Implementation of Unified Power Flow Controller (UPFC) for Power Quality Improvement in IEEE 14-Bus System

Arup Ratan Bhowmik¹, Champa Nandi² M.Tech Student¹, Assistant Professor² Department of Electrical Engineering Tripura University, Tripura, India. E-mail:arup.tripurauniversity@gmail.com, chmpnandi@gmail.com

Abstract

In this paper the performance of Unified Power Flow Controller (UPFC) is investigated in controlling the flow of power over the transmission line. This research deals with digital simulation of standard IEEE 14-bus power system using UPFC to improve the real and reactive power flow control through a transmission line by placing UPFC at the sending end using computer simulation. When no UPFC is installed, real and reactive power through the transmission line cannot be controlled. The circuit model for UPFC is developed using rectifier and inverter circuits. The Matlab simulation results are presented to validate the model. The result of network with and without using UPFC are compared in terms of active and reactive power flows in the line and active and reactive power flows at the bus to analyze the performance of UPFC.

1. Introduction

The demand of efficient and high quality power is escalating in the world of electricity. Today's power systems are highly complex and require suitable design of new effective and reliable devices in deregulated electric power industry for flexible power flow control. In the late 1980s, the Electric Power Research Institute (EPRI) introduces a new approach to solve the problem of designing, controlling and operating power systems: the proposed concept is known as Flexible AC Transmission Systems (FACTS) [1]. It is reckoned conceptually a target for long term development to offer new opportunities for controlling power in addition to enhance the capacity of present as well as new lines [2] in the coming decades. Its main objectives are to increase power transmission capability, voltage control, voltage stability enhancement and power system stability improvement. Its first concept was introduced by N.G.Hingorani in April 19, 1988. Since then different kind of FACTS controllers have been recommended. FACTS controllers are based on voltage source converters and includes devices such as Static Var Compensators

(SVCs), Synchronous Compensators static (STATCOMs), Thyristor Controlled Series Compensators (TCSCs), Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controllers (UPFCs). Among them UPFC is the most versatile and efficient device which was introduced in 1991. In UPFC, the transmitted power can be controlled by changing three parameters namely transmission magnitude voltage, impedance and phase angle. Unified Power Flow Controller (UPFC) is the most promising version of FACTS devices as it serves to control simultaneously all three parameters (voltage, impedance and phase angle) at the same time. Therefore it is chosen as the focus of investigation.

For the last few years, the focus of research in the FACTS area is mainly on UPFC. Many researchers have proposed different approaches of installing UPFC in power systems [3, 4, 5]. The concepts of characteristics have been broadly reported in the literature [5]. The UPFC has been researched broadly and many research articles dealing with UPFC modelling, analysis, control and application have been published in the recent years. Mathematical models of UPFC has been developed to study steady state characteristics using state space calculations without considering the effects of converters and the dynamics of generator [6,7]. The performance of UPFC has been reported by designing a series converter with conventional controllers [8, 9]. Many power converter topologies have been proposed for the implementation of FACTS devices such as multipulse converter like 24 pulses and 48 pulses and multi level inverters [10, 11, 12]. The advantages and limitations of high power converters have been discussed [13]. In [14] the dynamic control of UPFC has been analyzed with six pulse converter using switching level model. Their proposed technique aims at to control the real and reactive power flow in the transmission lines, by effectively changing the firing angle of shunt converter and modulation index of the series converter. Limyingcharoen et al investigated the mechanism of three control strategy of a UPFC in enhancing power

system damping [15].A current injected UPFC model for improving power system dynamic performance was developed by Meng and So [16] where a UPFC was represented by an equivalent circuit with a shunt current source and a series voltage source [17]. Fujita et al. [18] investigated the high frequency power fluctuations induced by a UPFC. Different algorithms have been proposed to increase the power flow control with UPFC in power transmission systems [19]. Different case studies have been carried on standard bus network. Baskar et. al. proposes a technique to control the real and reactive power in the transmission

line by the two leg three phase converters based on UPFC. In this paper dynamic control of UPFC has analyzed with two leg three phase converters by switching level model with linear and nonlinear loads. They suggests that the UPFC with their proposed controller successfully increase the real as well as reactive power flow and improves voltage profile for the duration of the transient conditions in the power transmission systems [20]. Some results of network with and without UPFC are also been compared in terms of active and reactive power flows in the line and reactive power flow at the bus to compare the performance of UPFC. A number of simulation results have compared when UPFC is connected between different buses in a specified transmission system. Ch. Chengaiah et. al. found that a system performs better when the UPFC is connected to a bus which has low voltage profile [21]. Based on IEEE 14-bus test system [22] a simulation study of UPFC is carried out in this paper. The performance of UPFC in controlling power flow over the transmission line is investigated. We also propose a model which can improve and control the active as well as reactive power by placing UPFC at midpoint of a standard IEEE 14-bus system. A comparative performance evaluation with and without UPFC has been studied. The proposed technique successfully improves the voltage and power profile in the power transmission systems.

This paper is organized as follows: After this introduction, section II describes the operating principle and the mathematical equations of a UPFC connected to a network, section III provides the Simulation results and discussion and finally section IV Concludes this paper.

2. Operating Principle of UPFC

The UPFC is the most versatile and complex of the FACTS devices, combining the features of the STATCOM and the SSSC. The main reasons behind the wide spreads of UPFC are: its ability to pass the real power flow bi-directionally, maintaining well

regulated DC voltage, workability in the wide range of operating conditions etc [19]. The basic components of the UPFC are two voltage source inverters (VSIs) sharing a common dc storage capacitor, and connected to the power system through coupling transformers. One VSI is connected to in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer. The DC terminals of the two VSCs are coupled and this creates a path for active power exchange between the converters. Thus the active supplied to the line by the series converter can be supplied by the shunt converter as shown in figure 1 [23]. Therefore, a different range of control options is available compared to STATCOM or SSSC. The UPFC can be used to control the flow of active and reactive power through the transmission line and to control the amount of reactive power supplied to the transmission line at the point of installation [24]. The series inverter is controlled to inject a symmetrical three phase voltage system of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor V_{dc} constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line. The UPFC can also provide simultaneous control of all basic power system parameters, viz., transmission voltage, impedance and phase angle. The UPFC has many possible operating modes: Var control mode, automatic voltage control mode, direct voltage injection mode, phase angle shifter emulation mode, line impedance emulation mode and automatic power flow control mode [25].



Figure 1. Basic circuit arrangement of UPFC





3. Mathematical modelling of UPFC

In this model, we have considered the UPFC is placed at the centre of a 300km transmission line. This model was derived with to study the relationship between electrical transmission system and UPFC in steady state conditions. The basic scheme is shown in fig.3 [26]. A UPFC can be represented by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance of the two coupling transformers [27].



Figure 3. Equivalent circuit of UPFC

Based on the basic principle of UPFC and network theory, the active and reactive power flows in the line, from bus-i to bus-j, having UPFC can be written as [28],

$$P_{ij} = (V_i^2 + V_T^2)g_{ij} + 2V_iV_Tg_{ij}\cos(\phi_T - \delta_j) -V_jV_T [g_{ij}\cos(\phi_T - \delta_j) + b_{ij}(\sin(\phi_T - \delta_j)] -V_iV_j(g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij})....(1) Q_{ij} = -V_iI - V_i^2(b_{ij} + B/2) -V_iV_T[g_{ij}\sin(\phi_T - \delta_i) + b_{ij}\cos(\phi_T - \delta_i)] -V_iV_j(g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij})....(2)$$

Where $g_{ij} + jb_{ij} = \frac{1}{r_{ij} + jx_{ij}}$ and I_q is the reactive

current flowing in the shunt transformer to improve the voltage of the shunt connected bus of UPFC. Similarly, the active and reactive power flows in the line, from bus-j to bus-i, having UPFC can be written as,

$$P_{ji} = v_j^2 g_{ij} - V_j V_T [g_{ij} \cos(\phi_T - \delta_j) - b_{ij} g \sin(\phi_T - \delta_j)] - V_i V_j (g_{ij} \cos \delta_{ij} - b_{ij} \sin \delta_{ij})....(3)$$

$$Q_{ji} = -V_j^2 (b_{ij} + B/2) - V_j V_T (g_{ij} \sin(\phi_T - \delta_j)) - b_{ij} \cos(\phi_T - \delta_j)) + V_i V_j (g_{ij} \sin \delta_{ij} + b_{ij} \cos \delta_{ij})....(4)$$
The real neural and reactive neural injections at hyperbolic density of the set of the s

The real power and reactive power injections at bus-i with the system loading (λ) can be written as [26],

$$p_{i} = P_{Gi} - P_{Di}^{0}(1+\lambda) = \sum_{j \in N_{b}} P_{ij}....(5)$$
$$Q_{i} = Q_{Gi} - Q_{Di}^{0}(1+\lambda) = \sum_{j \in N_{b}} Q_{ij}....(6)$$

Where P^{O}_{Di} and Q^{O}_{Di} are the initial real and reactive power demands. P_{Gi} and Q_{Gi} are the real and

reactive power generations at bus-i respectively. N_{h} is

the number of system buses and λ is the sensitivity of system loading [26]. In equation (5), uniform loading with the same power factor at all the load buses has been considered and the increase in the loading is assumed to be taken care by the slack bus whereas any sharing of generation amongst the generators can be easily incorporated in this model.

4. Simulation Results and Discussion

Digital simulation is done using the blocks of Matlab Simulink and the results are presented here. Standard IEEE 14-bus test system is shown in the figure 4. Figure 5 shows Simulation model in MATLAB/Simulink Environment. The Simulink Model/diagram for Standard IEEE 14-bus network with UPFC in MATLAB/Simulink Environment developed is shown in the Figure 6. The respective waveforms are given in the figure below. A comparative performance evaluation with and without UPFC in the transmission line has been studied. The line impedance is represented by series RL combination. Figure 7 shows the waveform of output voltage across load-1 without UPFC. Figure 8 shows the waveform of output voltage across load-2 without UPFC. Figure 9 and 10 illustrates the waveform of output voltage across load-1 and load-2 when UPFC is introduced in the network. These waveforms are obtained by simulating the Simulink diagram for test system in the environment of Simpower toolbox of MATLAB. Simulation stop time is set from 0 to 6 to completely analyze the stabilization time for the active power outputs. Ode 23tb [stiff/TR-BDF2] Simulink solver is used as developed Simulink model involves nonlinear elements.

The magnitude of voltage at bus 1 is adjusted to 1.06 per unit. Line impedances are taken in per unit on a 100-MVA base. The UPFC is placed at buses 1 and 4 in the lines 1-2 and 4-7.Then the power injections at the corresponding buses and increase in the power at corresponding buses can observe in Table 1 and we can observe the increment in the active power at the corresponding buses. Line Data Results of 20 lines are given in table 2. The value of Resistance as well as Reactance is highest in case of line number 15. Table 3 shows the bus data and load flow result for bus 1-14.



Figure 4. IEEE 14-bus Test System.



Figure 5. Simulation model in MATLAB/Simulink Environment.



Figure 6. Standard IEEE 14-bus System with UPFC in MATLAB / Simulink Environment.



Figure 7. Waveform of real power across load-1 without UPFC.



Figure 8. Waveform of reactive power across load-2 without UPFC.



Figure 9. Waveform of real power across load-1 with UPFC.



Figure 10. Waveform of reactive power across load-2 with UPFC.

Table 1. Li	ne Flows w	ith and without	UPFC

Line No	Line Flows without UPFC		Line Flows with UPFC		
	P (MW)	Q	P (MW)	Q	
		(MVAR)		(MVAR)	
1	232.40	-16.01	326.91	81.23	
4	47.80	-3.90	176.89	10.28	

Table 2. Line Data Results

Line No.	Between Buses	Line Impedance		Susceptance (P.U)
		Resistance (P.U)	Reactance (P.U)	
1	1-2	0.01938	0.05917	0.02640
2	2-3	0.04699	0.19797	0.02190
3	2-4	0.05811	0.17632	0.01870
4	1-5	0.05403	0.22304	0.02460
5	2-5	0.05695	0.17388	0.01700
6	3-4	0.06701	0.17103	0.01730
7	4-5	0.01335	0.04211	0.00640
8	5-6	0.00000	0.25202	0.00000
9	4-7	0.00000	0.20912	0.00000
10	7-8	0.00000	0.17615	0.00000
11	4-9	0.00000	0.55618	0.00000
12	7-9	0.00000 0.11001		0.00000
13	9-10	0.03181	0.08450	0.00000
14	6-11	0.09498	0.19890	0.00000
15	6-12	0.12291	0.25581	0.00000
16	6-13	0.06615	0.13027	0.00000
17	9-14	0.12711	0.27038	0.00000
18	10-11	0.08205	0.19207	0.00000
19	12-13	0.22092 0.19988		0.00000
20	13-14	0.17093	0.34802	0.00000

Table 3: Bus Data and Load Flow Results

Bus No	Bus voltage		Generation		Load	
	Magnitude (P.U)	Phase angle (deg)	Real power (MW)	Reactive power (MVAR)	Real power(MW)	Reactive power (MVAR)
1	1.060	0.0	232.4	-16.01	0.0	0.0
2	1.045	-4.98	40.0	45.41	21.7	12.7
3	1.010	-12.74	0.0	25.28	94.2	19.0
4	1.019	-10.28	0.0	0.0	47.8	-3.9
5	1.020	-8.76	0.0	0.0	7.6	1.6
6	1.070	-14.22	0.0	13.62	11.2	7.5
7	1.062	-13.34	0.0	0.0	0.0	0.0
8	1.090	-13.34	0.0	18.24	0.0	0.0
9	1.056	-14.92	0.0	0.0	29.5	16.6
10	1.051	-15.08	0.0	0.0	9.0	5.8
11	1.057	-14.78	0.0	0.0	3.5	1.8
12	1.055	-15.07	0.0	0.0	6.1	1.6
13	1.050	-15.15	0.0	0.0	13.5	5.8
14	1.036	-16.02	0.0	0.0	14.9	5.0

5. Conclusion

simulation study, Matlab Simulink In the environment is used to simulate the model of UPFC connected to a 3 phase system. The modelling of UPFC and analysis of power systems embedded with UPFC has been presented, which is capable of solving large power networks very reliably with the UPFC. The investigations related to the variation of control parameters and performance of the UPFC on power quality results are carried out. The impact of UPFC on system power flow has been fully tested on standard IEEE 14-bus. The voltage compensation using UPFC system is also studied for standard IEEE 14- bus system. Simulation results show the effectiveness of UPFC to control the real and reactive powers. It is found that there is an improvement in the real and reactive powers through the transmission line when UPFC is installed.

6. References

[1] Vibhor Gupta, "Study and Effects of UPFC and its Control System for Power Flow Control and Voltage Injection in a Power System", International Journal of Engineering Science and Technology, vol.2 (7), 2010, pp-2558-2566.

[2] Distributed generation and FACTS Technology - Wikipedia, the free encyclopaedia.

[3] J. Hao, L. B. Shi, and Ch. Chen, "Optimizing Location of Unified Power Flow Controllers by Means of Improved Evolutionary Programming", IEE Proc. Genet. Transm. Distrib. 151(6)(2004), pp. 705–712.

[4] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York: IEEE Press, 2000.

[5] L. Gyugyi, T. Rietman, and A. Edris, "The UPFC Power Flow Controller: A New Approach to Power Transmission Control", IEEE Trans. on Power Delivery, 10(2) (1995), pp. 1085–1092.

[6] I.Papic, "Mathematical analysis of FACTS devices based on a voltage source converter, part II: steady state operational characteristics", Electric Power systems Research, vol. 56, pp. 149-157, 2000.

[7] I.Papic, "Mathematical analysis of FACTS devices based on a voltage source converter, part 1: mathematical models", Electric Power systems Research, vol. 56, pp. 139-148, 2000.

[8] S.D. Round, Q. Yu, L.E. Norum, T.M. Undeland, "Performance of a Unified power flow controller using a D-Q control system", IEEE AC and DC power transmission Conference, Pub.IEE No 423, pp. 357-362, 1996.

[9] Q. Yu, S. D. Round, L. E. Norum, T. M. Undeland, "Dynamic control of UPFC", IEEE Trans.Power Delivery.vol.9 (2), pp.508 – 514, 1996.

[10] D. Soto and T. C. Green, "A comparison of high-power converter topologies for the implementation of FACTS controllers," IEEE Trans. Industrial Electronics, vol. 49, no. 5, pp. 1072–1080, October 2002.

[11] M. S. El-Moursi and A. M. Sharaf, "Novel controllers for the 48-pulse VSC STATCOM and SSSC for voltage regulation and reactive power compensation," IEEE Trans. Power System, vol. 20(4), pp. 1985–1997, Nov. 2005.

[12] J. Rodriguez, J. S. Lai, and F. Z. Peng, "Multilevel Inverters: A survey of topologies, controls and applications," IEEE Trans. Industrial Electronics, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[13] C. k. Lee, J. S. K. Leung, S. Y. R. Hui, and H. S. H. Chung, "circuit level comparison of STATCOM technologies", IEEE Trans. Power Electronics, vol.18, no.4, pp.1084-1092, July 2003.

[14] S. Baskar, N. Kumarappan and R. Gnanadass," Switching Level Modelling and Operation of Unified Power Flow Controller", Asian Power Electronics Journal, vol.4, No.3, December 2010.

[15] S. Limyingcharoen, U. D. Annakkage, and N. C. Pahalawaththa, "Effects of Unified Power Flow Controllers on Transient Stability", IEEE Proceedings Generation Transmission and Distribution, 145(2), 1998, pp. 182–188.

[16] Z. J. Meng and P. L. So, "A current Injection UPFC Model for Enhancing Power System Dynamic Performance", Proceedings of IEEE Power Engineering Society Winter Meeting, 2(23– 27) (2000), pp. 1544–1549.

[17] M. A. Abido, "Power System Stability Enhancement using FACTS Controllers: A Review", The Arabian Journal for Science and Engineering, Volume 34, Number 1B, April 2009.

[18] H. Fujita, Y. Watanabe, and H. Akagi, "Control and Analysis of a Unified Power Flow Controller", IEEE Transactions on Power Electronics, 14(6)(1999), pp. 1021–1027.

[19] Samina Elyas Mubeen, R.K.Nema and Gayatri Agnihotri, "Power Flow Control with UPFC in Power Transmission System", World academy of science, Engineering and Technology,2008.

[20] S. Baskar, N. Kumarappan and R. Gnanadass, "Enhancement of Reactive Power Compensation using Unified Power Flow controller", Elektrika, Vol.13, No. 1, 2011, pp-13-23.

[21] Ch. Chengaiah, G.V.Marutheswar and R.V.S.Satyanarayana, "Control Setting of Unified Power Flow Controller through Load Flow Calculation", ARPN Journal of Engineering and Applied Sciences, Vol.3, No. 6, December 2008.

[22] B.M. Zhang, S.S. Chen, "Advanced Power Network Analysis", Tsinghua Publishing House, 1996, pp. 311-313.

[23] M. Noroozian, L. Anguist, M. Ghandhari and G. Andersson, Use of UPFC for optimal power flow control. IEEE Trans. on Power Delivery, Vol.17, No.4 (1997), pp. 1629–1634.

[24] "The symmetrical Hybrid Power Flow Controller- A New technology for Flexible AC Transmission (FACTS)".

[25] S. Tara Kalyani and G.Tulasiram Das, "Simulation of Real and Reactive Power Flow Control with UPFC Connected to a transmission line", Journal of Theoretical and Applied Information Technology, 2008.

[26] S. N. Singh and I. Erlich, "Locating Unified Power Flow Controller for Enhancing Power System Load ability.

[27] A. Mete Vural, Mehmet Tumay, "Mathematical modelling and analysis of a unified power flow controller: A comparison of two approaches in power flow studies and effects of UPFC location", Electrical Power and Energy Systems, vol. 29, pp. 617–629, 2007.

[28] K.S. Verma, S.N. Singh and H.O. Gupta, "Optimal location of UPFC for congestion management", Electric Power Systems Research, Vol. 58, No.2, pp. 89-96, July 2001.