$$I = \dot{I}_R + \dot{I}_L \tag{12}$$

$$I_R = \frac{V_{SE}\angle\rho}{R} \tag{13}$$

$$I_L = \frac{V_{SE}\angle\rho}{jX} \tag{14}$$

Replacing the equations 13 and 14 in equation 12, we conclude:

$$I = \frac{V_{SE}\angle\rho}{R} + \frac{V_{SE}\angle\rho - 90}{X} \tag{15}$$

By expanding the above equation:

$$I = \frac{V_{SE}}{R}\cos\rho + \frac{V_{SE}}{X}\sin\rho + j\frac{V_{SE}}{R}\sin\rho - j\frac{V_{SE}}{X}\cos\rho \tag{16}$$

Using this equation and $S_R = V_R * \overset{*}{I}$, we will have:

$$S_R = \frac{V_{SE}V_R}{R}\cos\rho + \frac{V_{SE}V_R}{X}\sin\rho - j\frac{V_{SE}V_R}{R}\sin\rho + j\frac{V_{SE}V_R}{X}\cos\rho \tag{17}$$

The active and reactive power absorbed by the R bus:

$$P_R = \frac{V_{SE} * V_R}{R} \cos\rho + \frac{V_{SE} * V_R}{X} \sin\rho \tag{18}$$

$$Q_R = -\frac{V_{SE} * V_R}{R} \sin\rho + \frac{V_{SE} * V_R}{X} \cos\rho \tag{19}$$

Inserting equations 5 and 6 in 18 and 19, we have:

$$P_R = \frac{V_S * V_R}{X_L} \sin(\delta) + \frac{V_R * V_{SE}}{X_L} \sin(\rho) \tag{20}$$

$$Q_R = \frac{V_S * V_R}{X_L} \cos(\delta) - \frac{V_R * V_{SE}}{X_L} \cos(\rho) - \frac{V_R^2}{X_L} \tag{21}$$

Comparing the equations 10, 11, 20 and 21, we can say that the active and reactive power absorbed by the R bus in the systems shown in figures 2 and 3 are the same. Consequently UPFC series converter can be modeled with resistance and reactance.

Direct calculation of resistance and reactance equivalent to series converter

Inserting relations (10) and (11) in (5) and (6) we have :

$$R = \frac{V_{SE} * X_L}{V_S \sin(\delta - \rho) + V_R \sin\rho} \tag{22}$$

$$X = \frac{V_{SE} * X_L}{V_S \cos(\delta - \rho) - V_R \cos\rho + V_{SE}} \tag{23}$$

In this relationship , V_S and V_R are the amplitude of buses voltage , δ is the angle between buses voltage , V_{SE} , ρ are the amplitude and angle of injected voltage to series converter and X_L is the line reactance .

Assuming the series converter and buses voltage and also load angle are fixed , the resistance and reactance are only a subordinate of series converter fire angle and can replace the series converter.

In order that this model can be simulated in load flow program , parallel elements convert to series elements.

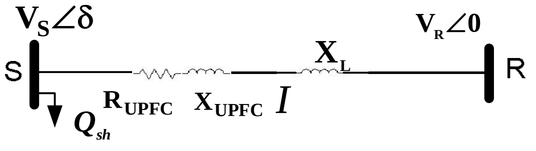

FIGURE 4: Modelling the UPFC in two –bus power system

The impedance equivalent to parallel elements equals to:

$$R_{UPFC} = \frac{R * X^2}{R^2 + X^2} \tag{24}$$

$$X_{UPFC} = \frac{X * R^2}{R^2 + X^2} \tag{25}$$

Therefore , by having buses voltage and the injected voltage of series converter values and the active and reactive power value the series converter exchanges with network , the values of resistance and reactance can be calculated , and put instead of series converter and also show the reactive power of parallel converter as connected power to bus.

Modelling the UPFC in the exact transmission line model

In the previous section, we obtained the UPFC model based on the circuitry in the approximate transmission line model. In this section, we model it in the exact transmission line model. To perform this modelling, we consider the UPFC in the two–bus single-machine system in the exact transmission line model in which the effects of the line capacitors are also considered. Figure 5 depicts the described model.

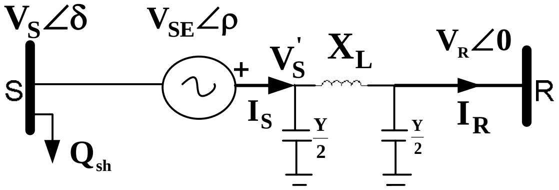

FIGURE 5: UPFC placed in exact line model

To calculate the active and reactive power exchanged between the series converter and the network, we first obtain the current I_S considering the equations between the current and voltage of the line model which is a bipolar network:

$$\begin{bmatrix} V'_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{26}$$

in which:

$$V'_S = V_S\angle\delta + V_{SE}\angle\rho \tag{27}$$

$$A = D = (1 + \frac{YZ}{2}) \tag{28}$$

$$B = Z \tag{29}$$

$$C = Y(1 + \frac{YZ}{2}) \tag{30}$$

Considering figure 5, we can write:

$$Z = jX_L \tag{31}$$

$$Y = j\omega c = \frac{j}{X_C} \tag{32}$$

Using equation 26, the transmitter line current equation can be written:

$$I_S = \frac{D}{B} V'_S + \frac{CB - AD}{B} V_R \tag{33}$$

Inserting equations 27 to 32 in equation 33, the current equation is achieved as follows:

$$I = \frac{V_S\angle\delta + V_{SE}\angle\rho - V_R\angle 0}{jX_L} + \frac{V_S\angle\delta + V_{SE}\angle\rho}{-j2X_C} \qquad (34)$$

The active and reactive power that the series converter exchanges with the network is obtained as follows:

$$P_{SE} - jQ_{SE} = V_{SE}^{*} * I \qquad (35)$$

in which:

$$\overset{*}{V}_{SE} = V_{SE}\angle -\rho \qquad (36)$$

Inserting equations 34 and 36 in equation 35 yields the following results:

$$\begin{aligned} P_{SE} - jQ_{SE} = {} & \frac{V_S * V_{SE}}{X_L}\angle(2\delta - \rho - 90) - \frac{V_R * V_{SE}}{X_L}\angle(\delta - \rho - 90) + \\ & \frac{V_{SE}^2}{X_L}\angle -90 + \frac{V_{SE}^2}{2X_C}\angle 90 + \frac{V_S * V_{SE}}{2X_C}\angle(\delta - \rho + 90) \end{aligned} \qquad (37)$$

By expanding the above equation, the active and reactive power injected by the series converter is achieved as follows:
the active power that the series converter injects into the network:

$$P_{SE} = \frac{V_S * V_{SE}}{X_L}\sin(\delta - \rho) + \frac{V_R * V_{SE}}{X_L}\sin(\rho) + \frac{V_S * V_{SE}}{2X_C}\sin(\rho) \qquad (38)$$

the reactive power that the series converter exchanges with the network:

$$Q_{SE} = \frac{V_S * V_{SE}}{X_L}\cos(\delta - \rho) - \frac{V_R * V_{SE}}{X_L}\cos(\rho) + \frac{V_{SE}^2}{X_L} - \frac{V_{SE}^2}{2X_C} - \frac{V_S * V_{SE}}{2X_C}\cos(\delta - \rho) \qquad (39)$$

According to the figure 3, we can model the series converter active and reactive power with a negative resistance and a capacitor or inductive reactance, respectively. It means:

$$R = \frac{V_{SE}^2}{P_{SE}} \qquad (40)$$

$$X = \frac{V_{SE}^2}{Q_{SE}} \qquad (41)$$

Inserting equations 38 and 39 in equation 40 and 41, we can write:

$$R = \frac{V_{SE}}{\frac{V_S}{X_L}\sin(\delta - \rho) + \frac{V_R}{X_L}\sin\rho + \frac{V_S}{2X_C}\sin\rho} \qquad (42)$$

$$X=\frac{V_{SE}}{\frac{V_S}{X_L}\cos(\delta-\rho)-\frac{V_R}{X_L}\cos\rho+\frac{V_{SE}}{X_L}-\frac{V_{SE}}{2X_C}-\frac{V_S}{2X_C}\cos(\delta-\rho)} \tag{43}$$

Using equations 24 and 25, the parallel reactance and resistance elements are converted to series elements and according to figure 6, the UPFC series converter in the exact line model, is modeled.

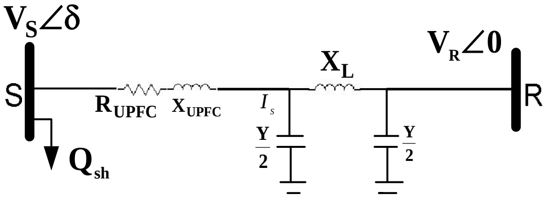

FIGURE 6: The UPFC series converter model in two-bus power system exact transmission model line

3. Simulation

In this section, we study the UPFC model based on circuitry elements in the 14- and 30-bus power system. Performing load flow using the Newton-Raphson method [7]in the 14- and 30-buses power system, the results of flowed power in the lines and voltage angle and amplitude of buses is calculated. The results are summarized in table 1-9.

Load flow results in 14-bus system without UPFC series converter

The results show that the bus number 5 has the lowest voltage and based on voltage, is a weak bus. Therefore we put UPFC converter as an example in line 1-5. By putting UPFC and changing the amplitude and angle of voltage injected by the series converter, the active and reactive power passing from line 1-5 will be controlled. The reactive power range is shown in figure 7 with respect to the active power. From this curve, it is obvious that using UPFC, we can change and control the active power in the range of 40 to 78 MW and reactive power between -8 to 42 MVAR.

bus number	bus voltage amplitude	bus voltage angle
1	1.06	0
2	1	-5.043
3	0.999	-13.362
4	.989	-11.428
5	.969	-9.151
6	1.02	-15.233
7	1.016	-14.628
8	1.05	-14.628
9	.998	-16.333
10	.998	-16.563
11	1.007	-16.095
12	1.012	-16.337
13	1.009	-16.526
14	.995	-17.72

TABLE 1: buses voltage amplitude and angle.

First bus	End bus	MW	MVAR
1	2	161	73.391
1	5	57.7	40.61
2	3	74.7	17.859
2	4	63.8	25.351
2	5	40.8	36.253
4	3	19.5	-7.468
4	7	27.4	-2.434
4	9	15.6	4.373
5	4	46.3	-24.413
5	6	44.5	8.218
6	11	7.7	7.208
6	12	7.77	3.345
6	13	17.8	9.045
7	9	27.4	16.563
8	7	0	21.284
9	10	4.72	0.712
9	14	8.89	1.102
11	10	4.27	5.193
12	13	1.68	1.569
13	14	6	4.303

TABLE 2: Active and reactive power lines without UPFC.

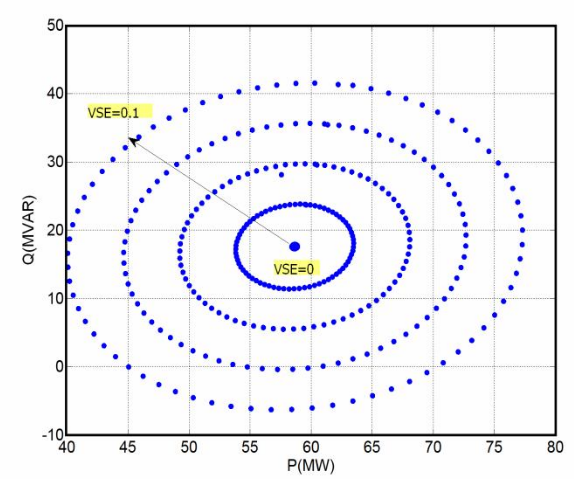

FIGURE 7: Changes in reactive power in terms of active power in line 1-5

For instance, we want the active power passing from line 1-5, to increase from 57.7 to 75.2 MW which is about 30 percent, and the reactive power of line 1-5 to decrease from 40.6 to 39.8 MVAR, which is around 1.7 percent. Therefore, assuming that the voltage amplitude injected by the series converter is fixed and equals to 0.1, using equations 38 and 39, we obtain the voltage phase angle of the series converter as follows:

$V_{SE} = 0.1$ and $\rho = -130^\circ$

Knowing the voltage phase and amplitude injected by the series converter, the resistance and reactance values that are equivalent to the series converter, is calculated using equations 24, 25, 42 and 43:

$R_{UPFC} = -0.0028$ And $X_{UPFC} = -0.0975$

Inserting the equivalent UPFC series converter resistance and reactance values in the line 1-5 and performing load flow calculations using Newton-Raphson method, the voltage and angle of buses and also the active and reactive power of lines can be calculated. The results are shown in tables 3 and 4.

Results of load flow with UPFC series converter in 14-bus power system

The results of tables 3 and 4 show that this model, like the other models of UPFC, is also able to control the active and reactive power of lines, stabilize the buses voltage and use the transmission lines in the optimized way. The flowed active and reactive power in line 1-5 is depicted in figures 8 and 9, with and without UPFC.

bus number	bus voltage amplitude	bus voltage angle
1	1.06	0
2	1	-4.476
3	0.999	-12.4
4	1.006	-10.155
5	1.007	-7.604
6	1.02	-13.583
7	1.024	-13.203
8	1.05	-13.203
9	1.006	-14.843
10	1.004	-15.041
11	1.01	-14.51
12	1.013	-14.698
13	1.01	-14.896
14	1	-16.156

TABLE 3: buses voltage amplitude and angle

First bus	End bus	MW	MVAR
1	2	143.00	65.939
1	5	75.615	30.761
2	3	71.173	12.748
2	4	57.794	8.887
2	5	32.342	6.467
4	3	23.027	3.563
4	7	26.786	3.373
4	9	15.349	6.799
5	4	54.968	2.282
5	6	45.565	28.477
6	11	8.384	5.31
6	12	7.861	3.066
6	13	18.12	8.068
7	9	26.786	17.204
8	7	0	15.662
9	10	4.116	2.564
9	14	8.519	2.322
11	10	4.884	3.322
12	13	1.761	1.291
13	14	6.381	3.057

TABLE 4: Active and reactive power lines with UPFC

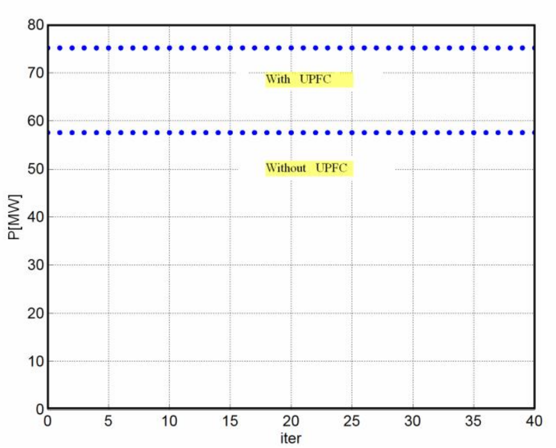

FIGURE 8: the curve of line 1-5 in active power with and without UPFC

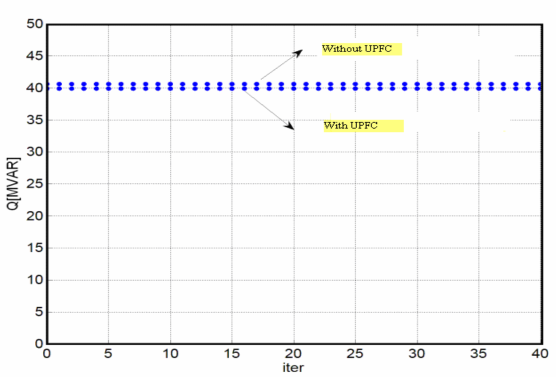

FIGURE 9: the curve of line 1-5 in active power with and without UPFC

In this system the load flow calculations are performed in the approximate transmission line model and its results are compared with the exact transmission line model. (See table 5)

	approximate model line	**exact model line**	**percentage change**
Voltage bus 5 (pu)	1.003	1.007	+0.39%
Active power line 1 - 5 (MW)	75.19	75.615	+0.56%
Reactive power line 1 - 5 (MVAR)	39.88	30.761	-22.86%

TABLE 5: changes of voltage and active and reactive power of line 1-5 with UPFC in approximation and exact transmission line model

Comparing the results, we conclude that the exact transmission line model yields more exact results. So, use of the exact transmission line model based on circuitry elements is preferred in comparison with the approximate model.
In the next section, the load flow calculations in 30-bus power system in presence of UPFC model in exact transmission line model will be investigated.

Results of load flow on 30–bus system without UPFC series converter

Performing the calculations of the load distribution, buses' voltage angles and amplitudes and also the active and reactive power passing from the lines are computed. The results for voltage and angle of buses number 2 and 5 and also the flowed power in line 2-5, are shown in tables 6 and 7.

bus number	bus voltage amplitude	bus voltage angle
2	1.043	-4.97
5	1.005	-13.54

TABLE 6: buses voltage amplitude and angle

First bus	End bus	MW	MVAR
2	5	78.7	25.2

TABLE 7: The active and reactive power line2-5 without UPFC

Results of load flow on 30–bus system in the presence of UPFC series converter

Using UPFC in line 2-5, we can control the passing active and reactive power from this line. Calculating the load flow by MATLAB software and use of Newton-Raphson method and for changes of voltage phase and amplitude injected by the series converter, the curve of reactive power changes has been plotted with respect to the active power in line 2-5 in figure 10

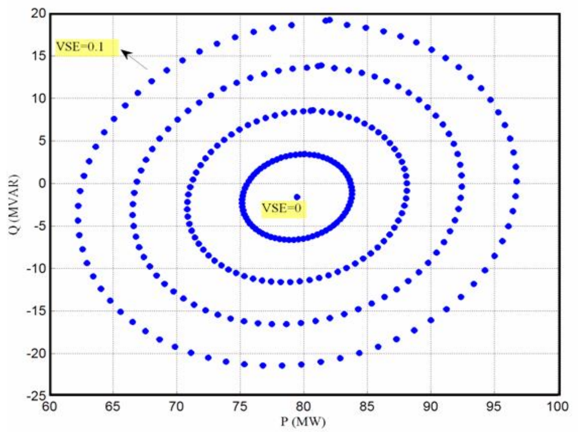

FIGURE 10: The reactive power changes in terms of active power in line 2-5

As this figure determines, by using the UPFC new model, the active power of line 2-5 of 30-bus power system can be controlled and changed between 63 to 97 MW and reactive power between -23 to 20 MVAR.

Therefore, for each value of voltage amplitude and phase of the series converter and using equations 24, 25, 42 and 43 the series converter equivalent resistance and reactance value will be calculated and used instead of the UPFC series converter . For example in work point:

$$V_{SE} = 0.1 \quad \text{and} \quad \rho = 80^\circ$$

The UPFC series converter equivalent series resistance and reactance values can be achieved as follows:

$$R_{UPFC} = -0.0016$$

And $X_{UPFC} = -0.077$

Putting the resistance and reactance values equivalent to the series converter and performing load flow, the results will be obtained according to tables 8 and 9.

bus number	bus voltage amplitude	bus voltage angle
2	1.043	-5
5	1.044	-11.1

TABLE 8: buses voltage amplitude and angle with UPFC

First bus	End bus	MW	MVAR
2	5	94.7	5.2

TABLE 9: The active and reactive power line2-5 with UPFC

Figures 11 and 12 show the curve for the active and reactive power passing from lines 2-5 with and without UPFC.

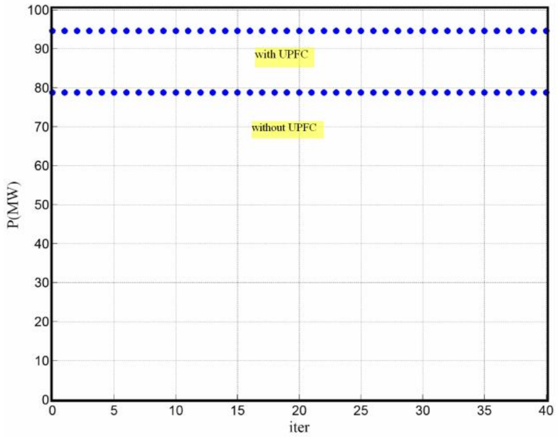

FIGURE 11: Active power curve passing line 2-5 in the presence and without UPFC

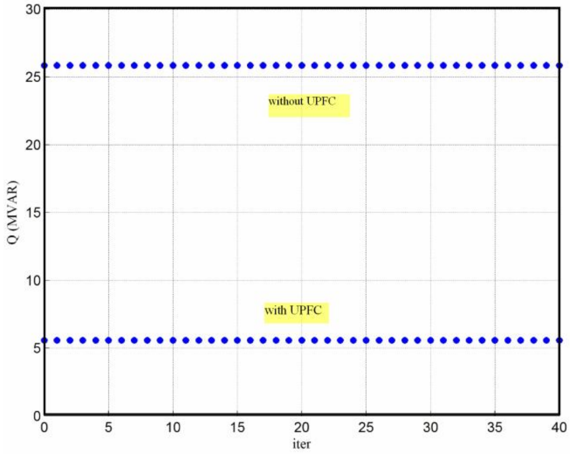

FIGURE 12: Reactive power curve passing line 2-5 in the presence and without UPFC

4. Conclusion

Considering the results of the simulation in figures 6 to 13 and tables 1 to 9, we can conclude:

- Like the other UPFC models, this model is also able to control the flowed power in transmission lines and as previously proved the results of this model and voltage injection model is the same. Therefore we can replace UPFC model on the basis of circuitry elements with other models.
- In this model a resistance is used instead of an injected active power, that the resistance value and polarity show the injected active powers value and direction; negative resistance shows the power injection and positive resistance shows the active power absorption.
- In this model instead of series converter reactive power, a capacitor or inductive reactance is used and its value indicates the rate of the reactive power. If the series converter injects reactive power into the network, the reactance will become capacitive (negative), and if the series converter absorbs reactive power from the network, the reactance will be inductive (positive).
- Unlike the previous models in which the active and reactive power of series converter could be modelled as connected power to bus and this leads to change of program structure and modification of Jacobian matrix, in this model the injected active and reactive power can be modelled with a resistance and reactance and in load flow programs only the network admittance matrix will change.
- Using the UPFC model based on circuitry elements in the exact transmission line model and adding the capacitors effects, yields more accurate load flow calculation results, so using the UPFC model in the exact transmission line model is preferred in comparison with the approximate model.

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