A Placement Method of Fuzzy based Unified Power Flow Controller to Enhance Voltage Stability Margin

Shameem Ahmad
Fadi M. Albatsh
Saad Mekhilef

Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, University of Malaya
50603 Kuala Lumpur, Malaysia
Tel.: +60379676851
Fax: +60379675316
E-Mail: saad@um.edu.my

Hazlie Mokhlis

Department of Electrical Engineering,
Faculty of Engineering,
University of Malaya,
50603 Kuala Lumpur, Malaysia

Acknowledgements

The authors would like to thank the Ministry of Higher Education of Malaysia and University of Malaya for providing financial support under the research grant No.UM.C/HIR/MOHE/ENG/16001-00-D000017 and FRGS project no. 53-02-03-1099.

Keywords

« Flexible AC Transmission Systems », « Unified Power Flow Controller », « Voltage Stability », « Fuzzy Logic », « PSCAD ».

Abstract

This paper presents a placement method of fuzzy logic based unified power flow controller (UPFC) in power system network by analyzing dynamic voltage stability. Voltage stability indices namely LQP and voltage collapse point indicators (VCPI) indices are used to determine the weakest line for UPFC by dynamic load variation. The controllers of the shunt and series converters of the UPFC are developed using fuzzy logic (FL) and proportional integral (PI) controllers respectively to enhance the dynamic voltage stability of the power system network.The simulation has been conducted in power system computer-aided design (PSCAD) environment where IEEE-5 and IEEE-14 bus system have been chosen as test bench systems. The results obtained through simulations have ensured the effectiveness of the proposed placement method since fuzzy based UPFC's placement in the obtained locations resulted in significant improvment in voltage stability.

Abbreviations

DE: Differential Evolution;
FACTS: Flexible AC Transmission Systems;
FL: Fuzzy Logic;
GA: Genetic Algorithm;
IGBT: Insulated Gate Bipolar Transistor;
PI: Proportional Integral;
PLL: Phase Locked Loop;
PSO: Particle Swarm Optimization;
PSCAD: Power System Computer Aided Design;
SVC: Static VAR Compensator;
UPFC: Unified Power Flow Controller;
VCPI: Voltage Collapse Point Indicators;

Introduction

In the last few years, significant increase of power demand has been observed all over the world. This increase however does not followed by increasing in power generation and transmission capacity. Hence, in order to meet the increasing electrical power demand power generating plants as well as transmission lines are always operating closer to their maximum stability limit. As a result, the power system networks are becoming less secure and always expecting the risk of voltage instability [1].

Different preventive measures using conventional electromechanical devices had been adopted to overcome voltage instability issue. However, most of these devices have the drawbacks like slowness and wear. For a better solution, keen attention has been paid to Flexible Alternating Current Transmission System (FACTS) devices which are driven from modern power electronics components. Among different types of FACTS devices UPFC has got the epic popularity. Since, it is capable of voltage regulation, series compensation, and phase angle regulation simultaneously, lead to the discrete control of active and reactive power transmitted through the line [2]. However, due to high cost and the voltage stability problem, it is highly preferred to place UPFC at appropriate locations in the power system network.

In previous studies, optimization techniques have been used to determine the location of FACTS controller based on steady state voltage stability analysis. For instance, differential evolution (DE) technique was used to find the optimal location of UPFC for enhancing power system security in [3]. Particle swarm optimization (PSO) is implemented in [4] for defining locations of FACTS devices considering congestion relief and voltage stability. In [5] a placement of shunt FACTS controller using Real Coded genetic algorithm (GA) is proposed to maintain voltage stability. To determine locations of SVC for maintaining the voltage stability hybrid DE technique is employed in [6]. In [7] harmony search and GA have been applied to determine optimal location of UPFC to improve voltage stability. Apart from optimization techniques, placement of FACTS devices has also conducted by using voltage stability indices. Index based methods like Modal analysis and tangent vector are used in [8] and [9] respectively to locate FACTS devices for system security enhancement. L-index used in [10-13], to determine the bus bars from where the collapse may originate, for FACTS devices allocations. Other indices like line security margin index [14], voltage security index [15], security index [16], controllability index [17] were also used to find the location of UPFC to fix voltage instability problems.

The shortcoming of both optimization and index based methods is the exploration FACTS devices locations are conducted by analyzing steady state voltage stability. This steady state analysis is suitable for the planning and designing stage of the power system network. However, during real time operations of power system networks, the problem of voltage instability occurs due to disturbances like load demand increment, line trip or generator outage which are dynamic phenomena. As a consequence, the need for a dynamic approach to determine the location of the FACTS controllers has become essential.

In this paper, the placement of UPFC has been conducted by dynamic analysis of voltage stability to enhance the voltage stability margin. The stability margin of the transmission lines are determined by using voltage stability indices namely LQP and VCPI which in turns calculated by dynamic variations of load. The control systems of dynamic UPFC's shunt and series controllers are developed using fuzzy and PI controllers respectively. Real time simulations have been carried out on IEEE-5 and 14 bus networks in PSCAD software. To verify the adequacy of the explored location, the improvement of voltage stability has been evaluated by connecting dynamic UPFC in this location.

The remaining paper is organized as follows: Section (2) contains explanation of the Voltage stability indices. Section (3) contains the flowchart of the proposed approach for UPFC placement. Section (4) focuses on dynamic UPFC model. Section (5) presents the shunt and series controllers of UPFC. In Section (6), the results obtained for UPFC's locations and voltage stability improvement are discussed. The significant points of this paper are summarized in the conclusion.

Index Explanation

The mentioned voltage stability indices are formulated based on the power transmission concept in a single line. A single line in an interconnected network is illustrated in Fig. 1 where suffice ‘s’ and ‘r’ denotes the sending and receiving end respectively.

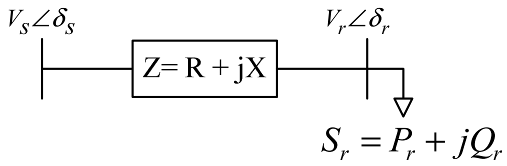

Fig. 1: Two bus network

Where,
V_s *and* V_r are the sending end and receiving end voltages, respectively.
δ_s *and* δ_r are the phase angle at the sending and receiving buses.
Z is the line impedance.
R is the line resistance.
X is the line reactance.
θ is the line impedance angle.
Q_r is the reactive power at the receiving end.
P_r is the active power at the receiving end.

LQP Index

This index defined in [18] which has been derived as following:

$$LQP = 4\left(\frac{V_s^2}{X}\right)\left(\frac{V_s^2}{X}P_s^2 + Q_r\right) \tag{1}$$

Voltage Collapse Point Indicators (VCPI)

The Voltage Collapse Point Indicators (VCPI) proposed in [19] are based on the concept of maximum power transferred through a line.

$$VCPI(P) = \frac{P_r}{P_{r(\max)}} \tag{2}$$

The numerator is the real power transferred to the receiving end and denominator is the maximum power that can be transferred to the receiving end at a particular instant. It can be calculated in the following way:

$$P_{r(\max)} = \frac{V_s^2}{Z}\frac{\cos\phi}{4\cos^2\left(\frac{\theta-\phi}{2}\right)} \tag{3}$$

where, ∅ is the load impedance $\phi = \tan^{-1}\frac{Q_r}{P_r}$

Methodology

The flowchart of the proposed approach to find the appropriate locations in power system network for UPFC placement is presented in Fig. 2.

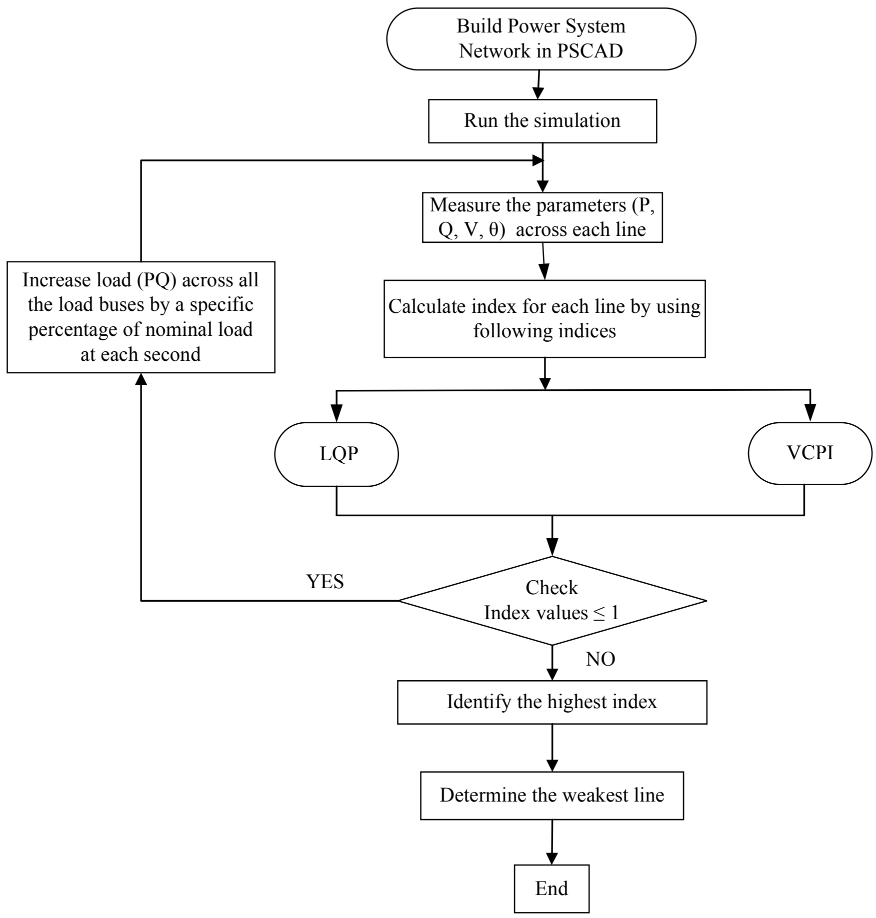

Fig. 2: Flow chart of the proposed approach

UPFC model

The dynamic model of the UPFC is given in Fig. 3. UPFC connects to the transmission line with shunt and series voltage source converters which are coupled via a common DC link. Low pass AC filters are connected in each phase to prevent the flow of harmonic currents generated due to switching. The transformers connected at the output of converters to provide the isolation, modify voltage/current levels and also to prevent DC link capacitor being shorted due to the operation of various switches. Insulated gate bipolar transistors (IGBTs) with anti-parallel diodes are used as switching devices for both converters [20-22].

UPFC Controller

Shunt Controller

The block diagram of UPFC shunt controller is shown in Fig. 4. The shunt converter draws controlled current from the transmission line for the following reasons:

- To keep the transmission line voltage at its reference value.
- To maintain DC voltage level at its reference value on the DC link.

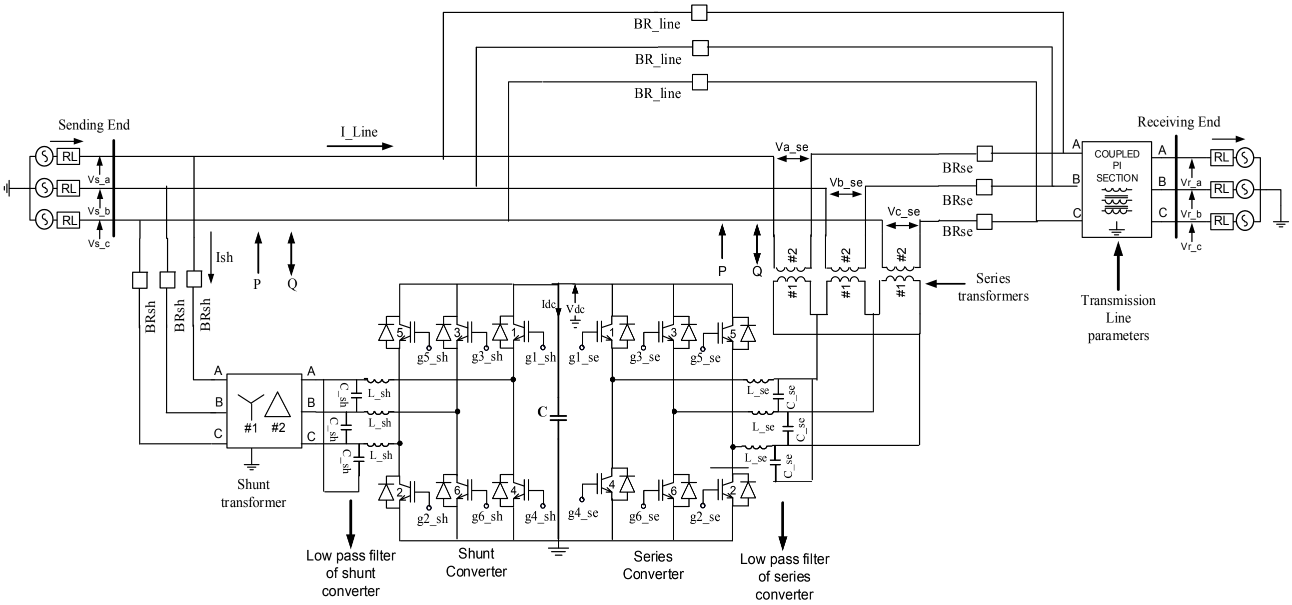

Fig. 3: UPFC model

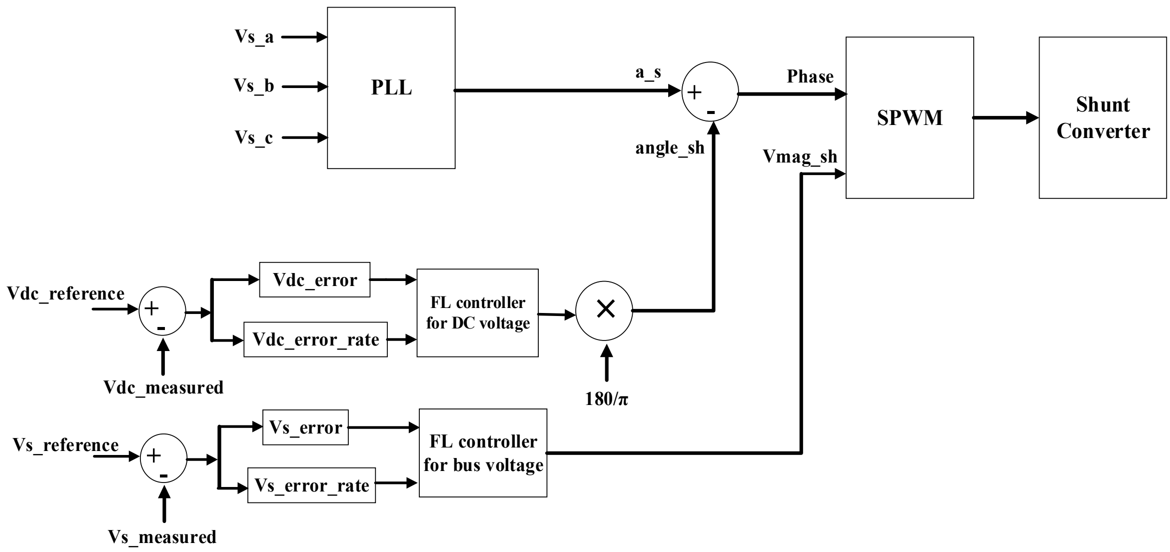

Fig. 4: Shunt controller of UPFC

In order to control the bus voltage, sending-end voltage (*Vs_measured*) is measured instantly and subtracted from its reference value (*Vs_reference*) as per unit (*p.u*) which reveals *Vs_error.* This error signal and the rate of change of error *(Vs_error_rate)* have been given as inputs to a FL block. The output of FL resulted in the magnitude of injected shunt volatge (*Vmag_sh*) in p.u. Meanwhile, (*Vdc_measured*) is measured and subtracted from its reference value (*Vdc_reference*) which reveals *Vdc_error*. The *Vdc_error* and its error-rate (*Vdc_error*_rate) have been given as inputs to another FL controller which reveals the angle (*angle_sh*). The difference of the angles (*a_s – angle_sh*) between the angle (*angle_sh*) and the phase angle of sending-end voltage (*a_s*) extracted from PLL block and the magnitude (*Vmag_sh*) have used in 'sin ()' function to obtain the reference signals for Pulse Width Modulation (PWM). In SPWM block, the reference signals are compared with carrier (triangle) signal which has a switching frequency of 3.5 KHz. The outputs of the comparators are used as switching signals to the converter switches.

Series Controller

The control system of series converter controller is illustrated in Fig. 5.The series converter controls the power flow across the line by injecting a voltage in series with the line current with controllable magnitude and angle. The receiving end real and reactive power ($P_{measured}$ and $Q_{measured}$) are measured and subtracted from their reference value ($P_{reference}$ and $Q_{reference}$). These revealed the error signals *P_error* and *Q_error* which sent through two PI blocks. The outputs of the two PIs provide the orthogonal components of the series injected voltage (V_q and V_d). The magnitude and phase angle of series injected voltage can be calculated by using the following equations:

$$Vmag\_se = \sqrt{V_d^2 + V_q^2} \quad (4)$$

$$angle\_se = \tan^{-1}\frac{V_q}{V_d} \quad (5)$$

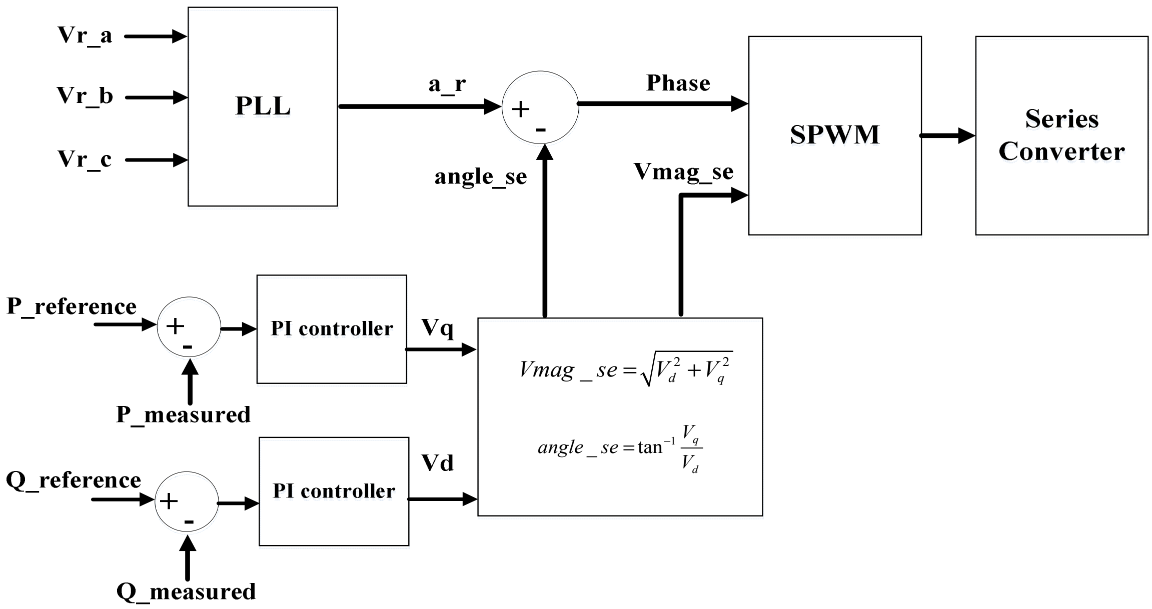

Fig. 5: Series controller of UPFC

The phase angle of receiving-end voltage (*a_r*) is obtained through *PLL*. The angle ($angle\_se$) obtained from equation (5) is subtracted from angle (*a_r*) of receiving-end voltage. The resultant angle and the magnitude of the voltage calculated from equation (4) are used in 'sin ( )' function block to obtain reference signals. In SPWM technique, the reference signals are compared with carrier (triangle) signals. The switching frequency of the carrier has considered as 3.5 KHz. The control signals of Insulated-gate bipolar transistor (IGBT) switches are generated by comparing references with carrier signals.

Result and discussion

IEEE-5 Bus Network

For voltage stability analysis, two voltage stability indices (LQP and VCPI) are employed to calculate the index value of each line. To calculate the line indices, both real and reactive load have been increased by 10 % and 20% respectively of the nominal load in all the load buses. Fig. 6 indicated that when the P and Q load have increased 30 % and 60 % respectively of nominal load line 2-3 has exhibited the unstable condition for both VCPI and LQP indices.

From Figs. 7 and 8, it has been observed that at unstable condition the voltages across buses 2 and 3 are found 0.8931 pu and 0.782 pu respectively. At 2.5s when UPFC has connected across line 2-3 the voltages have improved to 1.001 pu and 0.962 pu across buses 2 and 3 respectively. In Fig. 9 all the bus voltages before and after connecting UPFC are presented. It is noticed that after connecting UPFC the voltage profile of all the buses have improvement.

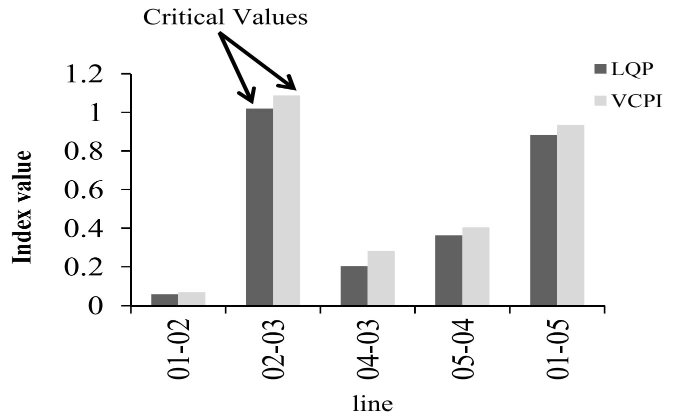

Fig. 6: Index values of all the lines in IEEE-5 bus system

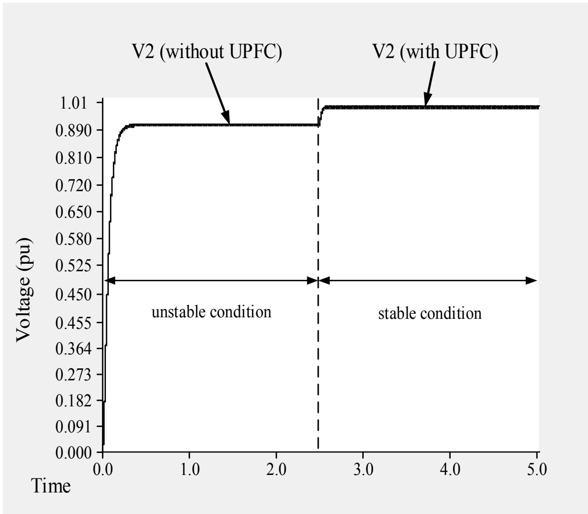

Fig. 7: Voltage across bus 2 in IEEE-5 bus system

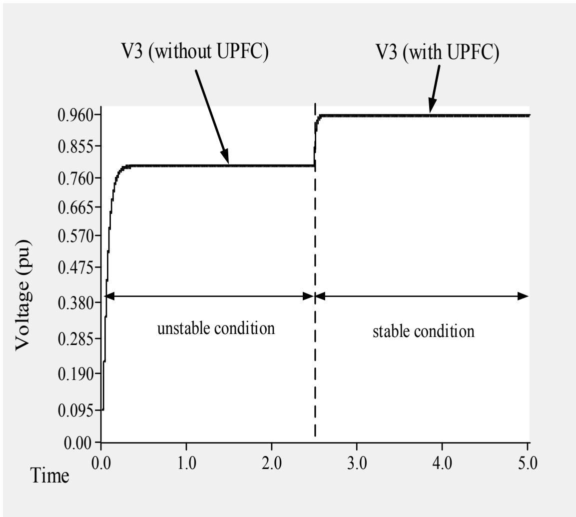

Fig. 8: Voltage across bus 3 in IEEE-5 bus system

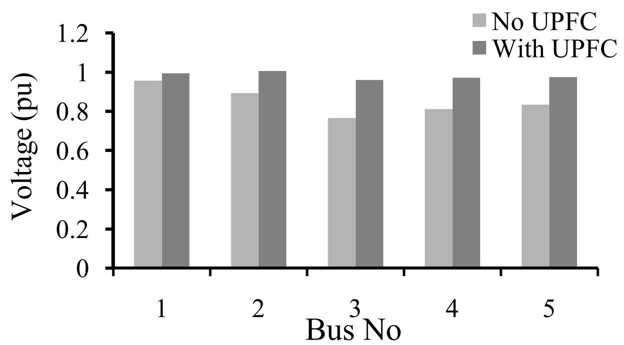

Fig. 9: Voltage profile across all the buses in IEEE-5 bus

IEEE-14 Bus Network

As like IEEE-5 bus network to calculate the line indices, in IEEE-14 bus also both real and reactive load have been increased in all PQ buses by 5 % and 15 % respectively.

As soon as the P and Q loads across all the load buses reached to 20% and 60% respectively of the nominal load line 9-14 has reached the unstable region for VCPI and LQP indices. The index values of all the lines are shown in Fig. 10.

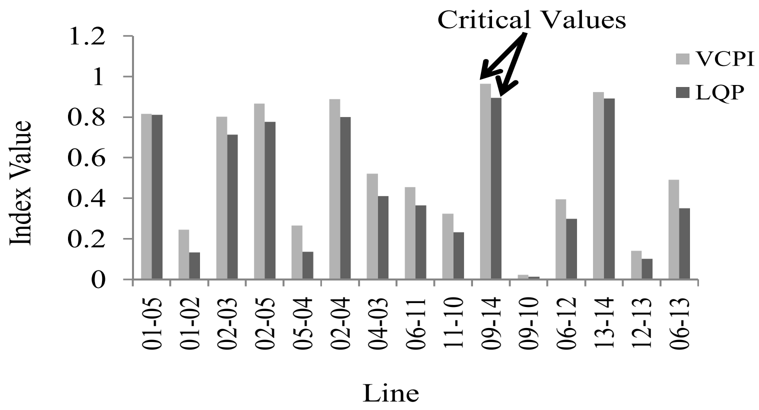

Fig. 10: Index values of all the lines in IEEE-14 bus system

During unstable period from Figs. 11 and 12, the voltages across buses 9 and 14 have been observed are 0.871 pu and 0.754 pu respectively. Due to the connection of UPFC at 2.5s across line 9-14 the voltages have improved by 10.49 % (0.9745 pu) and 23.59 % (0.956 pu) across buses 9 and 14 respectively. It has also been noticed from Fig. 13 that UPFC's presence in the network has ensured the improvement of voltage profile across all the buses.

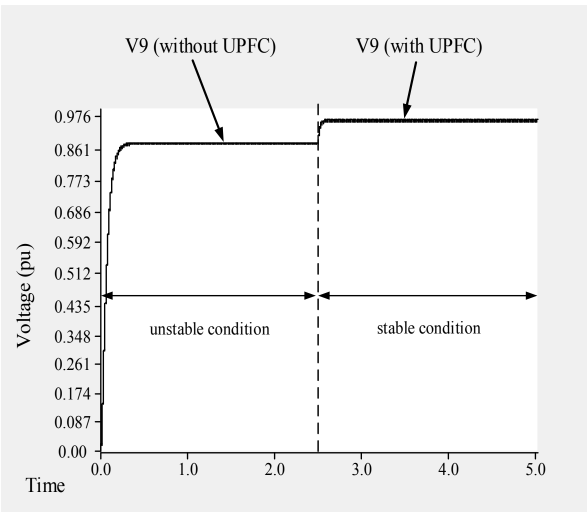

Fig. 11: Voltage across bus 9 in IEEE-14 bus system

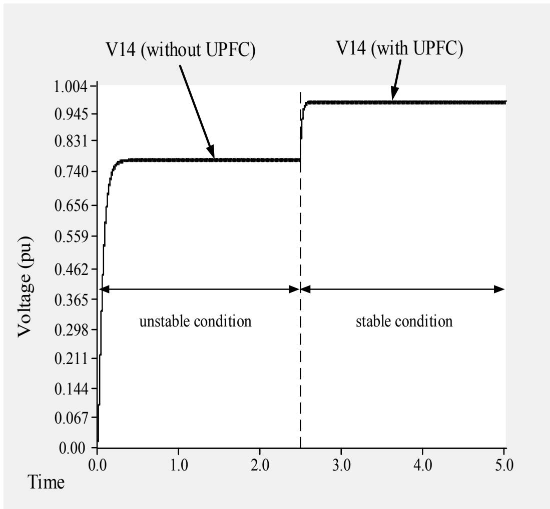

Fig. 12: Voltage across bus 14 in IEEE-14 bus system

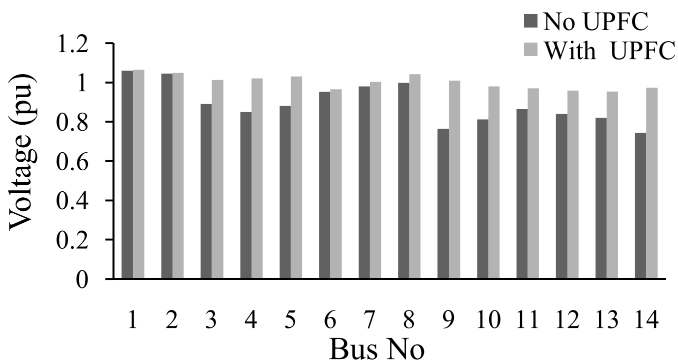

Fig. 13: Voltage profile across all the buses in IEEE-14 bus

Conclusion

An approach to find the location of UPFC in IEEE - 5 and 14 bus systems has been presented in this study by analyzing dynamic voltage stability. Voltage stability indices namely LQP and VCPI have been implemented to find voltage unstable condition in power system network by varying the load dynamically. From the simulations results it has been proved that the location obtained using the proposed approach is adequate. Since, after placement of fuzzy based UPFC in the explored location the voltages across the buses of the vulnerable line has boosted up to almost their nominal values. In addition, FL based UPFC has also improved voltage profile of all the buses when it is connected to the locations determined by using the proposed approach.

References

[1] T. S. Ustun and S. Mekhilef, "Effects of a Static Synchronous Series Compensator (SSSC) Based on a Soft Switching 48-Pulse PWM Inverter on the Power Demand from the Grid," Journal of Power Electronics, vol. 10, pp. 85-90, 2010.

[2] M. E. Elgamal, *et al.*, "Voltage profile enhancement by fuzzy controlled MLI UPFC," *International Journal of Electrical Power & Energy Systems,* vol. 34, pp. 10-18, 2012.

[3] H. I. Shaheen, *et al.*, "Optimal location and parameter setting of UPFC for enhancing power system security based on differential evolution algorithm," *International Journal of Electrical Power & Energy Systems,* vol. 33, pp. 94-105, 2011.

[4] R. S. Wibowo, *et al.*, "FACTS devices allocation with control coordination considering congestion relief and voltage stability," *IEEE Transactions on Power Systems,* vol. 26, pp. 2302-2310, 2011.

[5] A. Phadke, *et al.*, "A new multi-objective fuzzy-GA formulation for optimal placement and sizing of shunt FACTS controller," *International Journal of Electrical Power & Energy Systems,* vol. 40, pp. 46-53, 2012.

[6] C.-F. Yang, *et al.*, "Optimal setting of reactive compensation devices with an improved voltage stability index for voltage stability enhancement," *International Journal of Electrical Power & Energy Systems,* vol. 37, pp. 50-57, 2012.

[7] A. Parizad, *et al.*, "Application of HSA and GA in optimal placement of FACTS devices considering voltage stability and losses," in *International Conference on Electric Power and Energy Conversion Systems, EPECS*, 2009, pp. 1-7.

[8] R. Sirjani, *et al.*, "Optimal allocation of shunt Var compensators in power systems using a novel global harmony search algorithm," *International Journal of Electrical Power & Energy Systems,* vol. 43, pp. 562-572, 2012.

[9] Y.-C. Chang and R.-F. Chang, "Utilization performance based FACTS devices installation strategy for transmission loadability enhancement," in *4th IEEE Conference on Industrial Electronics and Applications, ICIEA*, 2009, pp. 2661-2666.

[10] P. S. R. B. Rajani, "Comparison of FACTS Controllers for Improvement of Voltage/Line Stability in Transmisson System Using SSSC & STATCOM," *Journal of Theoretical and Applied Information Technology,* vol. 41, pp. 192-200, 2012.

[11] H. Baghaee, *et al.*, "Improvement of voltage stability and reduce power system losses by optimal GA-based allocation of multi-type FACTS devices," in *11th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM*, 2008, pp. 209-214.

[12] P. S. P. H. B. Nagesh, "Power Flow Model of Static VAR Compensator and Enhancement of Voltage Stability," *International Journal of Advances in Engineering & Technology,* vol. 3, pp. 499-507, 2012.

[13] N. S. JE, "Enhancement of Voltage Stability through Optimal Placement of Facts Controllers in Power Systems," *American Journal of Sustainable Cities and Society,* vol. 1, pp. 36-44, 2012.

[14] J. Jafarzadeh, *et al.*, "Optimal placement of FACTS devices based on network security," in *3rd International Conference on Computer Research and Development, ICCRD)*, 2011, pp. 345-349.

[15] D. W. Lee, *et al.*, "A study on coordinated control of UPFC and voltage compensators using voltage sensitivity," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, IEEE*, 2008, pp. 1-6.

[16] J. U. Lim and S. I. Moon, "An operation scheme of UPFC's considering operating objectives and states," in *Power Engineering Society Summer Meeting, IEEE*, 2002, pp. 610-615.

[17] B. K. Kumar, *et al.*, "Placement of FACTS controllers using modal controllability indices to damp out power system oscillations," *Generation, Transmission & Distribution, IET,* vol. 1, pp. 209-217, 2007.

[18] A. Mohamed, *et al.*, "A static voltage collapse indicator using line stability factors," *Journal of industrial technology,* vol. 7, pp. 73-85, 1998.

[19] M. Moghavvemi and O. Faruque, "Real-time contingency evaluation and ranking technique," in *Generation, Transmission and Distribution, IEE Proceedings-*, 1998, pp. 517-524.
[20] S. Ahmad, *et al.*, "Fuzzy based controller for dynamic Unified Power Flow Controller to enhance power transfer capability," Energy Conversion and Management, vol. 79, 2014, pp. 652-665.
[21] S. Ahmad, *et al.*, " An Approach to Improve Active Power Flow Capability by Using Dynamic Unified Power Flow Controller," in *IEEE Innovative Smart Grid Technologies Conference – ISGT Asia,* 2014.
[22] F. Albatsh, *et al.,* " D – Q model of Fuzzy based UPFC to control power flow in transmission network," in *the 7th IET international conference on Power Electronics, Machines and Drives*, *PEMD*, 2014.