Modelling of Unified Power Flow Controller into Power Systems using P-Spice

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Abstract - ***Flexible AC Transmission Systems*** **(FACTS) use power electronic components to enhance controllability and capability of electrical power system. FACTS devices are able of opportunely modify voltage, phase angle and/or impedance and then the power flows at particular points in power systems [1-2].**

One of the more intriguing and potentially most versatile class of FACTS device is the *Unified Power Flow Controller* (UPFC).

Two are the main purposes of this paper. The first one is to illustrate a UPFC model with two separate control systems for the shunt and the series inverters realising an appropriate co-ordination between them. The second purpose is to implement this UPFC model using the P-Spice (Simulation Program with Integrated Circuit Emphasis) as simulation program.

Keywords: FACTS, power flow controller, UPFC, P-Spice.

I. INTRODUCTION

The deregulation and competitive environment in the contemporary power networks will imply a new scenario in terms of load and power flows condition and so causing problems of line transmission capacity. But, nowadays some problems exist to change the present structure of transmission system. So, the need for new power flow controllers capable of increasing transmission capacity and controlling power flows through predefined transmission corridors will certainly increase.

For this reason, as well known in recent years a new class of controllers, *Flexible AC Transmission System* (FACTS) controllers has rapidly met with favour. Indeed, the two main objectives of FACTS technology are to control power flow and increase the transmission capacity over an existing transmission corridor [1].

Nowadays, the improvements in the field of power electronics have had a major impact on the development of this technology. So, a new generation of FACTS controllers has emerged. The devices of this generation are based on the use of high power electronic components such as GTO (Gate Turn-Off thyristors) and IGBT (Insulated Gate Bipolar Transistor) which makes them respond quickly to the control inputs. So, these FACTS devices are able to act almost instantaneously to changes in power system [2].

Representative of the last generation of FACTS devices is the *Unified Power Flow Controller* (UPFC). The UPFC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle). Such "new" FACTS device combines together the features of two "old" FACTS devices: the *Static Synchronous Compensator* (STATCOM) and the *Static Synchronous Series Compensator* (SSSC) [3-6]. In practice, these two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer, connected to each other by a common dc link including a storage capacitor. The shunt inverter is used for voltage regulation at the point of connection injecting an opportune reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line. The series inverter can be used to control the real and reactive line power flow inserting an opportune voltage with controllable magnitude and phase in series with the transmission line. Thereby, the UPFC can fulfil functions of reactive shunt compensation, active and reactive series compensation and phase shifting [6]. Besides, the UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system.

As the need for flexible and fast power flow controllers, such as the UPFC, is expected to grow in the future due to the changes in the electricity markets, there is a corresponding need for reliable and realistic models of these controllers to investigate the impact of them on the performance of the power system. Different UPFC models have been investigated by several authors [5-7].

The main purposes of the paper has been firstly to illustrate a UPFC model with two separate control systems for the shunt and the series inverters realising an appropriate co-ordination between them, and then to describe the implementation of that UPFC model using P-Spice (Simulation Program with Integrated Circuit Emphasis) as simulation program.

P-Spice has been used as programming environment for its peculiarities in transient analysis, and its ease in the implementation. This permits more simple but at the same time realistic simulations to perform a preliminary analysis of the impact of a UPFC on the performance of a power system.

In particular, in the paper the UPFC characteristics are delineated, the proposed UPFC model is described, the control systems of the shunt and series inverters are discussed and, finally the P-spice implementation of UPFC model and some simulation results to test the proposed UPFC P-Spice model are illustrated.

II. UPFC CHARACTERISTICS

The basic components of the UPFC are two voltage source inverters (VSI's) sharing a common dc storage capacitor, and connected to the system through coupling transformers. One VSI is connected in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer. A basic UPFC functional scheme is shown in Fig.1.

The series inverter is controlled to inject a symmetrical three phase voltage system, v_{se}, of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor V_{dc} constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the two inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flow on the transmission line.

The UPFC has many possible operating modes. In particular, the shunt inverter is operating in such a way to inject a controllable current i_{sh} into the transmission line. This current consist of two components with respect to the line voltage: the real or direct component i_{shd}, which is in phase or in opposite phase with the line voltage, and the reactive or quadrature component, i_{shq}, which is in quadrature. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The quadrature component, instead, can be independently set to any desired reference level (inductive or capacitive) within the capability of the inverter, to absorb or generate respectively reactive power from the line. So, two control modes are possible:

- *VAR control mode*: the reference input is an inductive or capacitive var request;
- *Automatic Voltage Control mode*: the goal is to maintain the transmission line voltage at the connection point to a reference value.

Instead, the series inverter injecting the voltage v_{se} controllable in amplitude and phase angle in series with the transmission line influences the power flow on the transmission line. This series voltage can be determined in

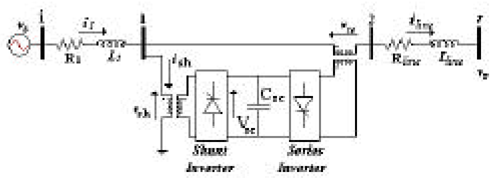

Fig. 1 UPFC functional scheme

different ways:

- *Direct Voltage Injection mode*: the reference inputs are directly the magnitude and phase angle of the series voltage;
- *Phase Angle Shifter Emulation mode*: the reference input is phase displacement between the sending end voltage and the receiving end voltage;
- *Line impedance emulation mode*: the reference input is an impedance value to insert in series with the line impedance;
- *Automatic Power flow Control mode*: the reference inputs are values of P and Q to maintain on the transmission line despite system changes.

In general the shunt inverter will be operated in Automatic Voltage Control mode and the series inverter in Automatic Power Flow Control mode.

III. UPFC MODEL

A. *Instantaneous power flow delivered by a VSI into a power system*

An inverter connected to a power system, which is able of power exchange between the power system and the dc storage capacitor, can be represented by a three symmetrical sinusoidal voltage sources.

A symmetrical three-phase system can be transformed into a synchronously-rotating orthogonal system. A new co-ordinate system, having the axes rotating at the synchronous angular speed of the fundamental network voltage ω, is defined on the basis of the d-q transformation. In the Fig. 2. a VSI is supplied by a voltage system v_{xa}, v_{xb}, v_{xc}, R and L are respectively the transformer equivalent resistance and inductances. The d-q transformation of the supply voltage system v_x is made using the following equations:

$$\begin{bmatrix} v_{xds} \\ v_{xqs} \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} v_{xa} \\ v_{xb} \\ v_{xc} \end{bmatrix} \quad \theta = \tan^{-1}\left(\frac{v_{xqs}}{v_{xds}}\right) \qquad (1)$$

$$\begin{bmatrix} v_{xd} \\ v_{xq} \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\vartheta - \frac{2}{3}\pi\right) & \cos\left(\vartheta + \frac{2}{3}\pi\right) \\ -\sin\theta & -\sin\left(\vartheta - \frac{2}{3}\pi\right) & -\sin\left(\vartheta + \frac{2}{3}\pi\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} v_{xa} \\ v_{xb} \\ v_{xc} \end{bmatrix} \qquad (2)$$

On the basis of this d-q transformation, the instantaneous active and reactive power flowing into the power system delivered by the VSI, neglecting transformer losses and assuming fundamental frequency and balanced conditions, and $v_{xd}=|v_{xa}|$, $v_{xq}=0$ are[6]:

$$p_x(t)=\frac{3}{2}v_{xd}\times i_{xd} \qquad q_x(t)=\frac{3}{2}v_{xd}\times i_{xq} \tag{3}$$

B. Series and Shunt inverter control

In the paper it has been chosen a UPFC model in terms of two ideal controllable voltage sources, connected respectively in series and in shunt to the transmission line as in Fig. 3, to represent respectively the series and the shunt inverters. So, the two UPFC control systems must be developed in such a way to evaluate the amplitude and the phase angle of these two voltage sources on the basis of operating functions required UPFC. Assuming the series inverter is operating in Automatic Power Flow Control mode, the amplitude and phase angle of the equivalent series voltage source are determined in such a way to control the power flows on the transmission line and so to obtain the active and reactive power flows desired at the receiving end. Instead, for the shunt inverter operating in Automatic Voltage Control or in VAR Control mode, the amplitude and phase angle of the equivalent shunt voltage source are calculated in such a way to control the voltage on the connection point (v_1) or to generate or absorb a specific reactive power at this point respectively and naturally to supply or absorb the active power demanded by the series inverter. On the basis of (3) the instantaneous power flow at the receiving end, assuming v_{rd} equal to the receiving end voltage amplitude v_r and $v_{rq}=0$ results:

$$p_r(t)=\frac{3}{2}v_{rd}\times i_{dline} \qquad q_r(t)=\frac{3}{2}v_{rd}\times i_{qline} \tag{4}$$

where i_{dline} and i_{qline} are respectively the values of the d-q line current components. So, it's possible to calculate the reference values of the d-q line current components as follows:

$$i^*_{dline}=\frac{2}{3}\frac{p^*_r}{v_{rd}} \quad i^*_{qline}=\frac{2}{3}\frac{q^*_r}{v_{rd}} \tag{5}$$

where p^*_r and q^*_r are the instantaneous active and reactive power flow required the receiving end. At the same way, the instantaneous active and reactive power flows provided by the shunt inverter at the connection point are:

$$p_{sh}(t)=\frac{3}{2}v_{1d}\times i_{dsh} \qquad q_{sh}(t)=\frac{3}{2}v_{1d}\times i_{qsh} \tag{6}$$

assuming v_{1d} equal to the sending end voltage amplitude v_1 and $v_{1q}=0$ and with i_{dsh} and i_{qsh} the d-q current components injected by shunt inverter into the transmission line. So, the reference values of these two current components are evaluated as follows:

$$i^*_{dsh}=\frac{2}{3}\frac{p^*_{sh}}{v_{1d}} \quad i^*_{qsh}=\frac{2}{3}\frac{q^*_{sh}}{v_{1d}} \tag{7}$$

where p^*_{sh} and q^*_{sh} are the instantaneous active and reactive power flow required to the shunt inverter. In the paper these control systems are based on the classical "decoupled watt-var algorithm" using the d-q axis decomposition above illustrated [6-7]. So, the implemented control schemes for the series and the shunt inverter are shown respectively in Fig. 4.-5.

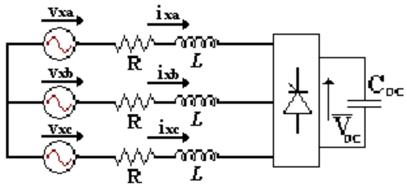

Fig. 2. Equivalent circuit of a VSI connected to a power system

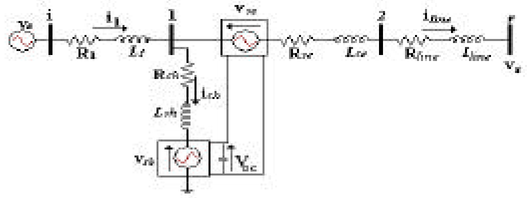

Fig. 3. UPFC equivalent circuit

The input values for the series inverter control system for the independent control of active and reactive power at the receiving end (p_r, q_r) of the power system are: instantaneous values of the sending and receiving end voltages and the line current, and the reference values p^*_r and q^*_r. The output variables x_{1se} and x_{2se} associated to the control scheme of Fig. 4. are used to evaluate the d-q components of the series inverter equivalent output voltage source, v_{sed} and v_{seq}, by the following equations:

$$\begin{aligned} v_{sed} &= (v_{1d}-v_{rd})-\frac{L'_{se}}{\omega}x_{1se} \qquad L'_{se}=\frac{\omega L}{z_b} \\ v_{seq} &= (v_{1q}-v_{rq})-\frac{L'_{se}}{\omega}x_{2se} \Rightarrow v_{seq}=-v_{rq}-\frac{L'_{se}}{\omega}x_{2se} \end{aligned} \tag{8}$$

assuming the d-axis is always coincident with the voltage amplitude at the sending end, $v_{1d}=|v_1|$, $v_{1q}=0$, the quantities expressed in per-unit, L the value of the combined series inductance of the line and series transformer as follows:

$$L=L_{line}+L_{se} \tag{9}$$

z_b the base-impedance that is $z_b=v_b/i_b$ where v_b and i_b are the chosen voltage and current base values for the power system. So, the amplitude and the displacement angle with respect to the voltage v_1-v_r of the equivalent voltage source of the series inverter are evaluated as follows:

$$|V_{se}|=\sqrt{v_{sed}^{\,2}+v_{seq}^{\,2}} \quad \alpha_{se}=arc\tan\frac{v_{seq}}{v_{sed}} \tag{10}$$

In VAR control mode the input values for the shunt inverter control system to control the active and reactive power flow provided to the sending end (p_{sh}, q_{sh}) are: instantaneous values of sending end voltage v_1, the instantaneous value of the current injected by shunt inverter i_{sh} into the transmission line, the reference value q^*_{sh} and the value of the active power p^*_{sh} evaluated so to balance the active power exchange between the series inverter and the transmission line.

As before, the output variables x_{1sh} and x_{2sh} associated to the control scheme of Fig. 5. are used to evaluate the d-q components of the shunt inverter equivalent output voltage source, v_{shd} and v_{shq}, by the following equations:

$$v_{shd} = v_{1d} - \frac{L'_{sh}}{\omega} x_{1sh}$$

$$v_{shq} = v_{1q} - \frac{L'_{sh}}{\omega} x_{2sh} \Rightarrow v_{shq} = -\frac{L'_{sh}}{\omega} x_{2sh} \qquad L'_{sh} = \frac{\omega L_{sh}}{z_B} \qquad (11)$$

assuming the d-axis is always coincident with the voltage amplitude at the sending end, $v_{1d}=|v_1|$, $v_{1q}=0$, the quantities expressed in per-unit, L_{sh} the value of the shunt transformer leakage inductance. So, the amplitude and the displacement angle with respect to the voltage v_1 of the equivalent voltage source of the shunt inverter are calculated as follows:

$$|V_{sh}| = \sqrt{v_{shd}^2 + v_{shq}^2} \quad \alpha_{sh} = arc\tan\frac{v_{shq}}{v_{shd}} \qquad (12)$$

In both control schemes the constants of the PI controller are calculated as follows:

<u>for the series control scheme</u>

$$K_{pse} = \frac{1}{T} \quad K_{ise} = \frac{R_{se} + R_{line}}{L_{se} + L_{line}} \omega \frac{1}{T} \quad K_{se} = \frac{R_{se} + R_{line}}{L_{se} + L_{line}} \omega \qquad (13)$$

<u>for the shunt control scheme</u>

$$K_{psh} = \frac{1}{T} \quad K_{ish} = \frac{R_{sh}}{L_{sh}} \omega \frac{1}{T} \quad K_{sh} = \frac{R_{sh}}{L_{sh}} \omega \qquad (14)$$

where the time constant T is equal to about 0.5ms or less in dependence of inverter characteristics, (R_{se}, L_{se}), (R_{sh}, L_{sh}) represent respectively the equivalent impedance of the series and shunt transformer and (R_{line}, L_{line}) the line equivalent impedance.

C. Inverter control technique

There are two basic strategies that can be utilised to control the GTO switching of an inverter. One approach involves multi-connected out of phase inverters with a common dc source and coupled through appropriate magnetic circuits [9]. Another approach is to use PWM switching techniques. In the paper the second control technique has been considered. In this case the three phases of the output inverter voltage result:

$$\begin{aligned} v_{y_a} &= \frac{1}{2} m_y V_{dc} sin(\omega t + \alpha_y + \theta) \\ v_{y_b} &= \frac{1}{2} m_y V_{dc} sin(\omega t + \alpha_y + \theta - \frac{2}{3}\pi) \\ v_{y_c} &= \frac{1}{2} m_y V_{dc} sin(\omega t + \alpha_y + \theta - \frac{4}{3}\pi) \end{aligned} \qquad (15)$$

where y is equal to "se" for the series inverter and "sh" for the shunt inverter. In (15) m_y is the index of modulation and α_y is the phase displacement with respect to v_1 for the shunt inverter and with respect to (v_1-v_r) for the series inverter and V_{dc} is the value of the voltage across the storage capacitor.

Moreover the following relations are valid:

$$m_y = 2\sqrt{2}\,\frac{\sqrt{v_{yd}^2 + v_{yq}^2}}{V_{dc}} \qquad \alpha_y = \tan^{-1}\left(\frac{v_{yq}}{v_{yd}}\right) \qquad (16)$$

where v_{yd} and v_{yq} are calculated by (8) and (11) respectively for the series and the shunt inverter.

D. DC-side control

For normal operation of two VSI's in an UPFC, the dc voltage across the dc storage capacitor C_{dc} must be kept constant. This implies that the active power exchanged between the UPFC and the power system is zero at steady-state operation:

$$p_{se} + p_{sh} = 0 \qquad (17)$$

that is, the active power delivered by the shunt inverter p_{sh} is equal to the active power exchange between the series inverter and the transmission line, p_{se}. Hence, a dc voltage control system must be realised to keep V_{dc} constant by taking the actual value of V_{dc} as the feedback signal against a dc reference signal V^*_{dc}, as in Fig. 6. The resulting dc voltage error processed by a proportional controller is added to a pre-value of the active power exchanged between the series inverter and the transmission line, p^*_{se} evaluated on the basis of the reference value of d-q line current components. So, the quantity p^*_{se} is calculated as follows:

$$\begin{aligned} p_{se} &= 3|V^*_{se}| * |V_1 - V_r| / X_{se} sin\alpha_{se} \\ |V^* se| &= \sqrt{v^{*2}_{sed} + v^{*2}_{seq}} \quad \alpha_{se} = arc\tan\left(v^*_{seq} / v^*_{sed}\right) \\ v^*_{sed} &= v_{1d} - v_{2d} - (R_{tse} + R_{line}) i^*_{dline} + (X_{tse} + X_{line}) i^*_{qline} \\ v^*_{seq} &= v_{1q} - (R_{tse} + R_{line}) i^*_{qline} - (X_{tse} + X_{line}) i^*_{dline} \end{aligned} \qquad \textbf{(18)}$$

assuming a series transformer voltage ratio unitary.

The output signal of this control system is the reference value for the active power which must provided by the shunt inverter, p^*_{sh}. Moreover, using (17) and computing p_{se} by (18) but now respect the actual d-q line current components, i_{dline} and i_{qline}, and p_{sh} as follows:

$$p_{sh} = 3|V_{sh}||V_1| / \omega L_{sh} * sin\alpha_{sh} \qquad (19)$$

we have at steady state:

$$\frac{dv_{dc}}{dt} = \frac{p_{se} + p_{sh}}{C_{dc} v_{dc}} \qquad (20)$$

assuming negligible the losses of the shunt and series inverters and coupling transformers.

So, the actual value of the dc capacitor voltage is computed using (20).

IV. P-SPICE MODEL AND SIMULATION RESULTS

In Appendix, in Fig. 8-9 the P-Spice code that implements the two control systems of the series and the shunt inverters is reported. It can be observed ideal current generator controlled in voltage and ideal voltage generator controlled in voltage have been used. Instead, in Fig. 10. the P-Spice code that implements the dc control system is showed.

A simple infinite bus test system introduced in [9]is used here to validate the UPFC model implemented using P-Spice as simulation program. The test power system operates at 112 kV and is shown in Fig. 7. The generator is assumed to be an ideal voltage source behind an equivalent Thevenin impedance. The UPFC model is located at the sending end of the transmission line and is controlled in such a way to follow the changes in reference values of the line active and reactive power, and the reactive power of its shunt inverter.

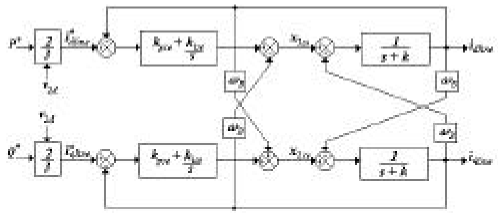

Fig. 4. UPFC- series inverter control scheme

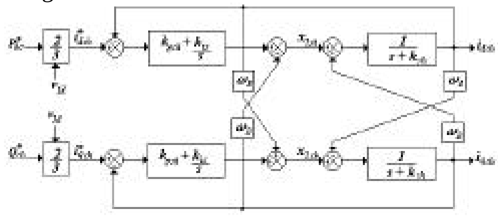

Fig. 5. UPFC- shunt inverter control scheme

In particular, the UPFC series inverter is designed to maintain a power flow at the receiving end at 0.15 p.u. from 50ms up to 550ms and after at 0.2 p.u. as in Fig. 11, and a reactive power flow is required of 0.1 p.u. as in Fig. 12. Moreover, a demand of 0.1 p.u. of shunt reactive power flow at the sending end is delivered by the shunt inverter, Fig. 13. During simulation the active power exchange between the series inverter and the power system is compensated by the active power exchange of the shunt inverter, evaluated by the dc control system, so to maintain the dc voltage across the storage capacitor constant at the specified value as in Fig. 14.

V. CONCLUSIONS

This paper after a brief summary of the principal characteristics of a UPFC, illustrates in detail the proposed UPFC model with two separate control systems for the series and shunt inverters and a control for their co-ordination. Finally, the implementation of this model using P-Spice as simulation program is shown and some simulation results are illustrated to validate the implemented P-Spice UPFC model. The results are obtained for a PWM-based control technique, but it's very simple to modify the inverter control technique such as phase control. The next aim of authors is to modify the illustrated UPFC P-Spice model in such a way to be able to perform a damping oscillation operating function.

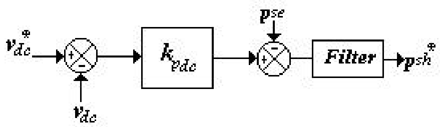

Fig. 6. dc voltage regulator scheme

Fig. 7. Test system

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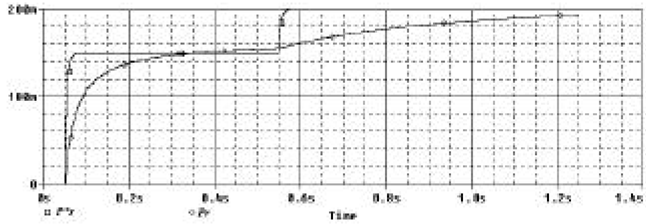

Fig. 11 Active power flow at the receiving end.

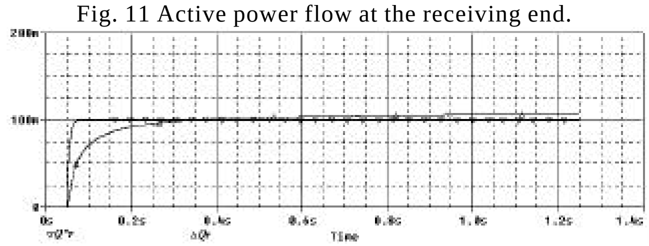

Fig. 12 Reactive power flow at the receiving end.

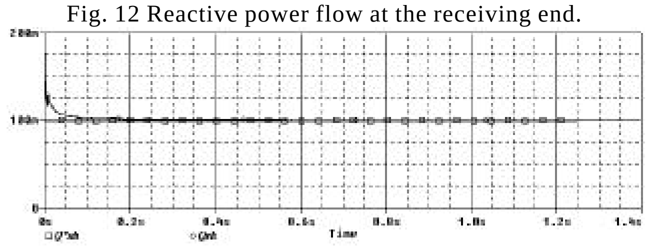

Fig. 13 Reactive power flow at the sending end.

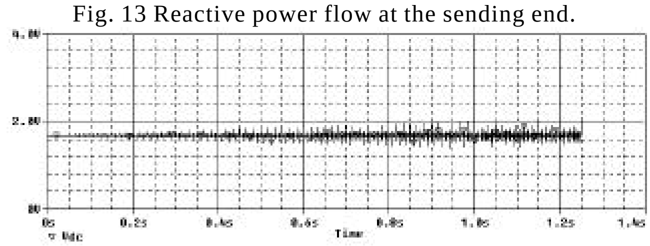

Fig. 14 dc voltage across the storage capacitor.

VII. APPENDIX

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******************************** Series Inverter control****************************************
Gqse    0  10  value={2/3*Qse/V(38)}  *******where V(38) is the direct component of the voltage ***********
*******************at the receiving end vr and Qse is the demand of line reactive power flow************
RIqse   10  0  1
Gq1se   0  11 value={V(10) - V(15)}
RIq1se  11  0  1
Gq2se   0  12 Laplace {V(11)}={kp + ki/s}
RIq2se  12  0  1
…………………………………………………….
Gdse    0  16  value={2/3*Pse/V(38)}  ***** and Pse is the demand of line active power flow *************
RIdse  16  0  1
Gd1se  0  17 value={V(16) - V(21)}
RId1se 17  0  1
Gd2se  0  18 Laplace {V(17)}={kpse + kise/s}
RId2se 18  0  1
Gdose  0  21 Laplace {V(20)}={1/(s+kse)}
RIdose 21  0  1
************************* Equivalent voltage source of the series inverter**************************
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Fig. 8. P-Spice code of the series inverter control

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******************************** Shunt Inverter control****************************************
Gqsh    0  22  value={2/3*Qsh/V(44)}  ******where V(44) is the direct component of the voltage ************
*******************at the sending end vr and Qsh is the demand of shunt reactive power flow************
RIqsh   22  0  1
Gq1sh   0  23 value={V(22) - V(27)}
RIq1sh  23  0  1
Gq2sh   0  24 Laplace {V(23)}={kpsh + kish/s}
RIq2sh  24  0  1
Gqosh   0  27 Laplace {V(26)}={1/(s+ksh)}
RIqosh  27  0  1
Gdsh    0  28  value={2/3*V(68)/V(44)}  ******where V(68) is the output of dc control *****************
RIdsh   28  0  1
………………………………………………………….
Gd2sh   0  30 Laplace {V(29)}={kp + kish/s}
RId2sh 30  0  1
…………………………………………………….
Gdosh   0  33 Laplace {V(32)}={1/(s+ksh)}
RIdosh 33  0  1
```

Fig. 9. P-Spice code of the shunt inverter control

```
************************************dc Control system*************************************
Edcerr    63  0  value={(Vdcs/tensb-V(60))}  ********************************V(60)=value of dc voltage
REdcerr 63  0  1
Ep       64  0  Laplace {V(63)}{kpdc/(1+s*kidc)}
Rep      64  0  1
Ersed    65  0  value={V(44)-V(38)-((0.861+2*3.0159)/zb)*V(16)+(wb*(23.78m+2*19.73m)/zb)*V(10)}
REsed  65  0  1
Erseq    66  0  value={V(45)-(wb*(23.78m+2*19.73m)/zb)*V(16)-((0.861+2*3.0159)/zb)*V(10)}
REseq 66  0  1
Eps      67  0  value={3*ase/xse*sqrt(pwr(V(65),2)+pwr(V(66),2))*sin(arctan(V(66)/V(65))+(pi/2)*(1-
+sgn(V(65)))*sgn(V(66)))*sqrt(pwr((V(44)-V(38)),2)+pwr((V(45)-V(39)),2))/sqrt(2)}   * active power exchange
```

Fig. 10. P-Spice code of the dc voltage control