THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE III, 2010, Vol.33, No.1, ISSN 1221-454X
ELECTROTECHNICS, ELECTRONICS, AUTOMATIC CONTROL, INFORMATICS

SIMULATION RESULTS OF CLOSED LOOP CONTROLLED INTERLINE POWER FLOW CONTROLLER SYSTEM

P. USHA RANI **S. RAMA REDDY**

Department of Electrical and Electronics Engineering, Jerusalem College of Engineering,
Centre for collaborative research with Anna University, Chennai, India.
E-mail: pusharani71@yahoo.com

Abstract: The Interline Power Flow Controller (IPFC) is the latest generation of Flexible AC Transmission Systems (FACTS) devices which can be used to control power flows of multiple transmission lines. A dispatch strategy is proposed for an IPFC operating at rated capacity, in which the power circulation between the two series converters is used as the parameter to optimize the voltage profile and power transfer. Voltage stability curves for test system are shown to illustrate the effectiveness of this proposed strategy. . In this paper, a circuit model for IPFC is developed and simulation of interline power flow controller is done using the proposed circuit model. Simulation is done using MATLAB simulink and the results are presented.

Keywords: Interline Power flow controller (IPFC), flexible AC transmission systems (FACTS), Voltage source converter (VSC), Static Synchronous Series Compensator SSSC).

1. INTRODUCTION

The last generation FACTS controllers using the self commutated VSC usually include static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC) and IPFC. The STATCOM is usually employed as shunt reactive compensator and SSSC as series active or reactive compensator. The UPFC concept provides a powerful tool for the cost effective utilization of individual transmission lines by facilitating the independent control of both active and reactive power flow and thus the maximization of real power transfer at minimum losses in the line. However, the UPFC and SSSC can control power flow of only one transmission line. Compared with the UPFC and SSSC, the IPFC has much more flexible topologies, consists of at least two converters and can be used to control power flows of a group of lines.

The power systems of today are mechanically controlled and as a result there is no high-speed control. Also, such mechanical controls cannot be initiated frequently because mechanical device tend to wear out very quickly compared to static electronic devices. The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability. The possibility of that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS controllers to enable corresponding power to flow through such lines under normal and contingency conditions. FACTS controllers can enable a line to carry power closer to its thermal rating. Interline Power Flow Controller (IPFC) is an extension of static synchronous series compensator (SSSC). A mathematical model of the IPFC in steady state operation has been developed in [1]. In [2], the basic principle of the IPFC is discussed in detail and simulation results are shown to demonstrate the capability of the IPFC to realize power balance between a transmission system with two identical parallel lines. The basic characteristics of the IPFC are discussed and two basic control systems for the IPFC are proposed to realize the power flow control in [3]. Flexible AC Transmission System (FACTS) controllers such as thyristor-based controllers are described in [4]. IPFC employs a number

This paper was recommended for publication by Emil Roşu

of VSCs linked at the same DC terminal, each of which can provide series compensation for its own line. In this way, the power optimization of the overall system can be realized in the form of appropriate power transfer through the common DC link from over-loaded lines to under-loaded lines [2, 3, 4]. The performance of a Generalized Interline Power Flow Controller (GIPFC) controlling two balanced independent AC systems is analyzed and evaluated in [5]. Literature [6] describes a combination of fuzzy scheme and Radial Basis Function Neural Network adopted for nonlinear control of Thyristor Controlled Series Capacitor (TCSC) and IPFC. The power flow control design for IPFC is proposed and transfer functions are analyzed in [7]. Paper [8] proposes a powerful tool applied on 3 machine 9 bus test system with two IPFCs, with one loop and optimal power flow method. Mathematical models of IPFC and Generalized UPFC and their implementation in Newton power flow have been presented in [9]. Paper [10] presents an approach to solve first swing stability problem using UPFC. Paper [11] proposes a new dispatch strategy for an IPFC operating at rated capacity. The circuit model for closed loop IPFC is not available in the literature [1] to [11]. An attempt is made in the present work to develop circuit model for closed loop controlled IPFC using the blocks of simulink. The dispatch strategy is illustrated with a four bus test system. For the system, we show the familiar PV curves for the IPFC dispatched below and at rated capacity. In particular, we show systematically how the dispatch of the circulating power between the two VSCs improves the system voltage profile and the power transfer capability.

2. BASIC PRINCIPLE OF INTERLINE POWER FLOW CONTROLLER

In its general form, the IPFC employs number of DC to AC inverters each providing series compensation for a different line as shown in Fig.1. IPFC is designed as a power flow controller with two or more independently controllable static synchronous series compensators (SSSC) who are solid state voltage source converters injecting an almost sinusoidal voltage at variable magnitude and are linked via a common DC capacitor. SSSC is employed to increase the transferable active power on a given line and to balance the loading of a transmission network.

In addition, active power can be exchanged through these series converters via the common DC link in IPFC. It is noted that the sum of the active powers output from VSCs to transmission lines should be zero when the losses of the converter circuits can be ignored. A combination of the series connected VSC can inject a voltage with controllable magnitude and phase angle at the fundamental frequency while DC link voltage can be maintained at a desired level. The common DC link is represented by a bidirectional link for active power exchange between voltage sources.

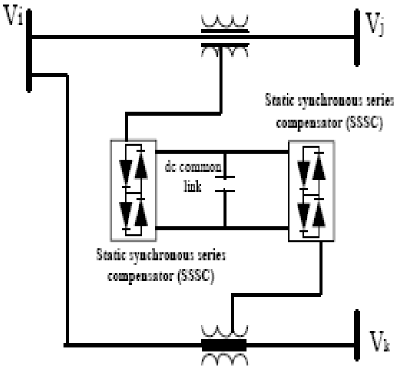

Fig.1 Schematic representation of IPFC

The equivalent circuit of the IPFC is shown in Fig.2.

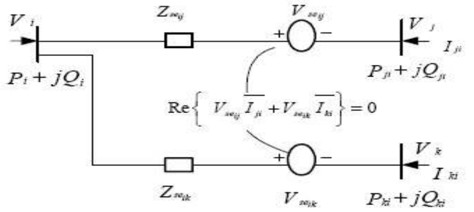

Fig.2 Equivalent circuit of IPFC

The power flow equations are as follows:

$$\begin{aligned} P_i = V_i^2 g_{ii} - \sum_{j=1,\, j\neq i}^{n} V_i V_j \left(g_{ij}\cos\left(\theta_j - \theta_i\right) + b_{ij}\sin\left(\theta_j - \theta_i\right)\right) \\ - \sum_{j=1,\, j\neq i}^{n} V_i Vse_{ij} \left(g_{ij}\cos\left(\theta_i - \theta se_{ij}\right) + b_{ij}\sin\left(\theta_i - \theta se_{ij}\right)\right) \end{aligned} \tag{1}$$

$$\begin{aligned} Q_i = V_i^2 b_{ii} - \sum_{j=1,j\neq i}^{n} V_i V_j \left(g_{ij}\sin\left(\theta_j - \theta_i\right) + b_{ij}\sin\left(\theta_j - \theta_i\right)\right) \\ - \sum_{j=1,j\neq i}^{n} V_i Vse_{ij} \left(g_{ij}\sin\left(\theta_i - \theta se_{ij}\right) + b_{ij}\sin\left(\theta_i - \theta se_{ij}\right)\right) \end{aligned} \tag{2}$$

where V : bus voltage magnitude
θ : bus angle
V_{se} : magnitude of injected voltage
θ_{se} : angle of injected voltage
g_{ij} : conductance
b_{ij} : susceptance

3. MODEL FOR IPFC SYSTEM

In this section, we illustrate the proposed IPFC dispatch strategy for maximizing voltage stability limited power transfer in a 4-bus test system. Perhaps the most common approach in voltage stability analysis is to increase the system loading P_{load} and observe the resulting voltage variation V on the critical buses. The analysis is frequently presented in the form of PV curves, which are now being used in many power control centers.

To generate consistent PV curves, we modify the IPFC control strategy slightly by enforcing the desired circulating power P_c at all operating conditions, regardless of whether the VSCs are at their rated capacities or not. That is, if both VSCs are below their rated capacities, then besides requesting a specific power circulation level, the series VSCs will regulate line active power flows. The reactive power flow is no longer enforced.

The 4 bus test system shown in Fig.3 has two equivalent generators and two equal amounts of loads at bus2 and bus4.

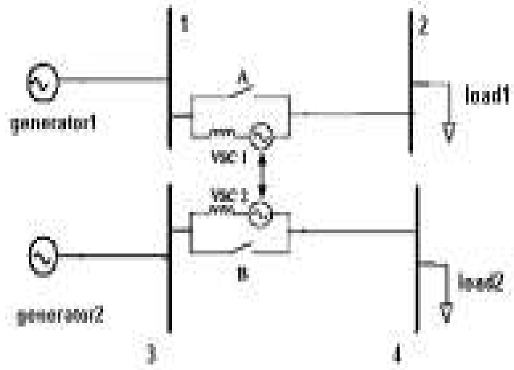

Fig.3 The 4 bus test system

There are two transmission paths with line 3-4 weaker than line 1-2 (stronger line 1-2 & weaker line 3-4). An IPFC is sited at bus 1 with each VSC on one of the parallel lines on the two transmission paths. It is noted that by closing the switches A and B, the IPFC is bypassed, which is referred to as the uncompensated system. The IPFC is in service if the switches A and B are opened.

By increasing the loads P_{load1} at bus 2, P_{load2} at bus 4 and the necessary amount of generation at bus 1and bus 3, we can investigate the variation of voltage V_2 at bus 2 and V_4 at bus 4, with and without the IPFC. Note that a positive Pc denoted that power is circulating from VSC 2 on line 3-4 to VSC 1 on line 1-2.

4. SIMULATION

4.1 Model of Closed loop IPFC with variations in firing angle of VSC 1

The single phase four bus closed loop IPFC system has been simulated in MATLAB/ SIMULINK using power system toolbox is shown in Fig.4. Switches A and B are opened for the time period of 0.3 sec to 0.6 sec. Then the IPFC is in service during the above mentioned time period, which is referred as the compensated system. The switches A and B are closed for the remaining time period; the IPFC is bypassed, which is referred to as the uncompensated system. By increasing the loads at bus 2 and bus 4, we can investigate the variation of output voltage and real power at bus 4, with and without IPFC.

Without IPFC, the output of stronger line is 2.1*(10^8) MW & 2.8*(10^8) MVAR and the output of weaker line is 2.0289*(10^8) MW & 2.7098*(10^8) MVAR, which are shown in Figs.5 & 6 respectively.

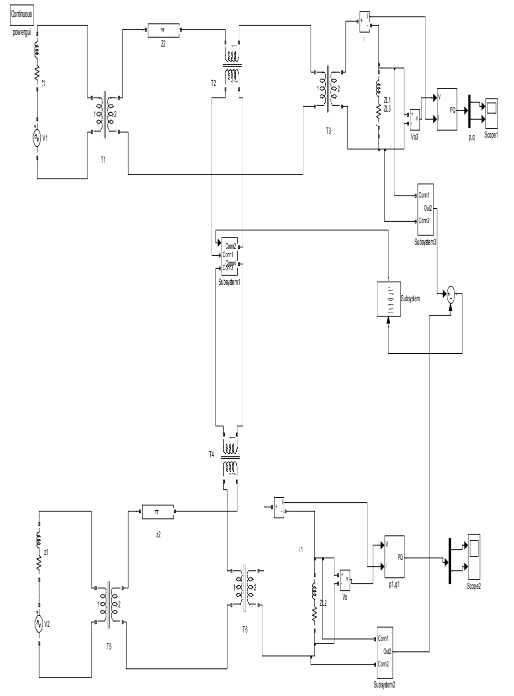

Fig. 4 Circuit model of closed loop IPFC system with the changes in firing angle of VSC 1

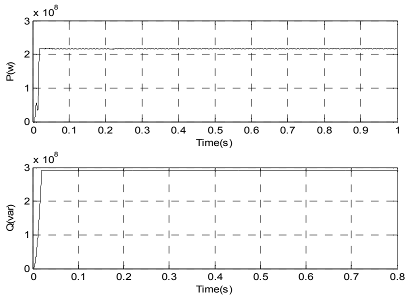

Fig.5 Real and reactive powers of stronger line.

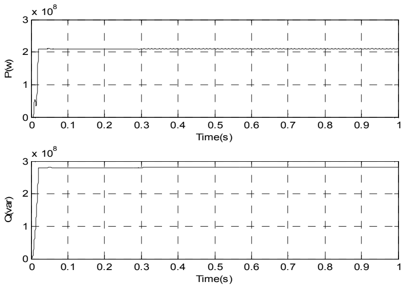

Fig.6 Real and reactive powers of weaker line.

The subsystem of the closed loop controlled IPFC system with firing angle changes in VSC 1 is shown in Fig.7. A reference signal is compared with a ramp signal and its output is given as pulse to switches of the converter. Firing angle of pulse generators in VSC 1 is varied and the corresponding variations in real power and output voltage are observed for different loads.

By increasing the power circulation from VSC 1 to VSC 2 for the load considered in the range of 600 MW to 800 MW, reactive power is taken from stronger line 1-2 and injected into weaker line 3-4, allowing higher voltage of bus 4. Conversely the load considered in the range of 800 MW to 950 MW, by increasing power circulation from VSC 2 to VSC 1, bus 4 voltage is decreased and bus 2 voltage is raised.

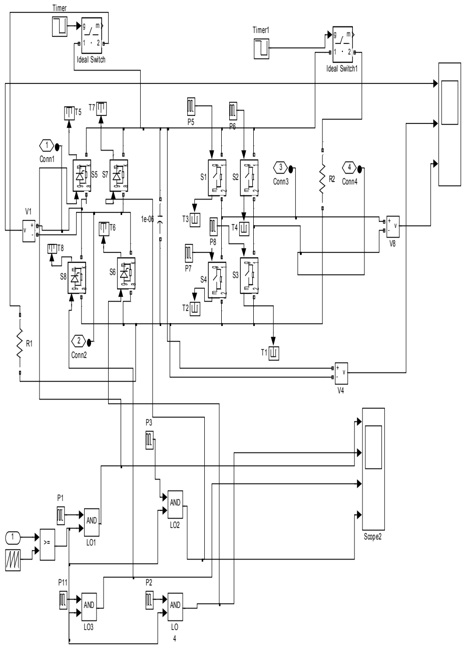

Fig.7 Subsystem of closed loop IPFC system with the changes in firing angle of VSC 1

For the load considered in the range of 600 MW to 800 MW, the real power flows from VSC1 to VSC2 and the output power variations in the weaker line 3-4 is as shown in Fig.8. For the load considered in the range of 800 MW to 950 MW, the real power flows from VSC2 to VSC1 is as shown in Fig.9.

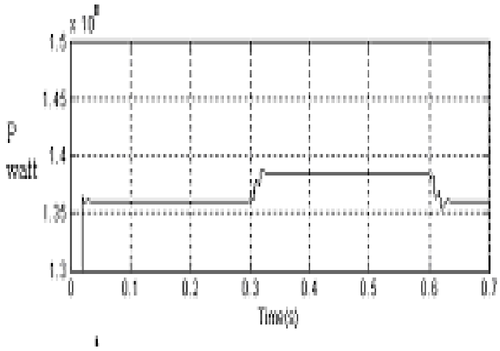

Fig.8 Real power in weaker line for 650 MW load

The change in real power for various loads from 600MW to 950MW with the change in power (P_c) is shown in Fig.10. The change in output voltage for various loads from 600MW to 950MW with the change in power (P_c) for bus 4 is shown in Fig.11.

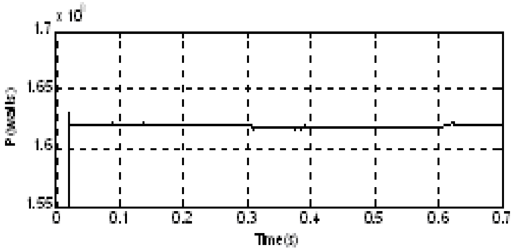

Fig.9 Real power in weaker line for 900 MW load

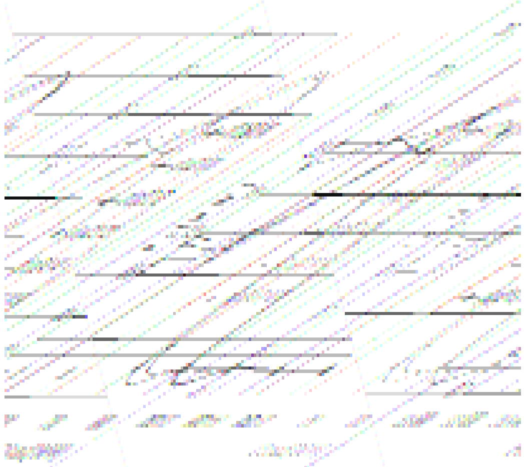

Fig.10 Change in real power of weaker line

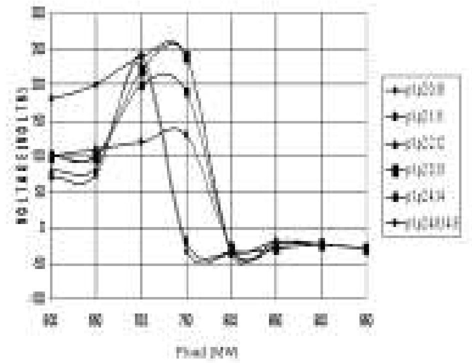

Fig.11 PV curve of weaker line

4.2. Closed loop controlled IPFC with variation in the firing angle of VSC2 taking sending end voltage as reference

The model of the closed loop controlled IPFC system with firing angle variations in VSC 2 taking sending end voltage as reference is shown in Fig.12 and the subsystem is shown in Fig.13. A reference signal is compared with a ramp signal and its output is given as pulses to switches of the converter. Firing angle of pulse generators in VSC 2 is varied and the corresponding variations in reactive power & output voltage of weaker line are observed for different loads.

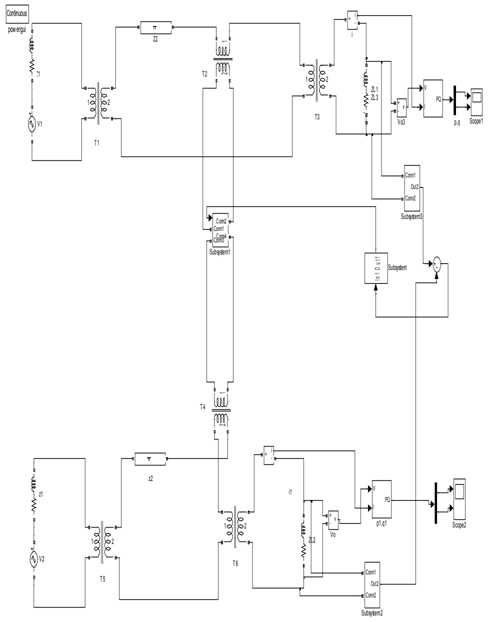

Fig.12 Closed loop controlled IPFC system with the variations in firing angle of VSC 2 taking sending end voltage as reference

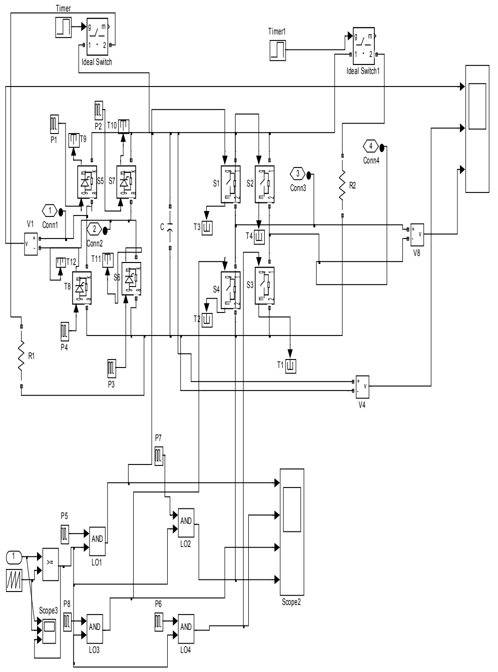

Fig.13 Subsystem of IPFC system with the changes in firing angle of VSC 2 taking sending end voltage as reference

The reactive power variation in weaker line 3-4 with load in the range of 600 MW to 750 MW is as shown in Fig. 14. It is observed that the reactive power increases from 1.6858*(10^8) VAR to 1.8934*(10^8) VAR and voltage increases from 1.631*(10^4) V to 1.73*(10^4) V. Thus there is a reactive power flow from VSC1 to VSC2.

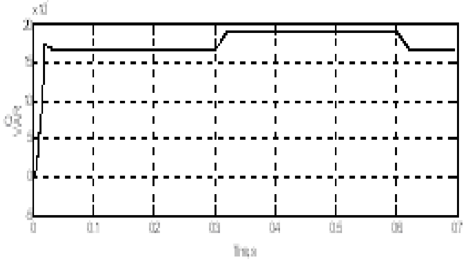

Fig.14 Reactive power in weaker line for 650 MW load

For the load considered in the range of 800MW to 950 MW, the reactive power variation in weaker line is as shown in Fig.15. It is observed that the power decreases from 1.92*(10^8) VAR to 1.89*(10^8) VAR and voltage decreases from 1.87*(10^4) V to 1.73*(10^4) V. Thus there is a reactive power flow from VSC2 to VSC1.

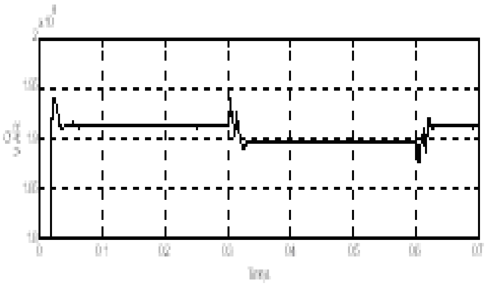

Fig.15 Reactive power in weaker line for 900 MW load

The change in output voltage for the loads considered in the range of 600MW to 950MW, with the change in reactive power (Q_c) for bus 4 is shown in Fig.16.

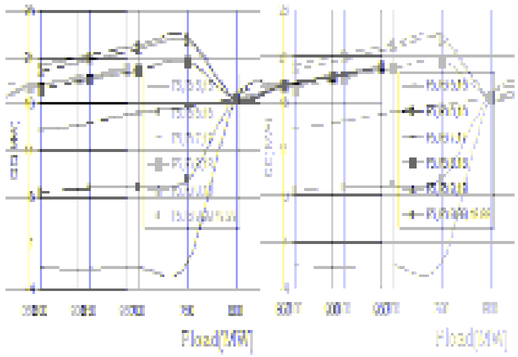

Fig. 16. Change in reactive power of weaker line

4.3 Closed Loop Controlled IPFC with variation in firing angle of VSC2 taking receiving end voltage as reference

The model of the closed loop controlled IPFC system with firing angle changes in VSC 2 taking receiving end voltage as reference is shown in Fig.17 and the subsystem is shown in Fig.18. A reference signal is compared with a ramp signal and its output is given as pulse to switches of the converter. Firing angle of pulse generators in VSC 2 is varied and the corresponding variations in reactive power & output voltage of weaker line are observed for different loads.

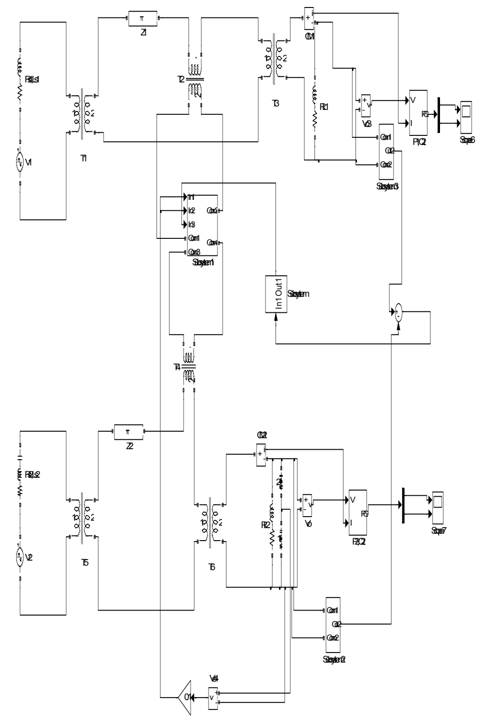

Fig.17 Closed loop IPFC with changes in firing angle of VSC 2 by taking receiving end voltage as reference

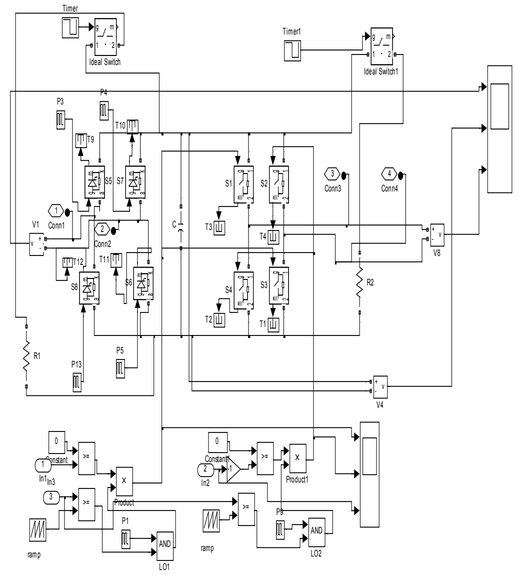

Fig.18. Subsystem of IPFC with changes in firing angle of VSC 2 by taking receiving end voltage as reference

For a load of 650 MW, the reactive power output in weaker line is shown in Fig.19. It is observed that the power increases from 1.97*(10^8) VAR to 1.99*(10^8) VAR and voltage increases from 1.7*(10^4) V to 1.73*(10^4) V. Thus there is a flow of reactive power from VSC1 to VSC2.

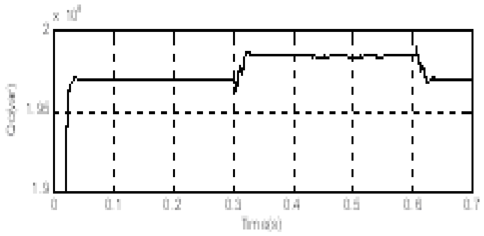

Fig.19 Reactive power and output voltage in weaker line for 650 MW load

The Fig. 20 shows the changes in reactive power for the loads considered in the range of 600MW to 950MW with the change in power (Q_c). Fig. 21 shows the changes in output voltages of the weaker line for the loads considered in the range of 600MW to 950MW with the change in voltage.

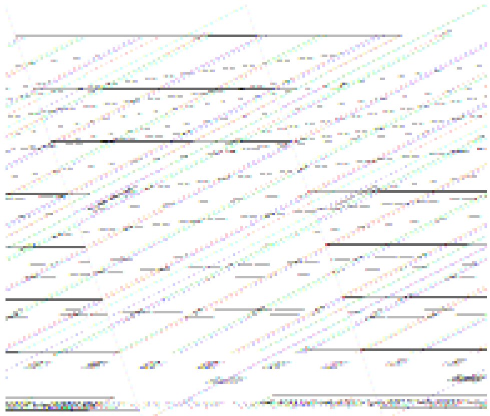

Fig. 20 Change in reactive power of weaker line with receiving end voltage as reference

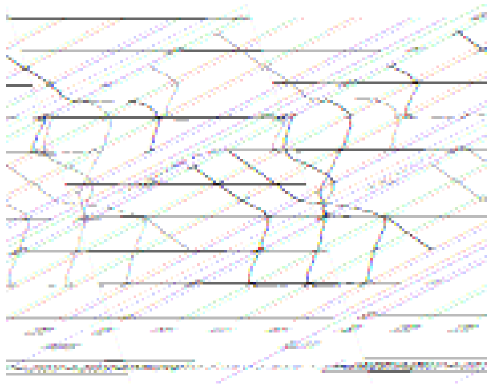

Fig.21 Change in voltage of weaker line with receiving end voltage as reference

5. CONCLUSION

The IPFC is simulated for the compensation and power flow management of multiline transmission system. In the IPFC structure, number of converters is linked together at their DC terminals. Each inverter can provide series reactive compensation, as an SSSC, for its own line. However, the converters can transfer real power between them via their common DC terminal. This capability allows the IPFC to provide both real and reactive compensation for some of the line and thereby optimize the utilization of the overall transmission system. In particular, the IPFC can equalize both real and reactive power flow in the lines, relieve the overloaded lines from the burden of reactive power flow, compensate against resistive as well as reactive voltage drops, and provide a concerted multiline counter measure during dynamic disturbances.

A new dispatch strategy for an IPFC operating at rated capacity is proposed in this paper. When the IPFC operates at its rated capacity, it can no longer regulate line active power flow set point or the reactive power flow set point or both. In such cases, the dispatch strategy switches to a power circulation set point control to co-optimize both series VSCs without exceeding one or both rated capacities. The concept can be used to generate PV curves associated with the voltage stability analysis for maximizing power transfer. The dispatch results show that the IPFC can improve the power transfer in the system. The power circulation between the two VSCs can be used to adjust bus voltages to improve the voltage stability limit transfer. The simulation results are in line with the predictions.

APPENDIX

The electrical data of the system used in the present work is as below:

Generator 1 & 2 :	15.7kV
Transformer :	15.7/ 400 kV, 1000MVA, r=0.0059p.u, l = 0.127 p.u.
Series transformer:	3/ 45 kV, 160 MVA, r=0.005p.u, l = 0.06 p.u.
Transmission line:	r = 3.2 □ / 100km, l=103 mH/100km, c = 1.1 F/ 100km

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P. Usha Rani is an Associate Professor in Electrical and Electronics Engineering Department, Jerusalem College of Engineering, Chennai, India. She received her B.E. degree in Electrical & Electronics Engineering from the Government College of Technology, Coimbatore, India in 1991, M.E. degree in Power Systems from College of Engineering, Anna University, Chennai, India in 2001. Her earlier industrial experience was with Chemin Controls, Pondicherry, India. She has 13 years of teaching experience. Her research interests on application of power electronics to power quality problems.

S. Rama Reddy is Professor of Electrical & Electronics Engineering Department, Jerusalem College of Engineering, Chennai, India. He obtained his D.E.E. from S.M.V.M. polytechnic, Tanuku,

A.P., A.M.I.E.
in Electrical Engineering from Institution of Engineers (India), M.E. in Power Systems from Anna University, Chennai and Ph.D in the area of Power Electronics from Anna University, Chennai, India. He has published over 20 technical papers in national and international conferences proceedings / journals. He has secured A.M.I.E. institution gold medal for obtaining highest marks. He has secured AIMO best project award and Vijaya Ratna Award. He has worked in Tata Consulting Engineers, Bangalore and Anna University, Chennai. He has 18 years of teaching experience. His research interests include the areas of resonant converters and FACTS. He is life member of Institution of Engineers (India), Indian Society for Technical Education, Systems Society of India, Society of Power Engineers and Institution of Electronics and Telecommunication Engineers (India). He has published text books on Power Electronics, Solid State Circuits and Electronic circuits.