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Analysis and Simulation of UPFC for Power Flow Control using PI-Controller

Naveen M R
Student, M.E (Power and Energy Systems),
Department of Electrical Engineering,
UVCE, Bangalore University,
Bengauluru, India.

Dr. T. S. Prasanna
Professor,
Department of Electrical Engineering,
UVCE, Bangalore University,
Bengauluru, India.

***Abstract* — To keep up a stable and efficient power system with ever-increasing demand there is a rapid development in power electronics that introduces the FACTS devices which can solve the instability problems easily and efficiently. The predominant FACTS device Unified Power Flow Controller (UPFC) is a solid-state controller that can be used to control active and reactive power flow in transmission lines. In this paper, we use a PI controller strategy for UPFC to regulate power flow as well as voltage at corresponding buses. The control strategy is evaluated using Matlab/Simulink for IEEE-9 bus power system network.**

Keywords: FACTS, UPFC, STATCOM, SSSC, IPFC, TCSC, PI, SVS, VSC.

I. INTRODUCTION

The present power system consisting of a complex power system network with the number of generating units interconnected. This complexity introduces instability and reduces the efficiency of the power system. The receiving and sending end voltages, phase angle between them and line impedance determines the transmitted electrical power over a line. FACTS [1,3] devices can enlarge the maximum power carrying capacity and control power flow of existing transmission lines. In general, the FACTS controller can be classified as a mechanical switch, voltage source converter (VSC) and hybrid devices. Different types of VSC FACTS devices are presented in fig. 1, such as Static Synchronous Compensator (STATCOM) [3] and Static Synchronous Series Compensator (SSSC) [3] are the one-port controller and Unified Power Flow Controller (UPFC) [2,3] and Interline Power Flow Controller (IPFC) [3] are the two-port controllers.

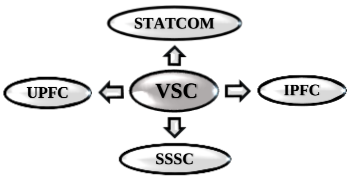

Fig. 1. Different FACTS devices based on VSC

UPFC is one of the most adaptable and a better FACTS device which can provide superior power flow and enhancement of the power system stability. Several articles and technical literature are found on utilizing UPFC in power system. Thyristor Controlled Series Compensator (TCSC) [3] and UPFC are commissioned in the power system to regulate the natural power-sharing between the two different parallel transmission lines and therefore allows the maximum transmission capacity for effective utilization. The UPFC is the series-shunt combined type FACTS controller. It is used to regulate real, reactive power and bus voltage. In this paper, the application of UPFC in power flow control in IEEE-9 [4] bus power system is investigated and the phasor model [8] of UPFC is used. Matlab/Simulink software package is used for the simulations.

II. UNIFIED POWER FLOW CONTROLLER

The UPFC is a generalized synchronous voltage source (SVS), represented at the fundamental frequency by voltage phasor V_{pq} with controllable magnitude V_{pq} $(0 \leq V_{pq} \leq V_{pq\,max})$ and angle ρ $(0 \leq \rho \leq 2\pi)$, in series with the transmission line and viewed as elementary two machine system in Figure 2. In this functionally unlimited operation, which clearly includes voltage and angle regulation, the SVS generally exchanges both reactive and real power with the transmission system.

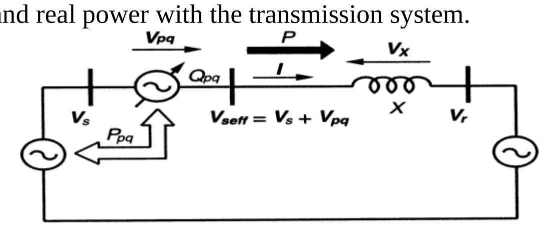

Fig. 2. Conceptual representation of the UPFC as two-machine power system.

The UPFC consists of two voltage source converters, as displayed in Figure 3. These back-to-back converters labelled "VSC-1" and "VSC-2". These are operated from a common dc link provided by a dc storage capacitor. As indicated before, this arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can autonomously generate (or absorb) reactive power at its own ac output terminal.

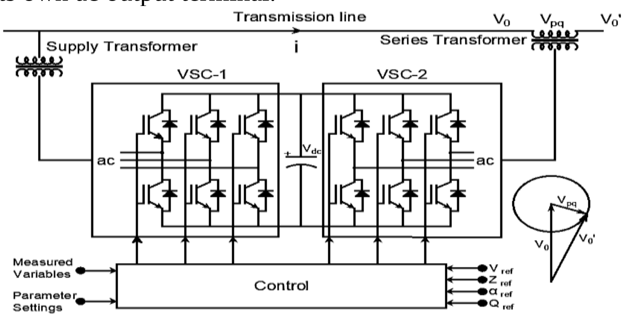

Fig. 3. UPFC connection diagram to the power system

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VSC-2 provides the main function of the UPFC by injecting a voltage V_{pq} with controllable magnitude V_{pq} and phase angle ρ in series with the line via series transformer at VSC-2 side. This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The reactive power exchanged at the ac terminal is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power which appears at the dc-link as a positive or negative real power demand.

The basic function of VSC-1 is to supply or absorb the real power which is demanded by VSC-2 at the common dc link to maintain the real power exchange resulting from the series voltage injection. This dc link power demand of VSC-2 is converted back to ac by the VSC-1 and coupled to the transmission line bus via shunt connected transformer. In addition to the real power need from VSC-2, VSC-1 can also generate or absorb controlled reactive power if desired, and thereby provide shunt reactive compensation independently for the line. Since there is a closed direct path for the real power negotiated by the action of series voltage injection through VSC-1 and 2 back to the line, the corresponding reactive power is supplied or absorbed locally by VSC-2 and therefore does not have to be transmitted by the line. Thus, the VSC-1 can be operated at a upf (unity power factor) or be controlled to have a reactive power exchange with the transmission line, independent of the reactive power exchanged by VSC-2. But there is no reactive power flow through the dc-link between the converters.

With reference to fig. 2, the transmitted power P and the reactive power $-jQ_r$, supplied by the receiving end, can be expressed as follows [3,9]:

$$P - jQ_r = V_r\left(\frac{V_s + V_{pq} - V_r}{jX}\right)^* \quad (1)$$

Where,

$$V_s = Ve^{j\delta/2} = V\left(\cos\frac{\delta}{2} + j\sin\frac{\delta}{2}\right) \quad (2)$$

$$V_r = Ve^{j\delta/2} = V\left(\cos\frac{\delta}{2} - j\sin\frac{\delta}{2}\right) \quad (3)$$

$$V_{pq} = V_{pq}e^{j(\delta/2+\rho)} = V_{pq}\left\{\cos\left(\frac{\delta}{2}+\rho\right) + j\sin\left(\frac{\delta}{2}+\rho\right)\right\} \quad (4)$$

By substituting equations 2, 3 and 4 in equation 1, we obtain the expression for P and Q_r,

$$P(\delta,\rho) = P_0(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{pq}}{X}\cos\left(\frac{\delta}{2}+\rho\right) \quad (5)$$

$$Q_r(\delta,\rho) = Q_{0r}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{pq}}{X}\sin\left(\frac{\delta}{2}+\rho\right) \quad (6)$$

Where,

$$P_0(\delta) = \frac{V^2}{X}\sin\delta \quad (7)$$

and

$$Q_{0r}(\delta) = -\frac{V^2}{X}(1-\cos\delta) \quad (8)$$

are the real and reactive power transmission of the uncompensated power system at a given angle δ. Since angle ρ is freely shifting between 0 to 2π at any given transmission angle δ ($0 \le \delta \le \pi$), it follows that $P_{pq}(\rho)$ and $Q_{pq}(\rho)$ are well- regulated between $-VV_{pq}/X$ and $+VV_{pq}/X$ independent of angle ρ.

Therefore, the transmittable real power P is regulated between

$$P_0(\delta) - \frac{VV_{pq\,max}}{X} \le P_0(\delta) \le P_0(\delta) + \frac{VV_{pq\,max}}{X} \quad (9)$$

and the reactive power Q_r is regulated between

$$Q_{0r}(\delta) - \frac{VV_{pq\,max}}{X} \le Q_{0r}(\delta) \le Q_{0r}(\delta) + \frac{VV_{pq\,max}}{X} \quad (10)$$

at any transmission angle δ.

III. SYSTEM UNDER STUDY AND SIMULATION PARAMETERS

A UPFC is used to control the power flow in IEEE 9 power system network as shown in the Fig. 4.

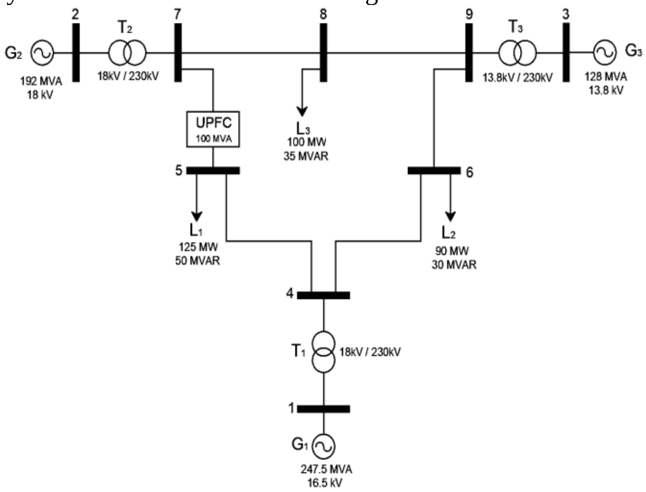

Fig. 4. Single line diagram of power system under study.

The simulation bock diagram of the power system with a UPFC in Matlab/Simulink environment is shown in Figure 5.

Optimal allocation of UPFC was concluded by the results obtained by the Newton Raphson method of power flow analysis carried on IEEE-9 [5] bus system. Table I shows the Voltage data at all the buses cosidering 100MVA base.

TABLE I. VOLTAGE MEASUREMENT FROM IEEE 9 NETWORK

Bus No.	Voltage Measured	
	Magnitude	***Angle***
1	1.04	0.00
2	1.025	9.17
3	1.025	4.56
4	1.026	-2.23
5	**0.996**	**-4.00**
6	1.013	-3.70
7	1.026	3.62
8	1.016	0.63
9	1.032	1.87

From Table I, the magnitude of voltage at bus-5 is 0.996 pu and its phase angle is -4.00 deg. Since the voltage at bus 5 is considerably low when compared to voltage at all the buses, UPFC is allocated nearer to bus-5.

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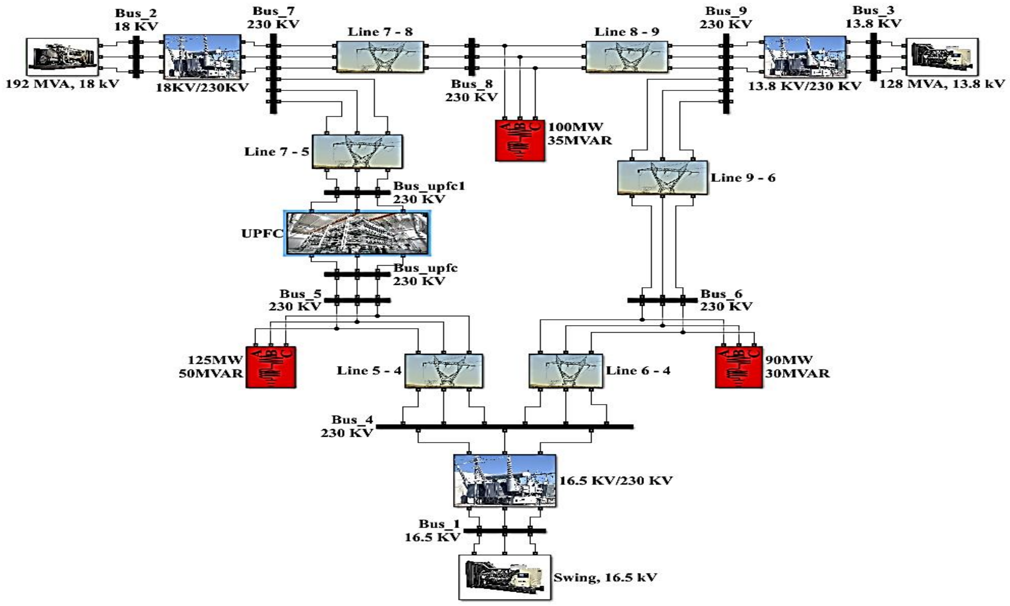

Fig. 5. Matlab/Simulink diagram of the IEEE-9 bus system with a UPFC

Matlab/Simulink simulation model is shown in the Fig. 5. The internal model configuration of UPFC is shown in Fig.6. Data configuration of UPFC simulink model is given in Table II.

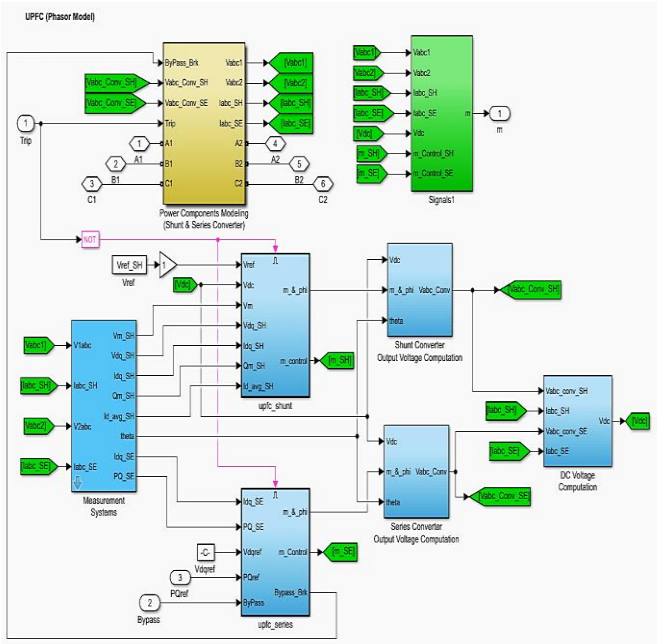

Fig. 6. Inside view of UPFC block.

TABLE II. UPFC BLOCK PARAMETERS

Parameters	Values
Shunt and Series converter rating	100MVA
Power Regulator gains	K_P = 0.025 and K_I =1.5
Vac Regulator gains	K_P = 5 and K_I = 1000
Current Regulator gains	K_P = 0.1667 and K_I = 8.3333
Bypass breaker	Initially closed and opens at t = 10s
P reference	-0.63 pu.
Q reference	0.3 pu.
DC link nominal voltage	40kV
DC link capacitance	750e-6 F

P_{ref} and Q_{ref} values are power flow controlling parameters which are initialized such that, these value increase/decrease the power flow through the corresponding line as per the equations 9 and 10, as well as its values never cause any instability or congestion of any power system parameter at any point of the power system parameter.

IV. SIMULATION RESULTS

To control the Voltage Source Converter (VSC) (i.e., both VSC-1 and 2) PI controller [6,7,9] is used. PI controller is necessary not only for UPFC control and also in order to damp out the oscillations in power systems. The proportional and integral gain constants used for power, voltage and current regulation are given in Table II. Matlab/Simulink simulation time called out for 20s. UPFC bypass switch is opened at 10s. The obtained injected series voltage and its phase angle is shown in Figure 7.

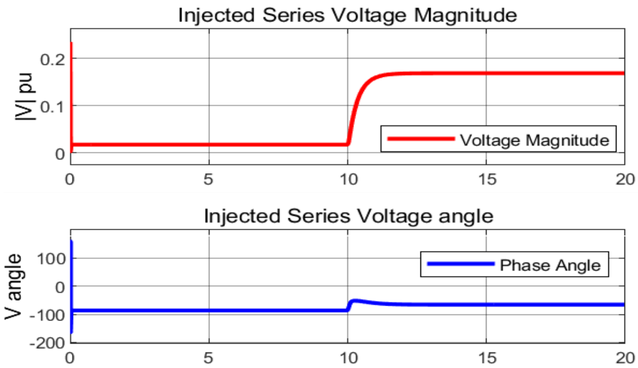

Fig. 7. Injected series voltage

This injected voltage of magnitude 0.17V and phase angle of -65 deg. causes change in active and reactive power flow through the line connecting bus-5 and 7. After the inject of series voltage at bus-5, at 10s the improvement of voltage profile at all buses as well as increase in active power through the corresponding line is noticed and same is shown in fig. 8. fig. 9 and table III. gives the active power changes at all buses before and after the switching of UPFC.

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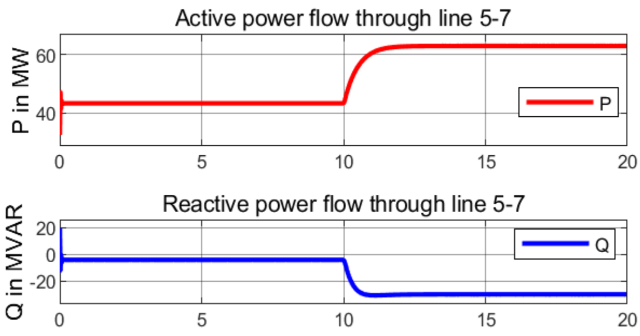

Fig. 8. Change in power flow through line 5-7 without and with UPFC

From fig. 8, it indicates that active power flow has increased from 43.23 MW to 63.00 MW i.e., increase of 45.75%. And reactive power is compensated by controlling reactive power flow through the line 5-7, it changes from -4.24 MVAR to -30.01 MVAR, to increase voltage profile in the system. Further the generation from slack bus i.e., swing generator is reduced from 129.2 MW to 124.6 MW i.e., a decrease of 3.5 %, nothing but losses are reduced by 4.58 MW and can be seen in the fig. 9 and table 3.

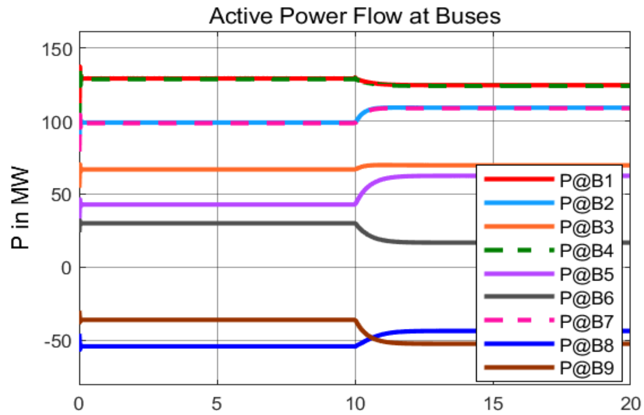

Fig. 9. Change in Active Power flow at all buses

TABLE III. ACTIVE POWER FLOW CHANGES AT BUSES

Bus No.	Without UPFC in MW	With UPFC in MW
1	129.2	124.6
2	98.97	109.2
3	66.84	69.74
4	128.7	124.1
5	42.8	62.5
6	30	16.7
7	98.61	108.8
8	-54.36	-43.8
9	-36.19	-52.6

And the changes in the reactive power at all bus is shown in the Table IV, followed by figure 10.

TABLE IV. REACTIVE POWER CHANGES AT BUSES

Bus No.	Without UPFC in MVAR	With UPFC in MVAR
1	-27.77	-26.15
2	-20.87	-32.5
3	-14.5	-18.13
4	-32.62	-30.63
5	68.58	56.7
6	16.4	25.42
7	-24.72	-37.01
8	-15.96	-29.05
9	19.84	12.68

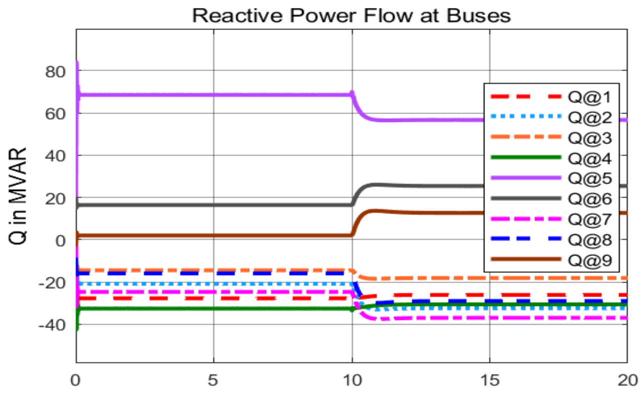

Fig. 10. Change in Reactive Power at all buses

As given in table II, to control the flow of active and reactive power at through the line connecting bus-5 and 7 using UPFC, the control or the reference values P_{ref} = -0.63 pu and Q_{ref} = 0.3 pu are set from 10s to stop time. The active and reactive power following the reference set by UPFC is shown in figure 11.

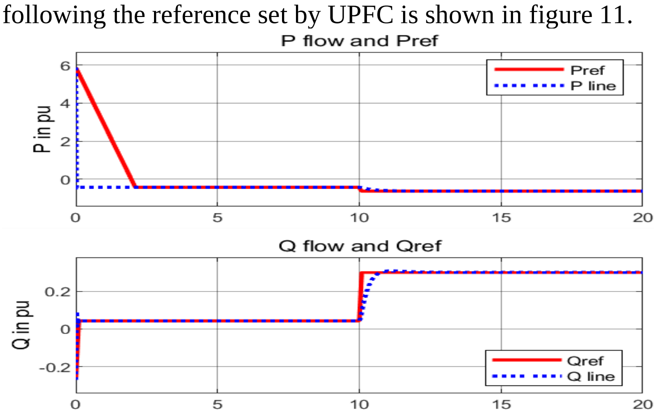

Fig. 11. Active and Reactive Power through the line following reference value

Change in positive sequence voltage profile of all the buses, before and after the introduction of UPFC is represented in the Figure 12 followed by Table V.

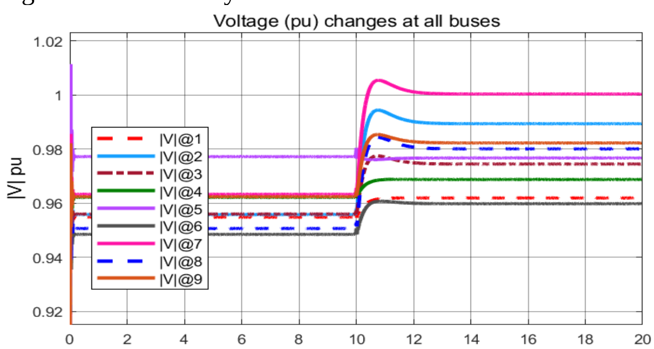

Fig. 12. Voltage changes at all buses

TABLE V. VOLTAGE CHANGES AT BUSES

Bus No.	Voltage Without UPFC		Voltage With UPFC	
	Magnitude	*Angle*	*Magnitude*	*Angle*
1	0.954	-33.14	0.962	-31.56
2	0.955	-32.64	0.989	-35.08
3	0.956	-33.11	0.974	-33.99
4	0.962	-34.09	0.968	-33.31
5	0.977	-39.12	0.976	-36.33
6	0.948	-37.89	0.959	-37.11
7	0.963	-34.55	1.00	-37.05
8	0.950	-36.95	0.98	-38.78
9	0.962	-34.73	0.982	-35.61

From figure 12 and Table V, the improvement in voltage profile at all buses are noted and essentially all are well within standard limit.

V. CONCLUSION

The main abilities of UPFC are voltage regulation, reactive power compensation and power flow control. The FACTS are integrated in power system to regulate the power flow in appropriate lines as well as to improve the security of transmission line. UPFC is one of the most secured FACTS device for power flow control and enhancing the stability of power systems. This paper concludes the influence of UPFC in IEEE-9 bus power system to improving stability by injecting voltage into the transmission lines to achieve better voltage profile at all buses and by regulating both power and voltages. With an advanced optimal allocation algorithm of FACTS devices and better control techniques of VSCs in UPFC, better results can be obtained and same can be simulated on different power system network using Matlab/Simulink.

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