DIGITAL SIMULATION OF IPFC FOR POWER FLOW USING PSPICE

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Abstract: *Interline Power Flow Controller (IPFC) is a new concept of Flexible AC Transmission System (FACTS) controller with the unique capability for series compensation with the unique capability of power flow management among multi-line of a substation. The IPFC employs a number of Voltage Sourced Converters (VSCs) linked at the same DC terminal, each of which can provide series compensation for the selected line of the transmission system. Through common dc link , any inverters within the IPFC is able to transfer real power to any other and thereby facilitate real power transfer among the line. . Interline Power Flow Controller (IPFC) can control the power flow in a multi-line system. Power imbalance between overloaded and under-loaded lines was corrected. Single phase circuit model for uncompensated system was developed.*

Key words: *FACTS, SSSC, IPFC, PSPICE.*

Fig. 1. IPFC power circuit

1. Introduction

An Interline Power Flow Controller (IPFC), shown in Fig.1, consists of two series VSCs, whose DC capacitors are coupled, allowing active power to circulate between different power lines. When operating below its rated capacity, the IPFC is in regulation mode, allowing the regulation of the P and Q flows on one line, and the Power flow on the other line. In addition, the net active power generation by the two coupled VSCs is zero, neglecting power losses. It can also be regarded as several SSSCs sharing a common DC link [1]. In this way, the power optimization of the overall system can be realized by appropriately transferring power through the common DC link from over-loaded lines to under-loaded lines [2, 3].
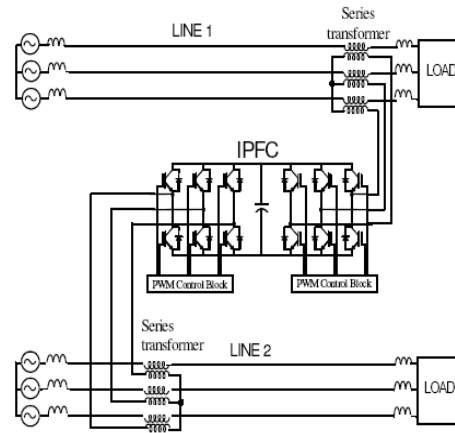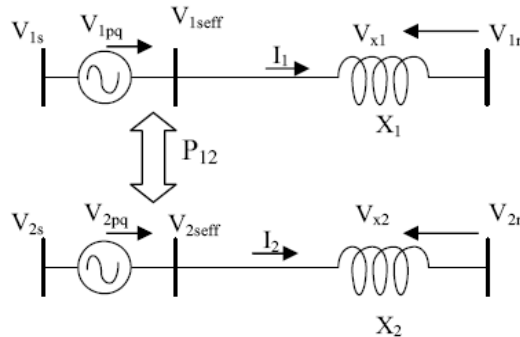

Fig. 2. Basic Two-Inverter Interline Power Flow Controller.

An elementary IPFC scheme consisting of two back-to-back dc to ac inverters is used as a tool to compensate a transmission line by series voltage injection. Two synchronous voltage sources, with phasors $V1_{pq}$ and $V2_{pq}$, in series with transmission line1 and 2 respectively, represent the two back-to-back dc to ac inverters as illustrated in Figure2.The IPFC is

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designed with a combination of the series connected VSC which 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 ($P_{12} = P_{1pq} = -P_{2pq}$) for real power exchange between voltage sources.

Transmission line1, represented by reactance X1, has a sending-end bus with voltage phasor V_{1s} and a receiving end voltage phasor V_{1r}. The sending end voltage phasor of Line2, represented by reactance X_2, is V_{2s} and the receiving end voltage phasor is V_{2r}. Simply, all the sending end and receiving end voltages are assumed to be constant with fixed amplitudes, $V_{1s} = V_{1r} = V_{2s} = V_{2r} = 1$ p.u., and with fixed angles resulting in identical transmission angle $s_1 = s_2$ for the two systems. The two line impedances, and the rating of the two compensating voltage sources, are also assumed to be identical. This means $V_{1pqmax} = V_{2pqmax}$ and $X_1 = X_2$. Although in practice system1 and system2 could be likely different due to different transmission line voltage, impedance and angle. We assumed system1 is arbitrarily selected to be the prime system for which free controllability of both real and reactive line power flow is stipulated to derive the constraints the free controllability of system1 forces on the power flow control of system2. A phasor diagram of system1 illustrated in Figure 3 defines the relationship between V_{1s}, V_{1r}, V_{x1} (the voltage phasor across X_1) and the inserted voltage phasor V_{1pq}, with controllable magnitude and angle. V_{1pq} is added to the sending end voltage $V_{1seff} = V_{1s} + V_{1pq}$. So V_{1seff} V_{1r}, the difference sets the compensated voltage phasor or V_{x1} across reactance X_1. As 1 is varied over its full 360 degree range, the end of phasor V_{1pq} moves along a circle with its center located at the end of phasor $V_{1s.}$ The area within this circle defines the operating range of phasor V_{1pq}.
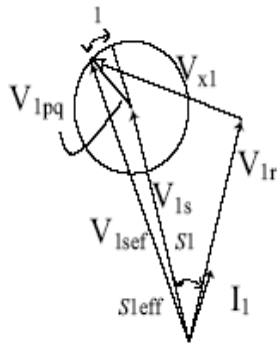

Fig. 3. Phasor diagram of system 1

So line1 can be compensated. The rotation with angle 1of phasor $V1_{pq}$ modulates both the magnitude and the angle of phasor V_{x1} and, therefore, both the transmitted real power, P_{1r}, and the reactive power, Q_{1r}, vary with 1. This process requires the voltage source representing Inverter1 (V_{1pq}) to supply and absorb both reactive, Q_{1pq}, and real, P_{1pq}, power [4, 5].

2. Equivalent Circuit Analysis of IPFC

An IPFC with combining two or more series connected converters working together extends the concepts of voltage and power flow control beyond the hat is achievable with a known one-converter FACTS controller-SSSC.A simplest IPFC consists of two converters, which are connected in series with two transmission lines, respectively. It can control total three power system quantities such as three independent power flows of two lines. Such an IPFC, which is shown in Fig.4 used to shown the basic operation principle for the sake of simplicity. The mathematical derivation is applicable to an IPFC with an arbitrary number of series converters [6].

The equivalent circuit of IPFC consisting two controllable series injected voltage sources is shown in Fig.5. Real power can be exchanged between series converters via the common DC link. The sum of real power exchange should be zero [7].
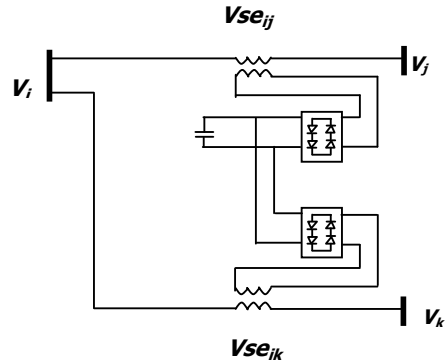

Fig. 4. Operational of IPFC system with two converters

According to the equivalent circuit of the IPFC shown in Fig.5. The power flow equations can be derived as follows

$P_i = V_i^2 g_{ii} - \sum_n V_i V_n (g_{in} cos\theta_{in} + b_{in} sin\theta_{in}) - \sum_n V_i Vse_{in}(g_{in} cos(\theta_i - \theta se_{in}) + b_{in} sin(\theta_i - \theta se_{in}))$ (1)

$Q_i = -V_i^2 b_{ii} - \sum_n V_i V_n (g_{in} sin\theta_{in} + b_{in} cos\theta_{in}) - \sum_n V_i Vse_{in}(g_{in} sin(\theta_i - \theta se_{in}) - b_{in} cos(\theta_i - \theta se_{in}))$ (2)

$$P_{ni}=V_n^2 g_{nn}\ -V_i V_n(g_{in}cos(\theta_n-\theta_i)+b_{in}sin(\theta_n\theta_i))$$
$$+V_n Vse_{in}(g_{in}cos(\theta_n-\theta_{se_{in}})+b_{in}sin(\theta_n-\theta_{se_{in}}))$$
$$(3)$$

$$P_{ni}=-V_n^2 b_{nn}\ -V_i V_n(g_{in}sin(\theta_n-\theta_i)-b_{ij}cos(\theta_n-\theta_i))$$
$$+V_n Vse_{in}(g_{in}sin(\theta_n-\theta_{se_{in}})-b_{in}cos(\theta_n-\theta_{se_{in}}))$$
$$(4)$$

Where $g_{in}+jb_{in}=1/Zse_{in}$, $g_{nn}+b_{nn}=1/Zse_{in}$,
$g_{ii=}\sum_n g_{in}$, $b_{ii}=\sum_n b_{in}$

Where $n=j,k,\ldots\ldots$
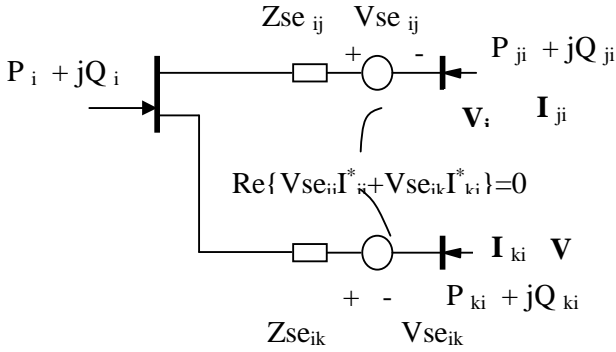
Fig. 5. The Equivalent circuit of IPFC

According to the operating principle of IPFC, The operating constraint representing active power change between series connected converters via the common DC link is given bellow.

$$PE=Re(\sum_n Vse_{in}I^*_{ni})=0 \qquad (5)$$
Where $n=j,k,\ldots\ldots$

The equivalent controllable injected voltage source bound constrains are given bellow
$$Vse_{in}^{min}\leq Vse_{in}\leq Vse_{in}^{max}$$
$$(6)$$
$$Qse_{in}^{min}\leq Qse_{in}\leq Qse_{in}^{max}$$

3. Simulation of IPFC System

Upper and lower lines are referred to as Line-1 and Line-2 respectively. Line-1 and Line-2 are connected by coupling transformers at the sending end. Diode Bridge, capacitor and VSC form the link permitting the real power transfer between lines. The circuit model of uncompensated system is shown in Fig.6.It is assumed that Line-1 is overloaded and Line-2 is under-loaded. During normal operating condition Line-1 and Line-2 are decoupled with the isolation of the coupling transformers.
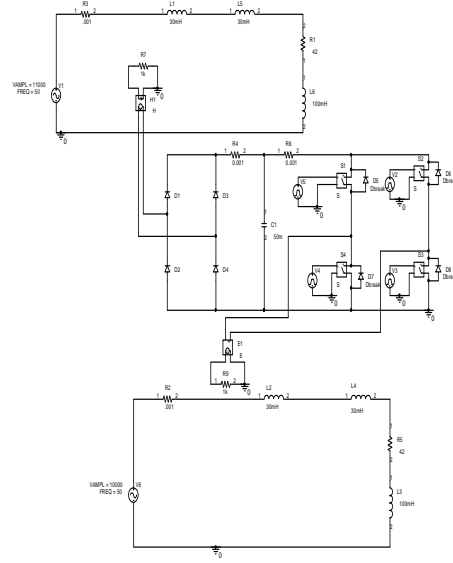
Fig. 6. Uncompensated System

Overloaded/ under-loaded Line-1 and Line-2 are linked by the dc Link via respective coupling transformers. Line-1 being overloaded will setup dc Link voltage depending on the extent of overload. VSC converts the dc to ac of required magnitude and phase angle due to self commutating nature of the power devices. Injected voltage modifies the sending end voltage to correct the under-loaded condition of the Line-2.

For uncompensated line

$$V_R=V_S-V_X \qquad (7)$$

$$I=V_S/(X+X_L+R_L) \qquad (8)$$

For compensated line
$$V_R=V_S+V_{pq} \qquad (9)$$

4. Simulation Results

Line-1 and Line-2 are assumed to be operating at 11KV and 10KV respectively. Operating status of Line-1 is overloaded and Line-2 is under-loaded. Lines 1 & 2 are connected to identical loads. Both are identical lines. For uncompensated condition IPFC is disabled as the coupling transformers are disconnected from the lines.
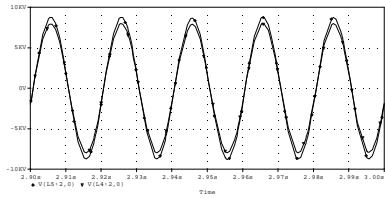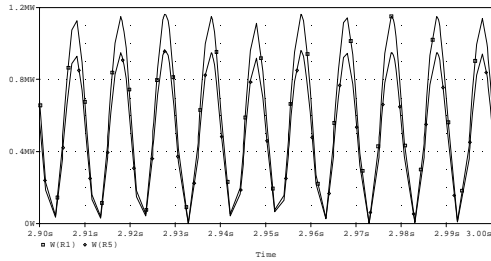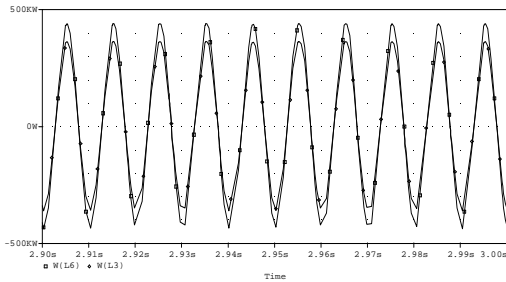
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Fig. 7a. Voltages

Fig. 7b. Real Powers

Fig. 7c. Reactive Powers

Fig. 7. Simulation Results of Uncompensated System

The Uncompensated system is shown in Fig4.The voltages V_{1R}&V_{2R} are shown in Fig 7a.The real power waveforms for P_1 & P_2 are shown in Fig.7b.The reactive power waveforms for Q_1&Q_2 are shown in Fig.7c.The circuit model of compensated system is shown in Fig.8 The wave forms with $\rho = -90°$ are shown in Fig 8a to 8f. The wave forms with $\rho = -180°$ are shown in Fig 9a to 9e.
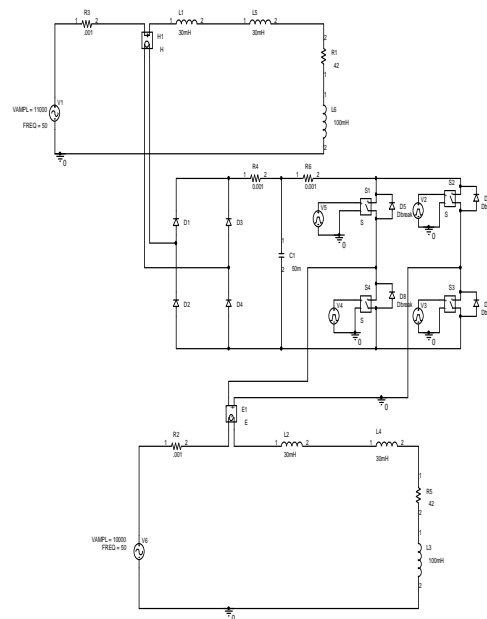
Fig. 8. Circuit Model for Compensated System

Compensated condition of IPFC is enabled by connecting the coupling transformers to the lines to form the dc link between Lines-1 & 2. Simulation results for ρ=-90° and -180°,-270° and 0°are presented in Table.1.
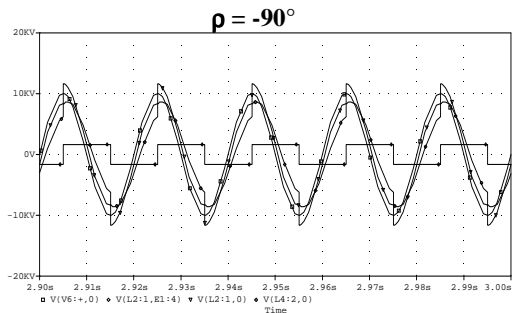

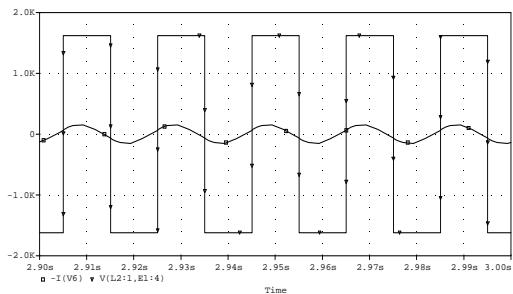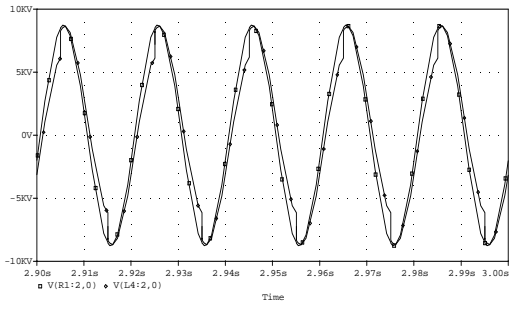Fig. 8a. V_{2S}, V2pq, V_{2Seff}, V_{2R}
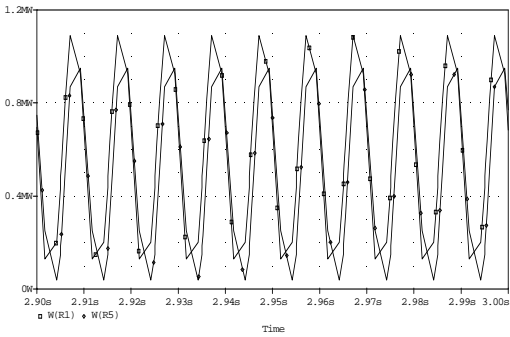

Fig. 8b. I2, V_{2pq}

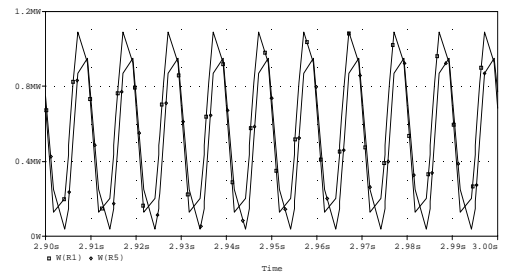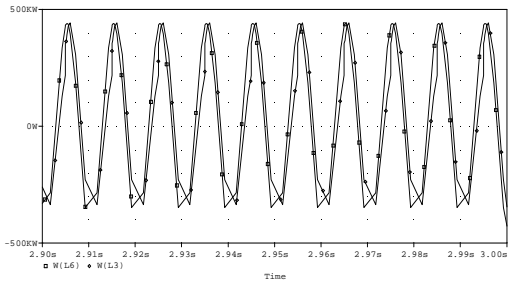Fig. 8c. V_{1R}, V_{2R}
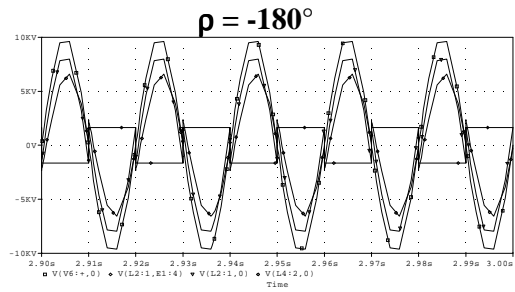

Fig. 8d. V_{1R}, V_{2R}

Fig. 8e P1,P2

Fig 8f . Q1, Q2

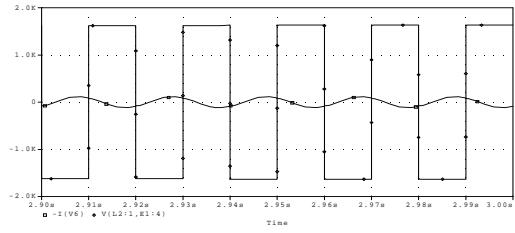$\rho = -180°$

Fig. 9a. V_{2S}, V_{2pq}, V_{2Seff}, V_{2R}
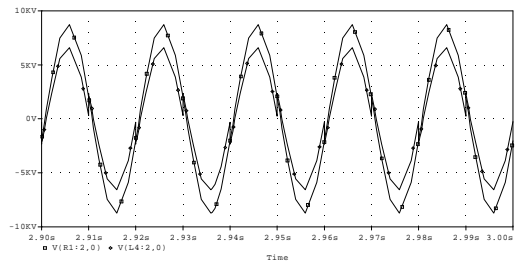

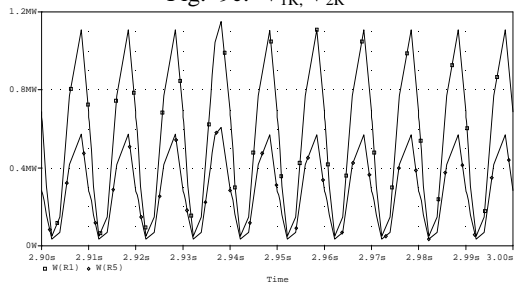Fig. 9b. I2, V_{2pq}
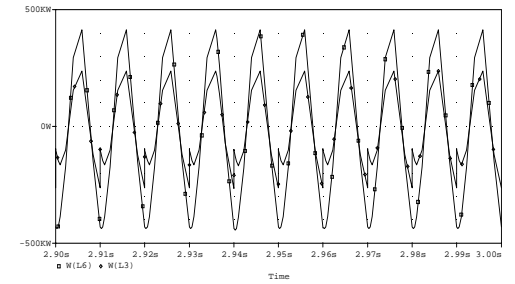

Fig. 9c. V_{1R}, V_{2R}

Fig. 9d. P1,P2

Fig. 9e. Q1,Q2

When ρ varies from 0° to -180° on Line-2 P2 and Q2 decreases and for 'ρ' from -180° to 0° on Line-2, (under-loaded) P2 & Q2 increases. P2 and Q2 attains maximum value for 'ρ' between -270° and 0°. The power transfer capability of Line-2 increases due to addition of IPFC.

Table. 1. Summary of voltages & powers

Compensation	V_{1S} KV	V_{2S} KV	V_{1R} KV	V_{2R} KV	P_1 MW	P_2 MW	Q_1 KW	Q_2 KW
Without	11	10	8.5	7.5	1.1	0.9	450	350
ρ=-90˚	11	10	8.5	8.5	1.1	0.9	420	420
ρ=-180˚	11	10	8.5	6.5	1.1	0.6	400	200
ρ=-270˚	11	10	8.5	9.0	1.1	0.9	420	500
ρ=0˚	11	10	8.5	9.0	1.0	1.2	350	400

5. Conclusion

Interline Power Flow Controller (IPFC) is a VSC based series compensation type FACTS controller. IPFC is used to balance the power in two or more lines originating from a sub-station. In this paper IPFC capable of balancing the power in a overloaded line and a under-loaded line is simulated. Simulated results demonstrate the power transfer capability of IPFC between two lines through dc link. IPFC system is successfully simulated for different angles of injection. The simulation results agree with the analytical results.

6. References

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