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RESEARCH ARTICLE

Loading Margin Enhancement in Power System via FACTS Devices Hybrid Structure

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Abstract— ***The FACTS (Flexible AC Transmission System) devices have been considered as excellent controllers in a power system for better reliability and transmission capacity on a long-term and cost-effective basis. In this paper, a novel power flow controller topology is proposed for FACTS in order to improve static voltage stability characteristics and loading margin enhancement. Employing hybrid topology of FACTS devices enables use of converters to enhance the functionality of existing equipment in a power system. Since existing equipment is fully utilized, the hybrid topology requires considerably lower total converter ratings compared to the UPFC. This paper presents a power injection model (PIM) of hybrid power flow controller for power flow and voltage stability analysis. P-V curves are constructed to calculate loadability margins. Static voltage stability margin enhancement using hybrid topology of FACTS device is compared in the IEEE 6-bus and 14-bus test system. The results used to demonstrate the effectiveness and performance of this model.***

Keywords— ***Loading Margin; Power Injection Model (PIM); FACTS; Newton Power Flow***

I. INTRODUCTION

Present power systems are now large, complex and interconnected systems, which consist of thousand of buses and hundreds of generators [1],[2].New installations of power stations and other facilities are primarily determined based on environmental and economic reasons. In addition, new transmission lines are expensive and take considerable amount of time to construct. Given these conditions, in order to meet ever-increasing load demands, electric utilities have to rely on power export/import arrangements through the existing transmission system, deteriorating voltage profiles and system stability in some cases. This situation has resulted in an increased possibility of transient, oscillatory and voltage instability, which are now brought into concerns of many utilities especially in planning and operation [3],[4].Moreover, the trend of the deregulated power system has led to some unexpected problems, such as voltage instability, etc.

Voltage stability plays a major role in keeping the system operational. Because of its importance an impressive amount of work has been devoted to it in view of recent blackouts that have been attributed to it. Voltage stability is mainly concerned with maintaining acceptable voltage profile under all operating conditions [3].

Voltage instability is the cause of system voltage collapse, which makes the system voltage decay to a level from which they are unable to recover. The consequence of voltage collapse may lead to a partial or full power interruption in the system. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse. Introducing the sources of reactive power, i.e., shunt capacitors and/or Flexible AC Transmission System (FACTS) controllers at the appropriate location is the most effective way for utilities to improve voltage stability of the system. The recent development and use of FACTS controllers in power transmission system have led to many applications of these controllers not only to improve the voltage stability of the existing power network resources but also to provide operating flexibility to the power system. FACTS devices have been defined by the IEEE as “alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability” [9].

In the past ten years, pilot installations of STATCOM, UPFC, and IPFC have been built and commissioned [3]–[6]. However, the considerable price of all current FACTS controllers remains as the major impediment to their widespread use. The equipment appropriation for converter based FACTS controllers is further setback by the existence of “classical equipment” – switched capacitors and static VAr compensators (SVCs) for voltage support, and switched series capacitors and thyristor controlled series capacitors (TCSCs) for line impedance control. In many applications these compensators were installed to mitigate critical contingency conditions, and while improvements in their performance would be worth considering, their complete replacement is prohibitive. It is therefore worthwhile to seek novel and cost effective converter based FACTS topologies that build upon existing equipment and provide improved control performance.

Hence, in this paper, by joining IPFC series compensation to the existing compensated system by STATCOM, while reducing investment cost in the system and improving equipment performance of the existing classical compensator, it has provided the way to achieve stability properties of static voltage almost similar to the new generation of devices based on voltage source converter (UPFC).

II. THE PROPOSED HYBRID TOPOLOGY OF FACTS DEVICES

A block diagrammatic view of the envisioned typical HPFC application is shown in Fig. 1. The HPFC is installed on a transmission line that connects two electrical areas. In general, its point of installation will be “within” the transmission line, i.e., at some distance from strong voltage busses. Central to the HPFC’s topology is the shunt connected source of reactive power denoted as B_M in Fig. 1 – this can be a switched capacitor bank, or a static VAr compensator. Next, there are two voltage–sourced converters (VSC_X and VSC_Y) connected in series with the associated line segments using coupling transformers. The converters share a common DC circuit, coupling each other’s DC terminals. The DC circuit permits exchange of active power between the converters. By controlling the magnitudes and angles of voltages supplied by the converters, the flow of active power through the line and the amounts of reactive power supplied to each line segment can be simultaneously and independently controlled. The control of the shunt connected reactive element is coordinated with the control of converters to supply the bulk of the total required reactive power [11].

A basic comparison of this topology with that of the UPFC highlights the important features of this new circuit. In short, UPFC’s shunt converter is substituted by a (presumably existing) switched capacitor, while its series converter is split into two “half-sized” ones, installed on each side of the shunt device. Such topological arrangement results in operating characteristics similar to those of the UPFC, while achieving considerable savings in the total required converter MVA ratings.

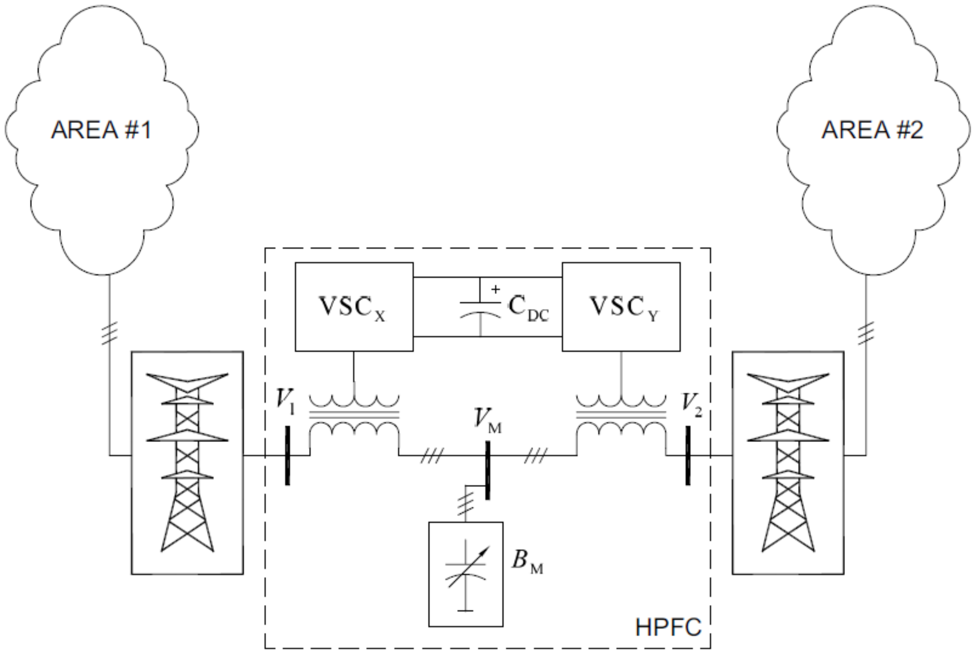

Fig. 1 A typical schematic of hybrid power flow controller.

III. STEADY-STATE OPERATION AND POWER INJECTION MODEL(PIM) OF HPFC

A. PIM for IPFC- Serie Part of HPFC

IPFC is a kind of VSC-based FACTS device. Just like UPFC, IPFC is also called combined compensator because it consists of at least two static synchronous series compensators (SSSCs) which are connected via a common dc voltage link that can be represented by a capacitor [12]. For simplicity, this paper deals with IPFC combining only two SSSCs, as shown in Fig. 2. However, following derivations can be applied to IPFCs consisting of more than two VSCs without much difficulty[9]. Usually, in the steady state analysis of power systems, the VSC is represented as a synchronous voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle (Fig. 3). As for IPFC, the two VSCs are connected in series with two lines as shown in Fig. 2. Vi, Vj and Vk are complex voltages at buses i, j and k, respectively. In the equivalent circuit shown, Vse_{ij}, Vse_{ik} are controllable complex voltages of synchronous voltage sources which are defined as $Vse_{in}\angle\delta se_{in}$ (n=j,k). yse_{ij} and yse_{ik} are the admittances of the transformers which are in series with (i-j), (i-k) lines , respectively.

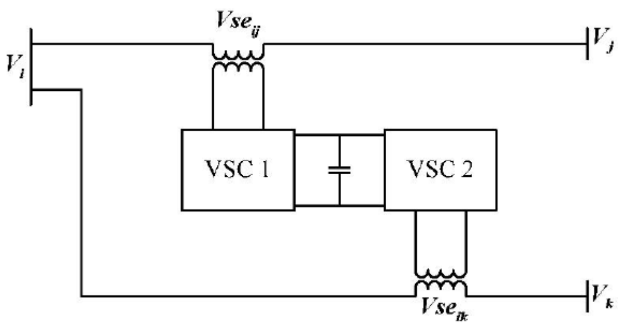

Fig. 2 Equivalent circuit of IPFC

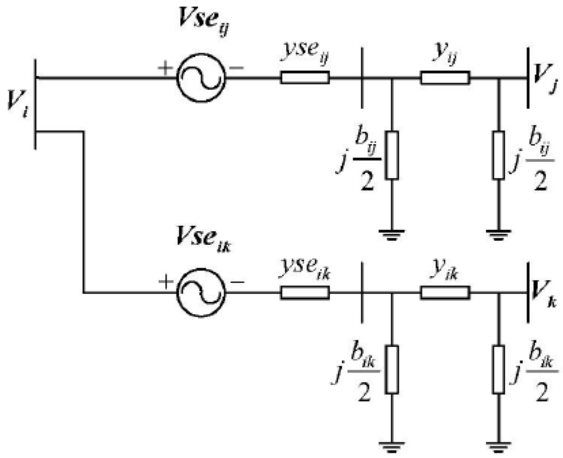

Fig. 3 Equivalent circuit of transmission lines embedded with IPFC

The application of the IPFC injection model provides certain convenience. However, it still requires the increase of bus number, and the buses and transmission lines have to be renumbered. In very large power systems and power systems with multiple IPFCs, it is not very convenient to do so [8]. Consequently, the following injection model of transmission lines embedded with IPFC is developed. In power system analysis, the transmission line is usually viewed as a π -circuit that is shown in Fig. 3.

In order to eliminate the additional buses, following transformations are adopted. For simplicity, only one branch of IPFC is taken as an example, as shown in Fig. 4. First, Y-Δ transformation [11] of the circuit in the dashed line rectangle in Fig. 4 (a) is carried out, yielding the equivalent circuit in Fig. 4 (b), Finally, we can obtain the π model of the transmission line coupled with transformer admittance of a series converter in Fig. 4(c) [11]. Equations governing these transformations are of the following form:

$$y'_{ij} = y_{se_{ij}} . y_{ij} /[y_{se_{ij}} + y_{ij} + j\frac{b_{ij}}{2}] \tag{1}$$

$$y_i^{shunt} = j\frac{bij}{2} \cdot y_{se_{ij}} /[y_{se_{ij}} + y_{ij} + j\frac{b_{ij}}{2}] \tag{2}$$

$$y_{j0} = y_{ij} . \left(j\frac{b_{ij}}{2}\right) / \left[y_{se_{ij}} + y_{ij} + j\frac{b_{ij}}{2}\right] \tag{3}$$

$$y_j^{shunt} = \left(j\frac{b_{ij}}{2}\right) + y_{ij} . \left(j\frac{b_{ij}}{2}\right) /[y_{se_{ij}} + y_{ij} + j\frac{b_{ij}}{2}] \tag{4}$$

The injected current from the buses i and j of the line coupled with series converters can be obtained from the following equations:

$$I_i = Y_{ii}(V_i - V_{se_{ij}}) + Y_{ij}V_j \tag{5}$$

$$I_j = Y_{ji}(V_i - V_{se_{ij}}) + Y_{jj}V_j$$

Matrix form of the equations above is:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} - \begin{bmatrix} Y_{ii}V_{seij} \\ Y_{ji}V_{seij} \end{bmatrix} \tag{6}$$

$$\begin{cases} Y_{ii} = y_i^{shunt} + y'_{ij} \\ Y_{ij} = Y_{ji} = -y'_{ij} \\ Y_{jj} = y_j^{shunt} + y'_{ij} \end{cases}$$

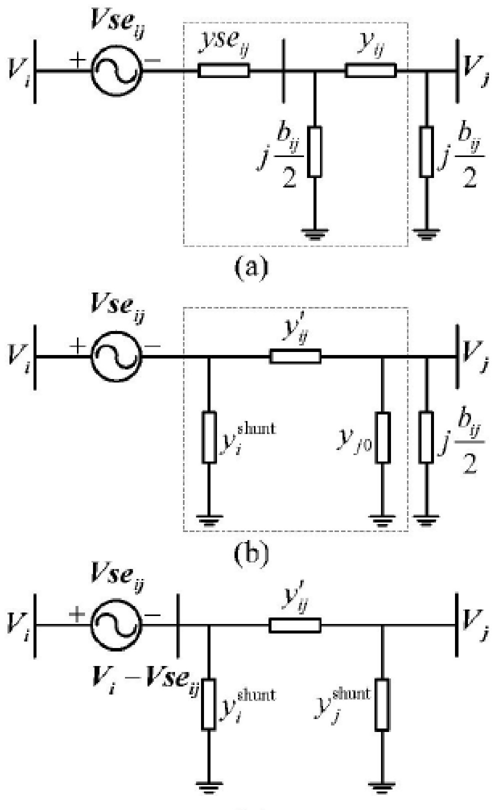

Fig. 4 Transformation process of the transmission line embedded with one branch of IPFC.

If the second part on the right side of (6) is regarded as the contribution of power injections, the injection model of this line is developed as shown in Fig. 5. In this figure, active and reactive power injections in buses i and j are matched with two current sources shown. Therefore, the π injection model of series converter coupled with (i-j) line is shown in Fig. 5.

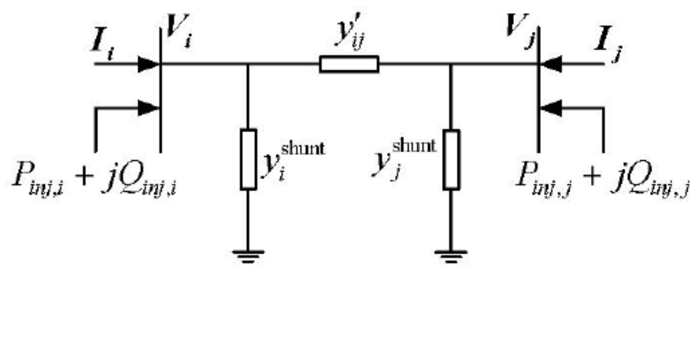

Fig. 5 Injection model of the transmission line embedded with one branch of IPFC.

Power injection in buses which end at lines coupled with a series converter follows the following equations (Fig. 6):

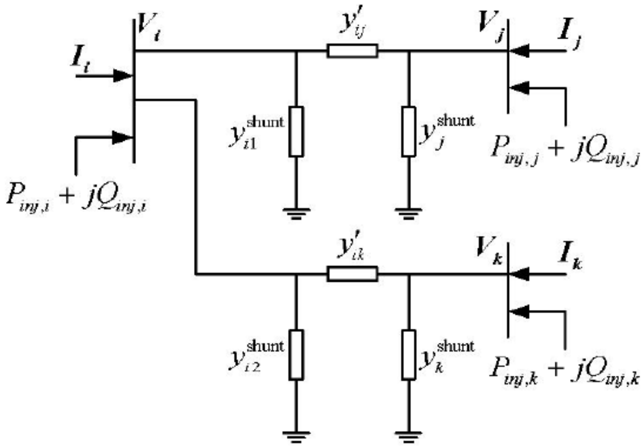

Fig. 6 Injection model of the transmission lines embedded with one IPFC.

$$P_i^{se} = \mathrm{Re}\left\{V_i\left[-(y'_{ij} + y_{i1}^{shunt})V_{se_{ij}} - (y'_{ik} + y_{i_2}^{shunt})V_{se_{ik}}\right]^*\right\} \tag{7}$$

$$Q_i^{se} = \mathrm{Im}\left\{V_i\left[-(y'_{ij} + y_{i1}^{shunt})V_{se_{ij}} - (y'_{ik} + y_{i_2}^{shunt})V_{se_{ik}}\right]^*\right\}$$

$$P_n^{se} = \mathrm{Re}\left\{ V_n\left[(y'_{in})V_{se_{in}}\right]^*\right\} \qquad (n = j, k)$$

$$Q_n^{se} = \mathrm{Im}\left\{ V_n\left[(y'_{in})V_{se_{in}}\right]^*\right\}$$

The active power exchanged between series converters through common dc connection must be zero under ideal conditions (lossless), therefore we have:

$$P_{dc} = \sum_n Pex_n = 0 \tag{8}$$

$$P_{dc} = -\sum_{n=j,k} \{|V_{se_{in}}||V_i|[G_n \cos(\delta_{se_{in}} - \delta_i) + B_n \sin(\delta_{se_{in}} - \delta_i)] - |V_{se_{in}}|^2 G_n$$
$$+ |V_{se_{in}}||V_n|[G'_{in} \cos(\delta_{se_{in}} - \delta_n) + B'_{in} \sin(\delta_{se_{in}} - \delta_n)]\} = 0$$

Where:

$$G'_{in} + jB'_{in} = y'_{in} \tag{9}$$

$$if \quad n = j, k \rightarrow \begin{cases} G_j + jB_j = y_{i_1}^{shunt} + y'_{ij} \\ G_k + jB_k = y_{i_2}^{shunt} + y'_{ik} \end{cases}$$

B. PIM for STATCOM- Shunt Part of HPFC

STATCOM is the Voltage-Source Inverter (VSI), which converts a DC input voltage into AC output voltage in order to compensate the active and reactive power needed by the system [7],[10]. Figs. 7 show the schematic diagram of STATCOM. From Fig. 7, STATCOM is a shunt-connected device, which controls the voltage at the connected bus to the reference value by adjusting voltage and angle of internal voltage source. Equations of STATCOM base on power flow analysis are presented.

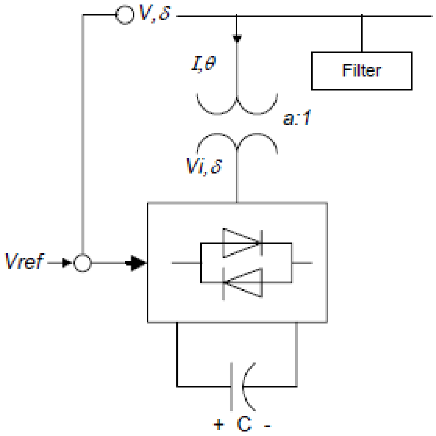

Fig. 7 Basic structure of STACOM

$$P_c(k) = P_{inject}^{statcom} + P_{Line,k} = P_{sh} + [E(k)\cdot a_s(k) + F(k)\cdot b_s(k)] \quad (10)$$

$$Q_c(k) = Q_{inject}^{statcom} + Q_{Line,k} = Q_{sh} + [F(k)\cdot a_s(k) - E(k)\cdot b_s(k)]$$

$$\begin{cases} a_s(k) = \sum_{j=1}^{N} (G_{kj} \quad e_j - B_{kj} \quad f_j) \\ b_s(k) = \sum_{j=1}^{N} (G_{kj} \quad f_j + B_{kj} \quad e_j) \end{cases} \quad \begin{cases} for \quad i = 1 : bus \\ E(i) = V(i)\cdot \cos(\delta_i) \\ F(i) = V(i)\cdot \sin(\delta_i) \end{cases} \quad (11)$$

$$P_{EP} = \mathrm{Re}\left\{ V_{sh}(I_{sh})^* \right\} = \circ$$

$$P_{EP} = G_{sh}|V_{sh}|^2 - |V_k||V_{sh}||Y_{sh}|\cos(\delta_{sh} - \delta_k - \theta_{sh}) = G_{sh}\left[e_{sh}^2 + f_{sh}^2 - e_k e_{sh} - f_k f_{sh}\right] + B_{sh}\left[e_{sh} f_k - e_k f_{sh}\right] \quad (12)$$

$$Q_{inj} = -B_{sh}|V_{sh}|^2 - |V_k||V_{sh}||Y_{sh}| \sin(\delta_{sh} - \delta_k - \theta_{sh}) = G_{sh}\left[e_{sh} f_k - e_k f_{sh}\right] + B_{sh}\left[-e_{sh}^2 - f_{sh}^2 + e_{sh} e_k + f_{sh} f_k\right] \quad (13)$$

$$\begin{cases} 0.9 \le |V_{sh}| \le 1.1 \\ -\pi \le \delta_{sh} \le \pi \end{cases} \qquad \begin{cases} |V_{sh}|^{\min} \le |V_{sh}| \le |V_{sh}|^{\max} \\ \delta_{sh}^{\min} \le \delta_{sh} \le \delta_{sh}^{\max} \end{cases} \quad (14)$$

$$\begin{cases} if \quad |V_{sh}| \ge |V_{sh}|^{\max} \longrightarrow |V_{sh}| = |V_{sh}|^{\max} \\ if \quad |V_{sh}| \le |V_{sh}|^{\min} \longrightarrow |V_{sh}| = |V_{sh}|^{\min} \end{cases} \quad (15)$$

$$\begin{cases} if \quad \delta_{sh} \ge \delta_{sh}^{\max} \longrightarrow \delta_{sh} = \delta_{sh}^{\max} \\ if \quad \delta_{sh} \le \delta_{sh}^{\min} \longrightarrow \delta_{sh} = \delta_{sh}^{\min} \end{cases}$$

IV. CASE STUDY

A 6-bus test system is used in this paper Fig. 8. Having 8 branches, 6 buses along with 6 loads with total of 415 MW and 183 MVAR are the specifications of the system. Results presented in this paper are obtained from M-file environment of MATLAB software. Devices presented in this paper are modeled in this environment and conventional power flow (PF) calculations and continuous power flow (CPF) with special algorithm (forecasting-correcting) are run on them. All of the loads are considered as fixed power and all of them increase simultaneously under a loading parameter (λ). Base MVA used in this paper is 100 MVA.

$$P_D = P_{D\circ} * (1+\lambda) \quad (16)$$

$$Q_D = Q_{D\circ} * (1+\lambda)$$

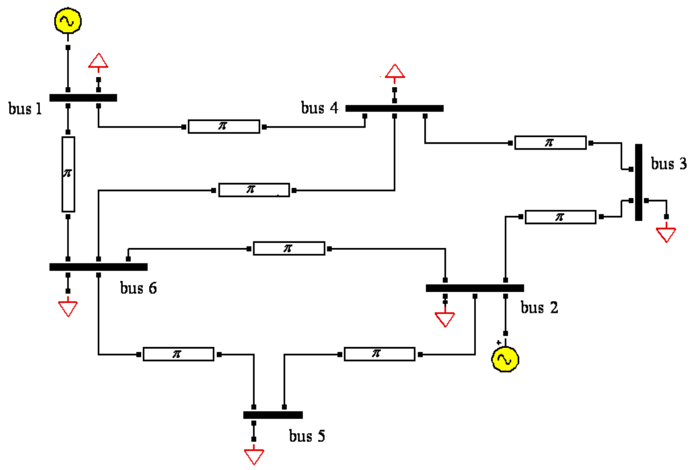

Fig. 8 6-bus test system

V. SIMULATION RESULTS

A. Conventional Load Flow

Table 1 shows the Newton load flow results under base loading conditions. The presence of HPFC {STATCOM+IPFC} in the system is analysed. STATCOM in the HPFC structure are considered as old and existing devices in power networks which we have coupled series compensation structure with them in order to improve the performance of existing equipments. Profile of bus voltages with HPFC and UPFC presence is presented in Fig. 9 and Fig. 10.

TABLE 1
Magnitude of bus voltages resulted from Newton-Raphson load flow

Bus	Voltage Magnitude [p.u]					
	Based Case	SVC	STATCOM	SSSC	UPFC	HPFC
1	1/05	1/05	1/05	1/05	1/05	1/05
2	1/04	1/04	1/04	1/04	1/04	1/04
3	0/9919	0/9942	0/9945	0/9913	1/0002	1/0005
4	0/9699	0/9759	0/977	0/9686	0/9928	0/9938
5	0/9208	1	1	0/9372	1	1
6	0/9894	1/0043	1/005	0/9859	1/0398	1/053

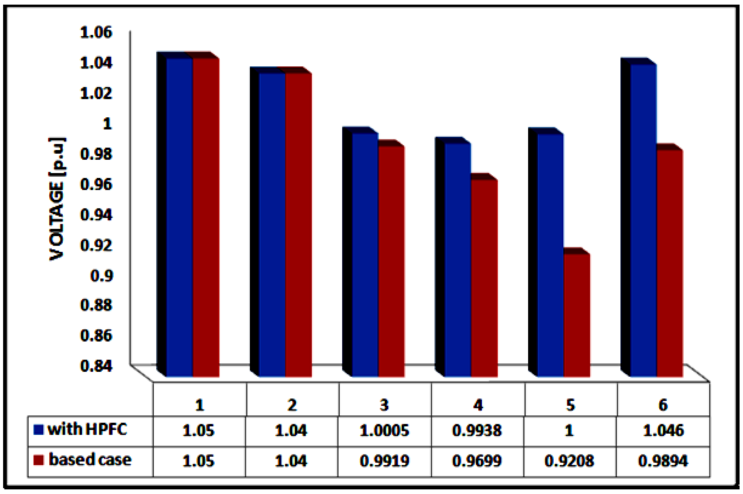

Fig. 9 Profile of bus voltages with HPFC compensator presence

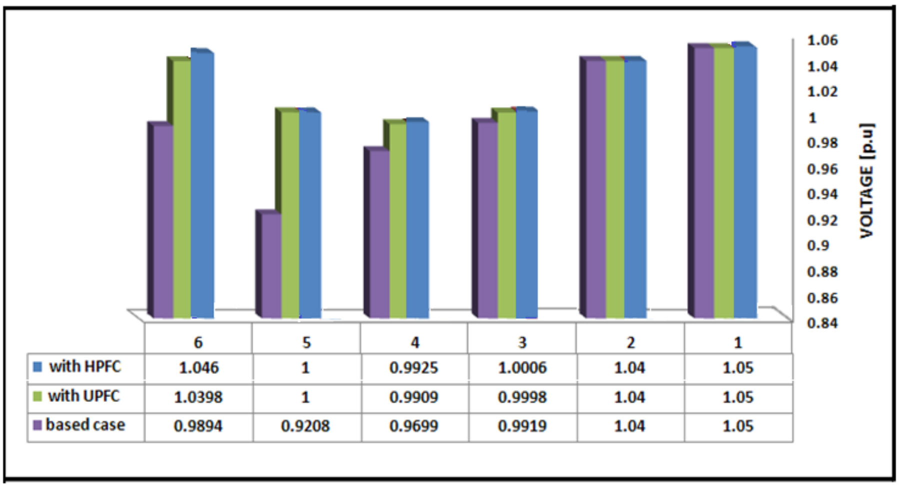

Fig. 10 Comparison among the Profile of bus voltages of the HPFC with UPFC

TABLE 2
Installation location of FACTS device

Compensator	Install Location	
	Bus	Line
STATCOM	5	---
UPFC	---	(5-6)
IPFC	---	(6-2)،(5-6)
HPFC	5	(6-2)،(5-6)

B. Continuous Load Flow

Continuous power flow provides a way for complete plotting of static analysis curves (P-V) by continuously changing the value of system loading coefficient (λ) up to the collapse point. The simulation results is shown in Fig. 11 until Fig. 14.

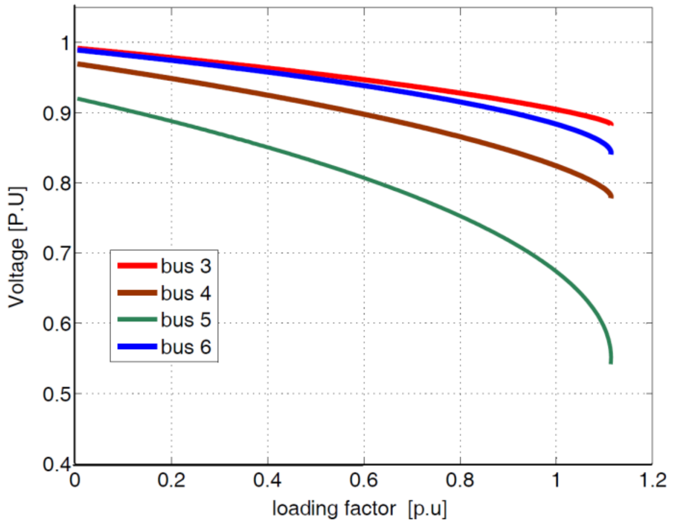

Fig. 11 P-V curves of the PQ buses of the system when there is no compensator.

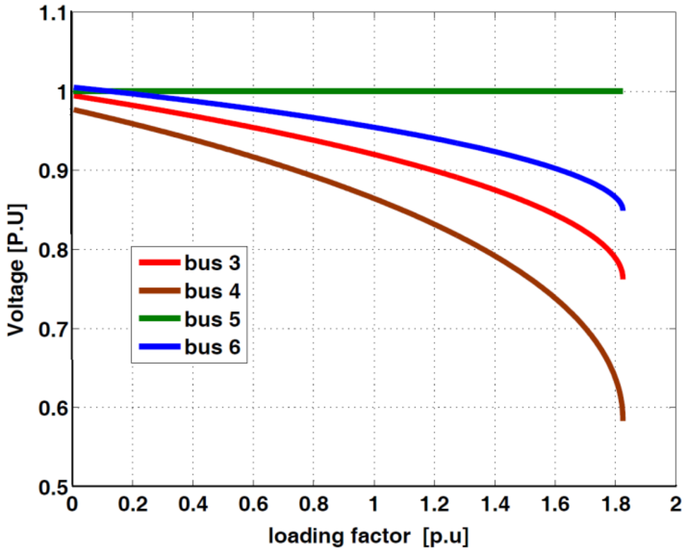

Fig. 12 P-V curves of the PQ buses of the system in presence of STATCOM.

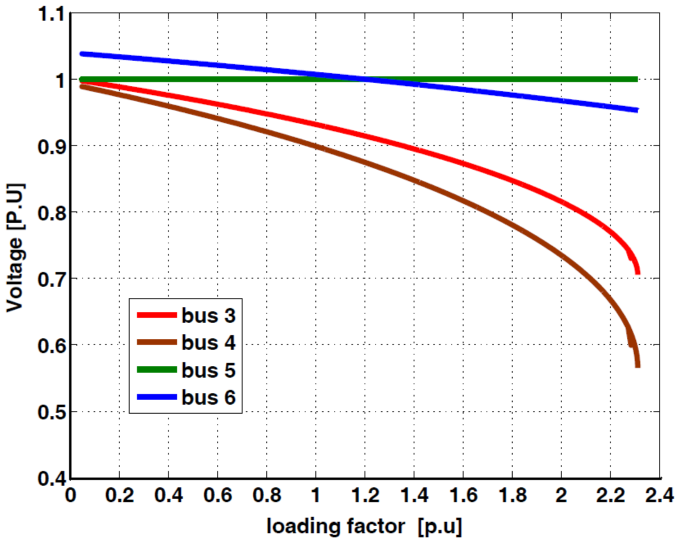

Fig. 13 P-V curves of the PQ buses of the system in presence of UPFC.

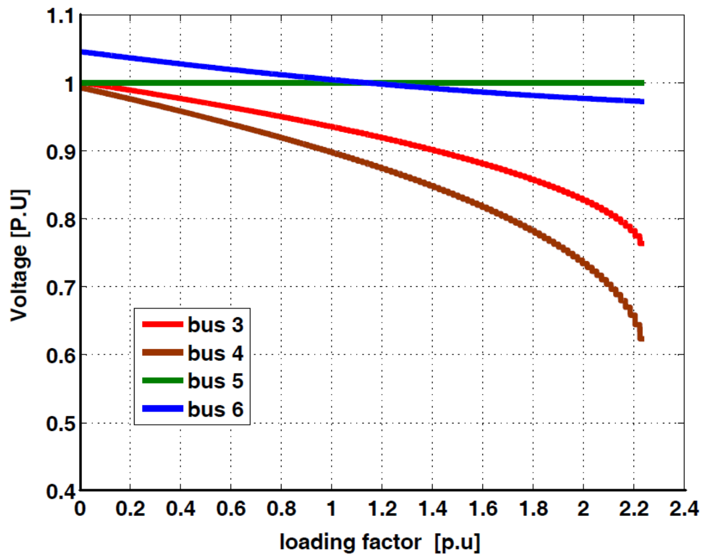

Fig. 14 P-V curves of the PQ buses of the system in presence of HPFC.

TABLE 3
Loading limit and its percent of increment in comparison with base state with presence of FACTS devices

Case	Loading margin	percent of increment
Based State	1.1139	–
STATCOM	1.8247	63.8
SSSC	1.434	28.74
UPFC	2.3108	107.45
HPFC	2.287	105.43

VI. CONCLUSION

In this paper, a power flow controller topology has been introduced. The first one utilizes a shunt connected source of reactive power (STATCOM) and uses two series connected voltage–sourced converters (IPFC) to achieve direct line control. This topology make combined use of passive components and converters, and can therefore be regarded as hybrid. A methodology for solving viable operating points of the HPFC has been proposed. The functional capabilities of the HPFC were discussed using simulation results. Thus, the performance characteristics of the HPFC were shown to be similar to those commonly associated with the UPFC.

REFERENCES

[1] H. Yangzan and W. Zengyin, "Power System Analysis, vol. I. (3rd edition)", Wuhan: *Huazhong University of Science and Technology Press*, 2002, pp. 254-256.

[2] G. Glanzmann, "FACTS, Flexible Alternating Current Transmission Systems", EEH-Power Systems Laboratory, Technical Report, ETH Zurich, Jan. 2005.

[3] H. K. Tyll, "FACTS Technology for Reactive Power Compensation and System Control", Transmission and Distribution Conference and Exposition: Latin America, IEEE/PES, pp.976 – 980, Nov. 2004.

[4] E. Uzunovic, “Transient Stability and Power Flow Models of VSC FACTS controllers,” Ph.D. dissertation, University of Waterloo, Waterloo, Canada,2001.

[5] N. Mithulananthan, C. A. Canizares, J. Reeve, and G. J. Rogers, “Comparison of PSS, SVC and STATCOM controllers for damping power system oscillations,” IEEE Trans. Power Systems, vol. 18, no. 2, pp. 786–792, May 2003.

[6] P.F. Puleston, S.A. Gonzalez, F. Valenciaga, “A STATCOM based variable structure control for power system oscillations damping,” Electrical Power and Energy Systems, pp.241–250,2007.

[7] P. Rao, M. L. Crow, and Z. Yang “STATCOM Control for Power System Voltage Control Applications”, *IEEE Transactions on Power Delivery*, vol. 15, no. 4, pp. 1311 – 1317, October 2000.

[8] Kazemi; V. Vahidinasab and A. Mosallanejad, “Study of STATCOM and UPFC Controllers for Voltage Stability Evaluated by Saddle-Node Bifurcation Analysis”, IEEE, *First International Power and Energy Conference*, pp. 191-195, PECon 2006.

[9] Sode-Yome; N. Mithulananthan and K.Y. Lee, “A Comprehensive Comparison_ of FACTS Devices for Enhancing Static Voltage Stability”, IEEE, *Power Engineering Society General Meeting*, _pp. 1-8, 2007.

[10] X.P. Zhang, “Modeling of the interline power flow controller and the generalized unified power flow controller in Newton power flow,” *Proc. Inst. Elect. Eng., Gen., Trans., Distrib.*, vol. 150, no. 3, pp. 268–274, May 2003.

[11] J.Z. Bebic; P.W. Lehn and M.R. Iravani, “The Hybrid Power Flow Controller A New Concept for Flexible AC Transmission”, IEEE, pp. 1066–1072, 2006.

[12] Jianhong Chen; T.L. Tjing and D.M. Vilathgamuwa, “Design of An Interline Power Flow Controller”, *14th PSCC*, Sevilla, 24-28 June 2002

