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Modeling, Simulation and Fault Diagnosis of IPFC using PEMFC for High Power Applications

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Abstract – An Interline Power Flow Controller (IPFC) is a converter based controller which compensates and balance the power flow among multi-lines within the same corridor of the multi-line subsystem. The Interline Power Flow Controller consists of a voltage source converter based Flexible AC Transmission System (FACTS) controller for series compensation. The reactive voltage injected by individual Voltage Source Converter (VSC) can be controlled to regulate active power flow in the respective line in which one VSC regulates the DC voltage, the other one controls the reactive power flows in the lines by injecting series active voltage. 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 PSPICE. The results obtained by MATLAB are compared with the results obtained by PSPICE and compared with theoretical values.

Keywords: IPFC model, Closed loop control, SSSC, Filters, FFT analysis, Flexible AC transmission system (FACTS), Interline power flow controller (IPFC), Voltage source converter (VSC)

1. Introduction

In a power system, due to power demand networks are facing problems. Due to environmental legislation, rights of way issues, construction costs, and deregulation policies, extremely difficult to build new transmission lines. Deregulation is aimed at a competitive energy market, in which the sellers and buyers of electric power are linked together with an independent transmission network. To obtain transmission power stability and avoid transmission congestion problems companies are forced to search for innovative techniques.In this background, EPRI introduced a very suitable concept of Flexible AC Transmission System (FACTS). The advantage of FACTS controllers is that - it can generate/absorb reactive power without the use of AC capacitors and reactors; - converter-based FACTS controllers are capable of independently controlling both active and reactive power flow in the power system [1]. The advanced developments of the semiconductor industry offer a new generation of FACTS controllers called VSC based FACTS controllers with shows potential features in flexible power flow control, transient stability and power system oscillation damping enhancement [2]. To enlarge and include power flow control, current and voltage harmonic compensation, voltage imbalance, reactive power, negative sequence current compensation, UPFC (Unified Power Flow Controllers) is used. They are classical series-parallel filters (or special matrix converter [3], which can control active and reactive powers transmitted through the line. The major purpose of the parallel filter is to keep voltage on the source element of constant value. The series filter has to inject controllable (with angle and magnitude) voltage and in this way control power flow. One of the disadvantages of this solution is needed to equip every transmission line with the independent UPFC system. In the problem of compensating a number of transmission lines at a given substation, a new concept of IPFC was proposed by first Gyugi in 1998, [4]. In General, the IPFC employs a number of VSCs linked at the same DC terminal, each of which can provide series compensation for its own line. A multi control functional model of static synchronous series compensator (SSSC) used for steady state control of power system parameters with current and voltage operating constraints has been presented [5, 6]. To analyze the power flow control in transmission lines in which IPFC is placed, Newton - Rapson (NR) power flow algorithm is incorporated [7]. The injection model for congestion management and total active power failure minimization in electric power system has been developed [8]. It can also be consists of more than a few SSSCs are giving out a common DC link. In this way, by properly transferring power through the common DC link from overloaded lines to under load lines, the overall power optimization can be realized [9]. A control scheme of an IPFC system with two VSCs to compensate the impedances of two similarly dimensioned parallel transmission lines is presented [10].

The paper is organized as follows. In section 1, the introduction is given in terms of the necessity of FACTS devices and IPFC. The source used here is Proton Exchange Membrane Fuel Cell an electrochemical device that converts hydrogen fuel into energy and water without

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combustion. The power output of a single PEM Fuel Cell is limited in the range of 0.7volts and hence multiple PEM Fuel Cell's attached in series to attain increased energy. Section 2 summarizes the basic concepts and operating principle of IPFC. The realization of IPFC with four bus systems in open loop and closed loop control for real power enhancement using MATLAB/SIMULINK are illustrated in section 3. Also the developed circuit is analyzed under fault condition and the corresponding waveforms are given. Section 4 describes the simulation studies and conclusions

2. PEMFC in IPFC System

In its general form the Interline power flow controller employs a number of DC to AC converters each providing series compensation for different lines. In other words, the IPFC comprises a number of static synchronous series compensators. Fig. 1 Shows the PEMFC which consists of porous carbon electrodes bonded to a very thin sulphonated polymer membrane. Electrodes cap either side of the Proton Exchange Membrane and are responsible for carrying the electric current. An electrolyte between the electrodes carries the hydrogen ions while not letting the electrons through.

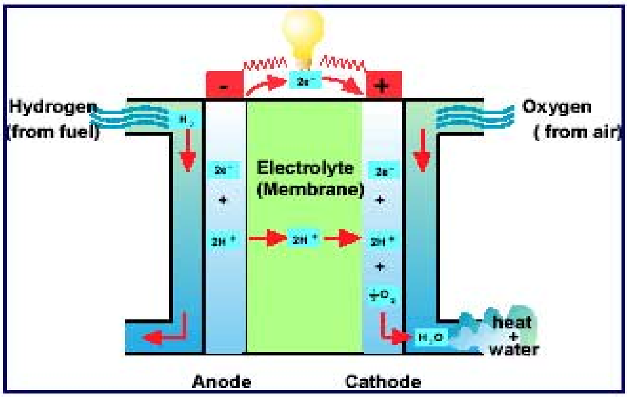


Fig. 1. PEMFC model.

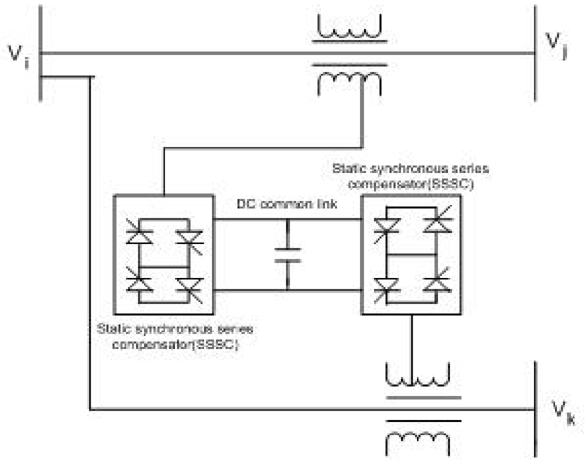


Fig. 2. Simplified schematic of the IPFC model.

However, within the general concept of the IPFC, the compensating converters are linked together at their DC terminals, as illustrated in Fig. 2 [4-6]. With this scheme, by providing series reactive compensation, any converter can be forbidden to supply real power to the general DC link from its own transmission line. Thus, an overall surplus power can be made available from the under-utilized lines which then can be used by other lines for real power compensation. In this, some of the converters, compensating overloaded lines or lines with a heavy burden of reactive power flow, can be equipped with full two – dimensional, reactive and real power control capability, similar to that offered by the UPFC. Obviously, this array mandates the exact maintenance of the overall power balance at the common DC terminal by suitable control action, using the general principle that the under loaded lines are to provide help, in the form of suitable real power transfer for the overloaded lines.

An elementary IPFC scheme consists of two back-to-back DC-to-AC converters, each compensating a transmission line by series voltage injection [3]. This arrangement is shown functionally in Fig. 3, where two synchronous voltage sources, with phasors V1pq and V2pq in series with transmission lines 1 and 2, represent the two back-to-back DC-to-AC converters.

The common DC link is represented by a bi-directional link for real power exchange between the two voltages of transmission lines, represented by reactance X1, as a sending end bus with voltage phasor V1s and a receiving end bus with voltage phasor V1r. The sending end voltage phasor of line 2, represented by reactance X2, is V2s and the receiving end voltage phasor is V2r. Without consideration of line resistance, the power flow at the receiving end can be approximated as in Eqs. (1) and (2).

$$P_r = \frac{V^2}{X}\sin\delta + \frac{V..V_{pq}}{X}\sin(\delta+\rho) \qquad (1)$$

$$Q_r = \frac{V^2}{X}\cos(\delta-1) + \frac{V..V_{pq}}{X}\cos(\delta+\rho) \qquad (2)$$

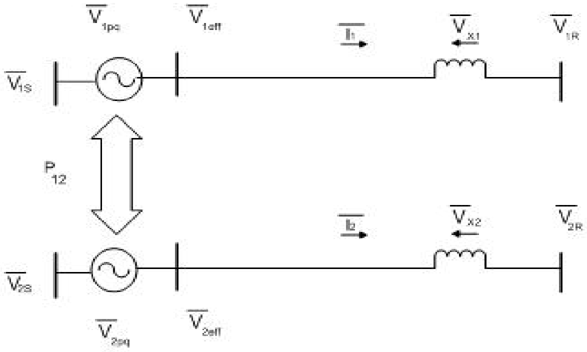


Fig. 3. Basic Two inverters Interline Power Flow Controller.

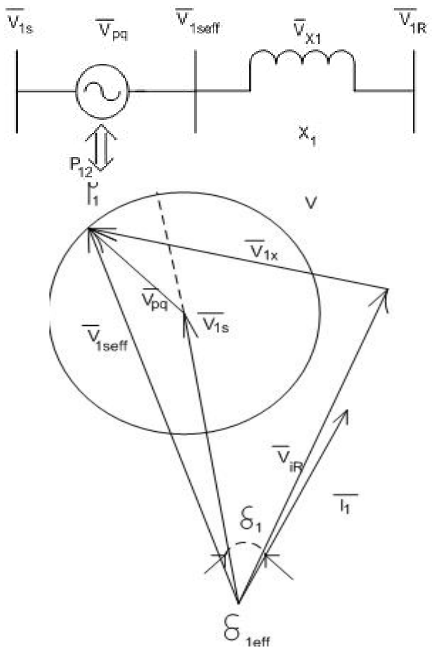


Fig. 4. Phasor diagram of the system.

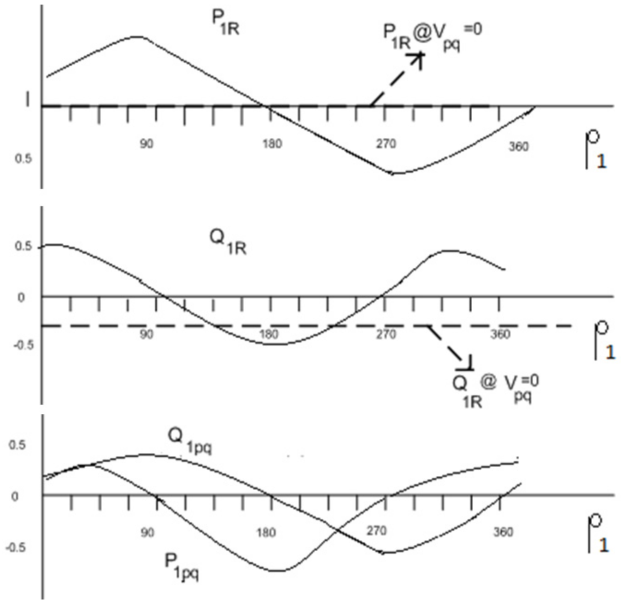
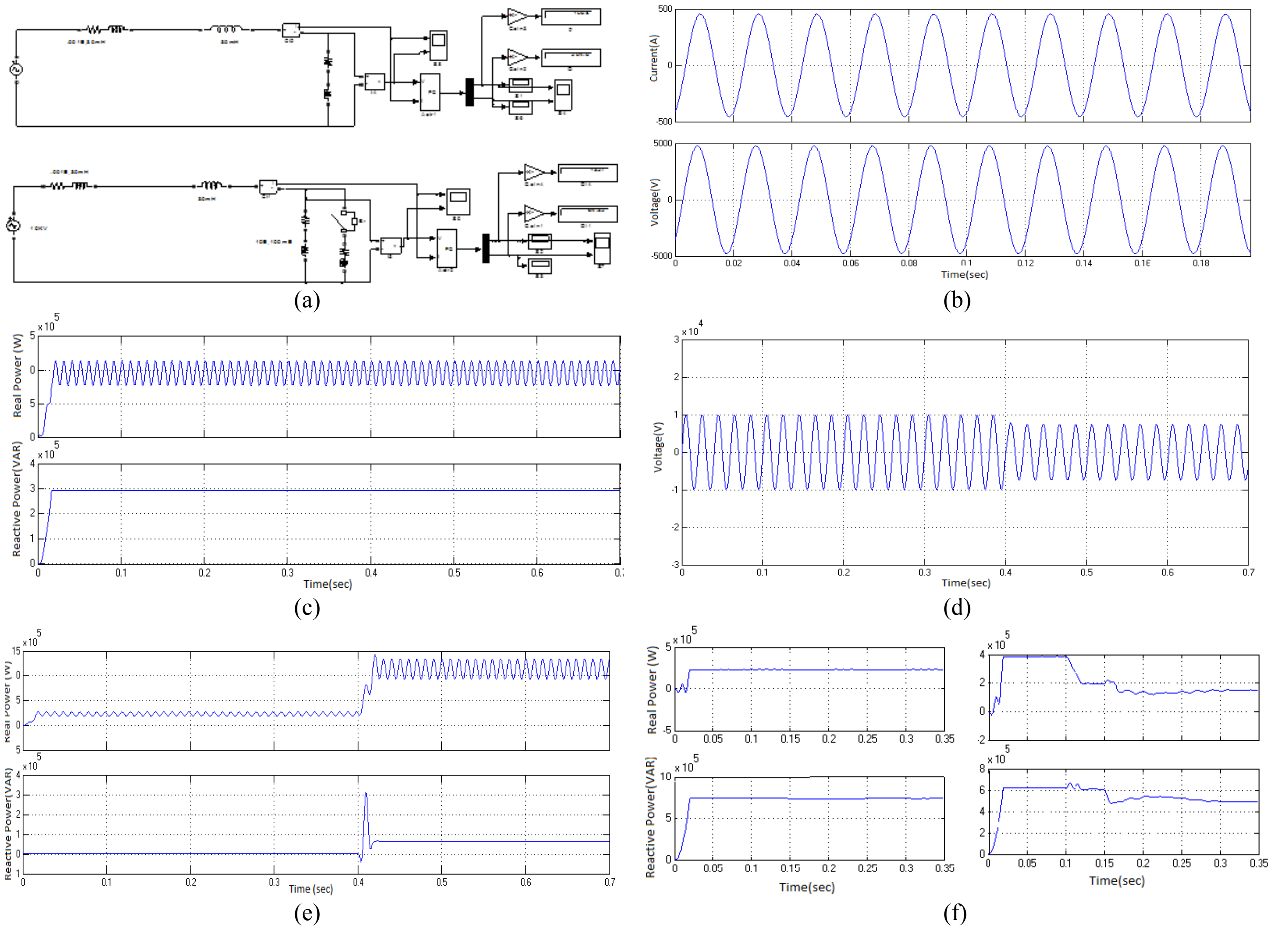


Fig. 5. Variation of the receiving end real and reactive Power and the compensating real and reactive power.



(a)
(b)
(c)
(d)
(e)
(f)

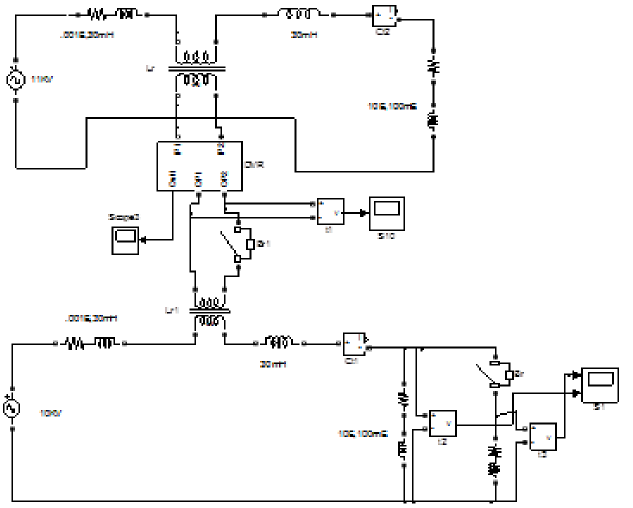
Fig. 6. (a) 4-bus system with equal loads and different Voltages; (b) (i) Current through line 1, (ii) Receiving end voltage; (c) Real and reactive powers in Line-1; (d) Voltage of Line-2 with sag; (e) Real and reactive powers in Line-2; (f) Without compensate-ion the Real and Reactive power at load 1 and Load 2 (Load 1 is constant and Load 2 variable)

All sending end and receiving end voltages are assumed to be constant with fixed amplitudes, $V1s = V1r = V2s = V2r = 1.0$ p.u., and with fixed angles resulting in identical transmission angles, $\delta 1 = \delta 2$ (=300), for the two systems. The two line impedances, and the rating of the two compensating voltage sources, are also assumed to be identical, i.e., $V1pqmax = V2pqmax$ and $X1 = X2 = 0.5$ p.u. respectively. In order to establish the transmission relationships between the two systems, system 1 is arbitrarily selected to be the prime system for which free controllability of both real and reactive line power flow is stipulated.

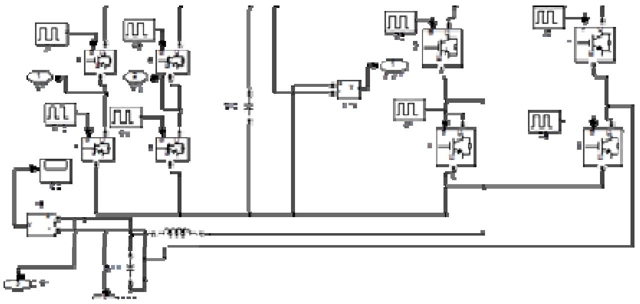
A phasor diagram of system 1, defining the relationship between V1s, V1r, V1x (the voltage phasor across X1) and the inserted voltage phasor V1pq, with controllable magnitude ($0 \leq V1pq \leq V1pqmax$) and angle ($0 \leq \rho 1pq \leq 3600$) is shown in Fig. 3. The difference between V1s eff and V1r gives the compensated voltage Vx1 across X1. As $\delta 1$ is varied over its full 360^0 range, the end of phasor V1pq moves along a circle with its center at the end of V1s. The rotation of phasor V1pq with angle $\delta 1$ modulates both the magnitude and phase angle of Vx1 and therefore both real power P1r and reactive power Q1r vary with $\delta 1$ in a sinusoidal manner. Thus the voltage source inverter can absorb or deliver both real powers (P1pq) and reactive power (Q1pq), which are also a sinusoidal function of angle ρ. The Phasor diagram of the System, variation of the receiving end real and reactive power and the compensa-ting real and reactive power, with the angular rotation of the injected voltage phasor are clearly shown in Fig. 4 and Fig. 5.

3. Simulation Results

Simulation was done in MATLAB/SIMULINK and the outcomes are presented. The analysis split into three categories like open loop control, closed loop control and fault analysis.



(a)



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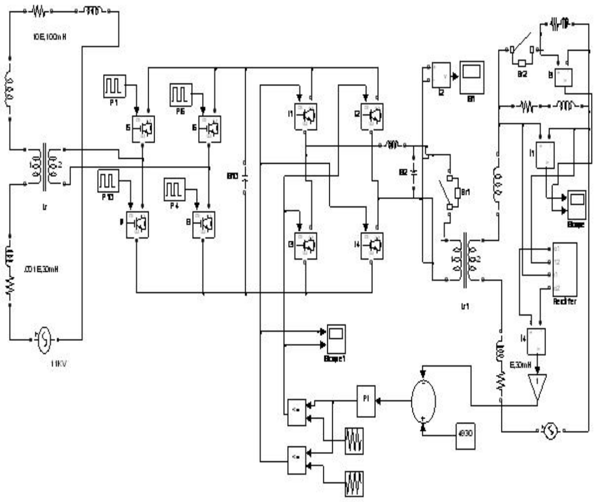

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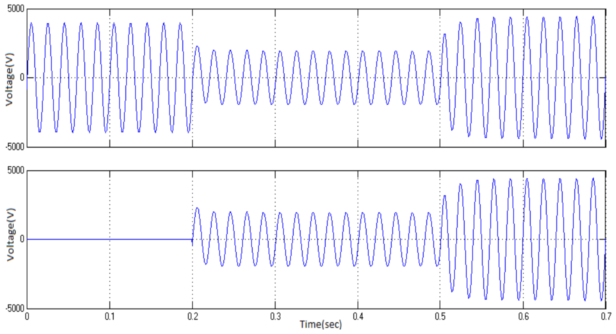

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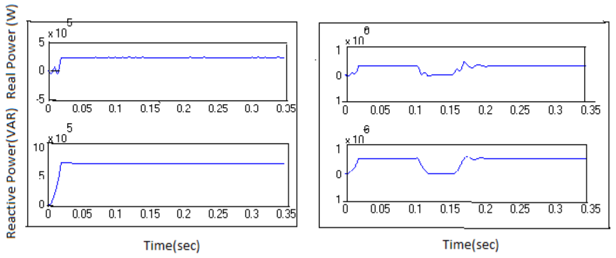


(e)

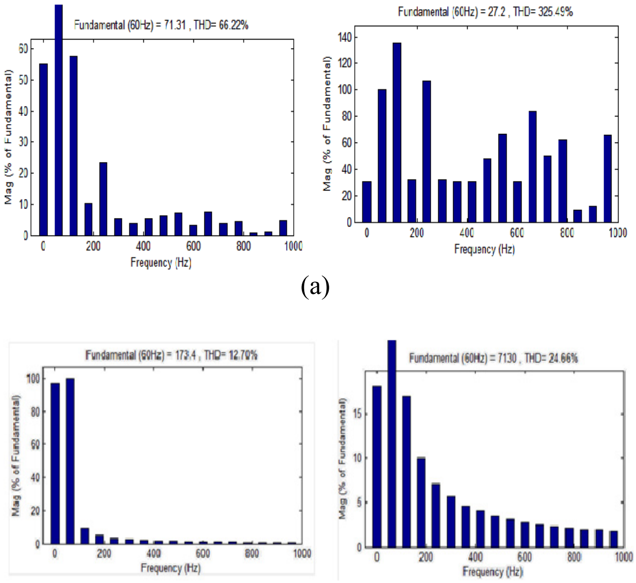
Fig .7. (a) 4-Bus system with IPFC; (b) Rectifier Inverter subsystem; (c) Closed loop circuit; (d) (i) Voltage across load-1, (ii) Voltage across load-2; (e) With compensation the Real and reactive power at load 1 and Load 2 in closed loop control.

3.1 Open loop control

Circuit model of 4-bus system is shown in Fig. 6(a). The current and voltage waveforms are shown in Fig. 6(b). The real and reactive powers are shown in Fig. 6(c). The output voltage of line 2 with additional load is shown in Figs. 6(d-e), where load -1 is constant and load-2 is increased to higher value. The corresponding changes in real and reactive power are shown in Fig. 6(f).

3.2 Closed loop control

The 4-transmission Line system with compensation is shown in Fig. 7(a), and the details of subsystem are shown in Fig. 7(b). The circuit model of closed loop system is shown in Fig. 7(c). The output voltage of load 2 is sensed and it is compared with a reference voltage.The error is fed to a PI controller. The output of the PI is compared with a triangular waveform. To drive IGBTs of the inverters, the outputs of the comparators are used. The voltage across loads 1 and 2 are shown in Fig. 7(d). Similar changes in load -2 are created, when the breaker 2 is closed, the voltage decreases and voltage comes back to normal value due to the action of closed loop system. Also the real power is enhanced due to compensation of IPFC which can prove by comparing Fig. 6(f) and Fig. 7(e), which means that the transient stability is enhanced. But at the same time The THD value at load-2 is becoming worse than the uncompensated line at load-1, which can be improved by placing an LC filter circuit as shown in Fig. 8(c).FFT analysis was done and the spectrum is presented here. The FET analysis shows that the THD value with IPFC is lower than without IPFC that means the power quality of the system is improved. Further improvement in THD is obtained by introducing an LC filter at the load side. All the related waveforms are shown in Figs. 6(a-c). The total harmonic distortion is 0.2%. The filter reduces the harmonics and therefore the heating in the injecting transformer is reduced.



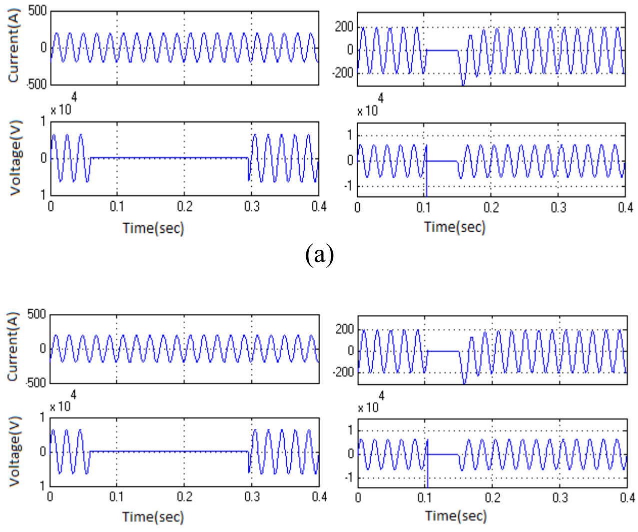
(a)

(a)

Fig. 8. (a) Without compensation the THD of the line current and voltage at load-1; (b) With compensation the THD of the line current and voltage at load-1.

4. Fault Analysis

To study the transient performance of this circuit when a 6-cycle fault is applied at load-2, a fault is simulated by the Breaker block. Switching times are defined in the Breaker block, that is closing at t = 3 cycles and opening at t = 9 cycles that means a line-to-ground fault is applied at t= 3 cycles, and cleared at t=9 cycles. The Fault current and voltage at load-2 is shown in Fig. 9(a). The Real and Reactive power at Load-2 where a fault occurs in the test system-without IPFC and with IPFC are shown in Fig. 9(b) (i-ii). The dip and overshoot in the real power are highly compensated due to the presence of IPFC also the fault clearance time is getting reduced.



(a)

(b)

Fig. 9. (a) (i), (ii) Line current and voltage at Load-2, where faults occur in the test system-without IPFC; (b) (i), (ii) Real and Reactive power at Load-2, where faults occur in the test system-with IPFC

Table 1. Specifications of the test system where the ipfc is to be incorporated

Components	Rating values
AC Voltage Source $_1$	11K V – 0.3KA – 50HZ
AC Voltage Source $_2$	10K V – 0.28KA – 50HZ
Transmission Line	R=0. 012Ω/Km, L=0. 09mH/Km
Series Transformer	250 MW, 315 KV/63 KV
Load $_1$	0.25 MW, 7 MVAR
Load $_2$	0.2 MW, 0.7MVAR

5. Conclusion

In this paper, circuit model of 4 - Bus system is presented. The open loop IPFC circuit model has been developed. A closed loop system circuit model was developed and used for simulation. From the simulation results, it is observed that real power flows from a bus with a higher bus angle to a bus with lower bus angle and the reactive power flows from a bus with higher voltage to a bus with lower voltage.

From the investigation, IPFC is a feasible resolution for paired the powers throughout the transmission lines. A line-to-ground fault is introduced and the response of the test system with and without IPFC is studied and found that the IPFC not only increase the transmission capacity but also improve the transient performance of the system.

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