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Modeling and Control of C-UPFC for Power System Transient Studies

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Abstract: - This paper presents the transient model of a new FACTS device, the center node unified power flow controller(C-UPFC), installed at the midpoint of a transmission line. The C-UPFC consists of three voltage source inverters (VSI) with common DC link. One of the converters is connected in parallel at the midpoint of line and the other two converters are connected in series. The simulation results indicate that the C-UPFC is capable of independently controlling the active and reactive power flows at the both ends of line and the magnitude of AC voltage at mid point of line. It is shown that by adding a supplementary signal to the shunt inverter control system, it is possible to balance line current too.

Key-Words: - FACTS, Transient Model, UPFC, C-UPFC, Line Current Balancing

1 Introduction

The concept of the flexible AC transmission systems (FACTS) based on the power electronics converters has introduced many possibilities for fast controlling and optimization of electric power flow in transmission lines and improving the power quality of distribution subsystems [1]. The FACTS devices can be categorized as:

a. Transformer based devices (e.g., Inter Phase Controllers) [2].
b. Thyristor based devices (e.g., Thyristor Controlled Series Capacitor) [3].
c. Self commutated based devices (e.g., STATIC Compensator [4], Static Synchronous Series Compensator [5, 6], Unified Power Flow Controller [7, 8]).

The UPFC is the most elegant device of FACTS controllers. It consists of two voltage source converters with one common DC link capacitor. The converters are connected in parallel and in series. Each converter can independently generate or absorb reactive power. This arrangement enables control of active and reactive power. The ordinary UPFC has 4 control variables (phase and magnitude of shunt and series converters). Using these control variables it is possible to control the line active power flow, sending or receiving end reactive power, shunt converter AC bus voltage and DC link voltage [9, 10]. Because of the limited number of control variables, the ordinary UPFC is not capable of controlling the line active and reactive powers of two machine system, simultaneously. To overcome this problem, a new topology of UPFC has been used. This new FACTS device is named center node UPFC (C-UPFC) installed at the midpoint of transmission line [11]. The proposed device consists of three IGCT based voltage source converters (see Fig.1). A shunt converter is connected at the midpoint of two series connected converters. In this paper the capabilities of this device will be discussed. It will be shown that this device can control the active and reactive powers of receiving and sending ends and simultaneously can regulate the midpoint voltage magnitude and DC link voltage. Also, in [11] C_UPFC with 2 DC links is presented for the steady state applications. In this paper the transient model of C_UPFC and its application for the line current balancing is presented and the suggested device needs only one DC link.

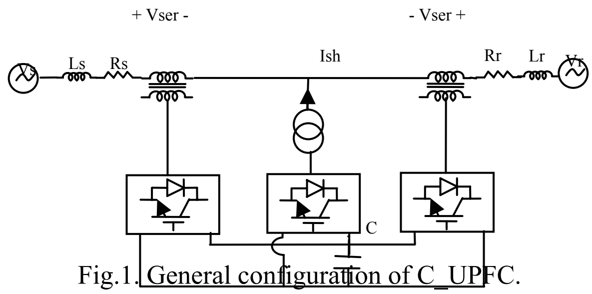

Fig.1. General configuration of C_UPFC.

2 Transient Model of C_UPFC

Fig.2 shows the transient model of the C-UPFC. The L_{sh}, L_{sr_s}, L_{sr_r} and R_{sh}, R_{sr_s}, R_{sr_r} represent leakage inductances of transformers and losses of inverters and transformers. The shunt converter of C-UPFC operates like a STATCOM [12]. It provides the path for the shunt current ($I_{sh} = I_s - I_r$) and sets the midpoint voltage magnitude on $|V_o| = |V_s| = |V_r|$. The series inverters act as SSSC.

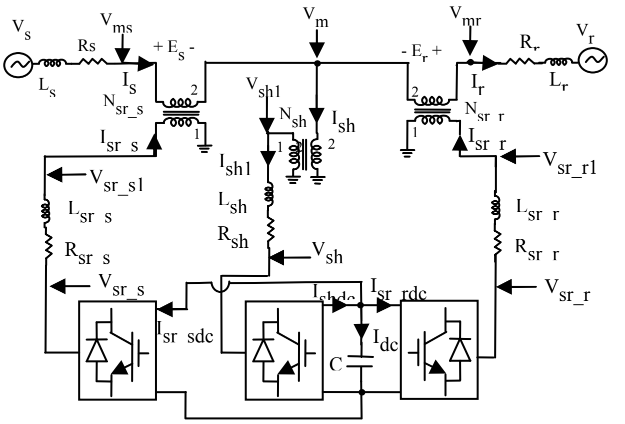

Fig.2. Transient model of C-UPFC.

They inject voltages, E_s and E_r, in series with the line. From [13, 14] the transient model equations of shunt and series inverters are obtained as bellow:

$$\begin{bmatrix} V_{shd} \\ V_{shq} \end{bmatrix} = \begin{bmatrix} N_{sh} V_{md} - R_{sh} I_{sh1d} - L_{sh} \frac{d}{dt} I_{sh1d} - \omega L_{sh} I_{sh1d} \\ N_{sh} V_{mq} - R_{sh} I_{sh1q} - L_{sh} \frac{d}{dt} I_{sh1q} + \omega L_{sh} I_{sh1q} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{sr\_sd} \\ V_{sr\_sq} \end{bmatrix} = \begin{bmatrix} N_{sr\_s}(V_{msd} - V_{md}) + R_{sr\_s} I_{sr\_sd} + L_{sr\_s} \frac{d}{dt} I_{sr\_sd} - \omega L_{sr\_s} I_{sr\_sd} \\ N_{sr\_s}(V_{msq} - V_{mq}) + R_{sr\_s} I_{sr\_sq} + L_{sr\_s} \frac{d}{dt} I_{sr\_sq} + \omega L_{sr\_s} I_{sr\_sq} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} V_{sr\_rd} \\ V_{sr\_rq} \end{bmatrix} = \begin{bmatrix} N_{sr\_r}(V_{mrd} - V_{md}) + R_{sr\_r} I_{sr\_rd} + L_{sr\_r} \frac{d}{dt} I_{sr\_rd} - \omega L_{sr\_r} I_{sr\_rd} \\ N_{sr\_r}(V_{mrq} - V_{mq}) + R_{sr\_r} I_{sr\_rq} + L_{sr\_r} \frac{d}{dt} I_{sr\_rq} + \omega L_{sr\_r} I_{sr\_rq} \end{bmatrix} \quad (3)$$

3 Control Strategy of Converters

3.1 Series Inverters

By controlling the magnitude and phase angle of line current, active and reactive power of sending and receiving ends can be controlled. The line current can be controlled by injection of series voltages, E_s and E_r. The sending and receiving ends active and reactive powers are calculated by equations (4) and (5).

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_{sd} & V_{sq} \\ -V_{sq} & V_{sd} \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} P_r \\ Q_r \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_{rd} & V_{rq} \\ -V_{rq} & V_{rd} \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} \quad (5)$$

The real power flow from sending and receiving ends can be independently controlled if the DC link is a DC voltage source. In this paper DC link is only a capacitor. Neglecting the line and inverters losses we have:

$$P_r = P_s = P \quad (6)$$

The reference currents of series inverters are obtained from equations (4) and (5) as bellow:

$$\begin{bmatrix} I^*_{sr\_s1d} \\ I^*_{sr\_s1q} \end{bmatrix} = \frac{2}{3} \frac{N_{sr\_s}}{\left(V_{sd}^2 + V_{sq}^2\right)} \begin{bmatrix} V_{sd} & -V_{sq} \\ V_{sq} & V_{sd} \end{bmatrix} \begin{bmatrix} P^* \\ Q^*_s \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} I^*_{sr\_r1d} \\ I^*_{sr\_r1q} \end{bmatrix} = \frac{2}{3} \frac{N_{sr\_r}}{\left(V_{rd}^2 + V_{rq}^2\right)} \begin{bmatrix} V_{rd} & -V_{rq} \\ V_{rq} & V_{rd} \end{bmatrix} \begin{bmatrix} P^* \\ Q^*_r \end{bmatrix} \quad (8)$$

Considering equations 2, 3, 7 and 8 the control system of series inverters can be formed as Fig. 3.

3.2 Shunt Inverter

The main tasks of shunt inverter are midpoint bus voltage regulation and DC link voltage control.

With controlling reactive power of shunt inverter the midpoint bus voltage is controlled. Q_{sh} can be calculated as follows:

$$Q_{sh} = \frac{3}{2}\left(V_{md} I_{shq} - V_{mq} I_{shd}\right) \quad (9)$$

The active power exchange of series inverters with the system changes the DC link voltage. Therefore, the shunt inverter must supply the active power of series inverters, P_{sr}, and the losses of three inverters, P_{loss}, to regulate the DC link voltage. P_{sr} can be calculated as follows:

$$P_{sr} = \frac{3}{2}\left(E_{sd} I_{sd} + E_{sq} I_{sq}\right) - \frac{3}{2}\left(E_{rd} I_{rd} + E_{rq} I_{rq}\right) \quad (10)$$

The active power of shunt inverter can be written as follows:

$$P_{sh} = P_{sr} + P_{loss} = \frac{3}{2}\left(V_{md} I_{shd} + V_{mq} I_{shq}\right) \quad (11)$$

Using equations (9), (11) and turn ratio of shunt transformer the reference currents of shunt inverter can be obtained as bellow:

$$\begin{bmatrix} I_{sh1d} \\ I_{sh1q} \end{bmatrix} = \frac{2}{3} N_{sh} \frac{1}{\left(V_{md}^2 + V_{mq}^2\right)} \begin{bmatrix} V_{md} & -V_{mq} \\ V_{mq} & V_{md} \end{bmatrix} \begin{bmatrix} P_{sh} \\ Q_{sh} \end{bmatrix} \quad (12)$$

The shunt converter can be used to balance the line current and to compensate line current harmonics. Therefore a supplementary control signal must be added to the control system of shunt converter. To obtain this signal, the active, P, and reactive, Q, powers of the load side are calculated.

$$P = \tilde{P} + \overline{P} = \frac{3}{2}(V_{md} I_{rd} + V_{mq} I_{rq}) \quad (13)$$

$$Q = \tilde{Q} + \overline{Q} = \frac{3}{2}(V_{md} I_{rq} - V_{mq} I_{rd}) \quad (14)$$

The unbalance current of load can be obtained as follows:

$$I_{unbal} = \frac{1}{3}\left(I_{La} + I_{Lb} + I_{Lc}\right) \quad (15)$$

The desired value of $\tilde{Q}, \overline{Q}, \tilde{P}$ and I_{unbal} is equal to zero. Therefore, the shunt branch must compensate these parameters. To extract undesired component of active power, i.e. $\widetilde{P}$, the instantaneous active power signal must pass through a high pass filter with a cut off frequency of 10 Hz. The d-q forms of the supplementary reference signal of shunt branch current are calculated using equations (16) and (17).

$$I_d^* = \frac{\widetilde{P}\, V_{md} - QV_{mq}}{V_{md}^2 + V_{mq}^2} \qquad (16)$$

$$I_q^* = \frac{\widetilde{P}\, V_{mq} - QV_{md}}{V_{md}^2 + V_{mq}^2} \qquad (17)$$

Now, they must be added to equation (12) (see equation 18).

$$\begin{bmatrix} I_{sh1d} \\ I_{sh1q} \end{bmatrix} = \frac{2}{3} N_{Sh} \left\{ \frac{1}{\left(V_{md}^2 + V_{mq}^2\right)} \begin{bmatrix} V_{md} & -V_{mq} \\ V_{mq} & V_{md} \end{bmatrix} \begin{bmatrix} P_{sh} \\ Q_{sh} \end{bmatrix} + \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} \right\} \qquad (18)$$

The reference currents of shunt inverter can be obtained by:

$$\begin{bmatrix} I_{Sha}^* \\ I_{Shb}^* \\ I_{Shc}^* \end{bmatrix} = T(\theta)^{-1} \begin{bmatrix} I_{Sh1d} \\ I_{Sh1q} \\ I_{unbal} \end{bmatrix} + \begin{bmatrix} I_{unbal} \\ I_{unbal} \\ I_{unbal} \end{bmatrix} \qquad (19)$$

Fig.4 shows the control system of this inverter. To consider the losses of inverters the DC link voltage error must be added to this control system.

$$V_{dcerr} = V_{dc}^* - V_{dc} \qquad (20)$$

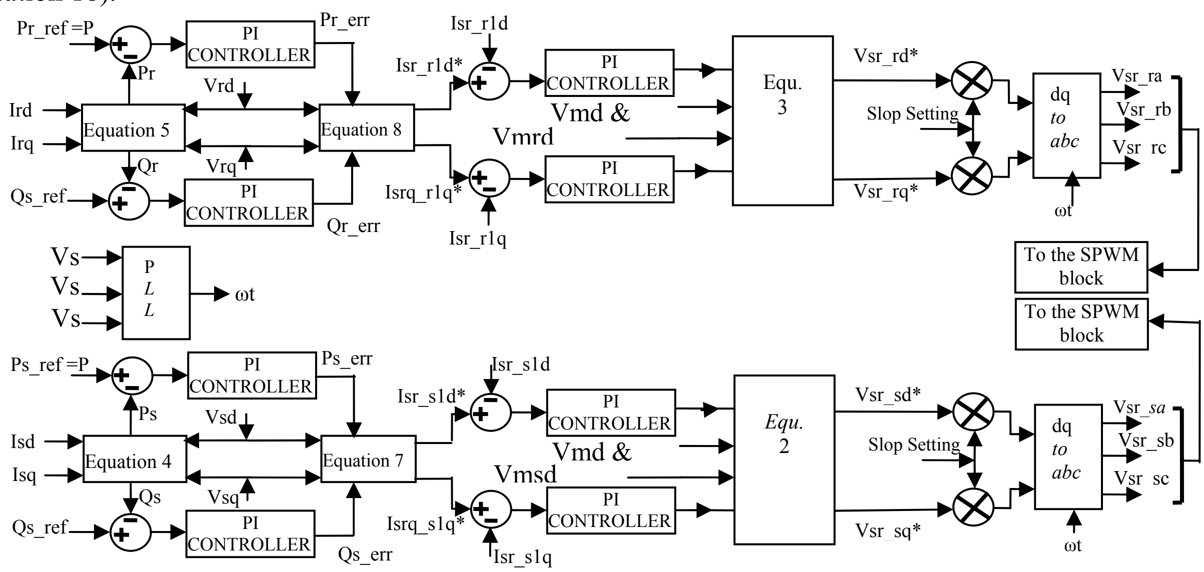

Fig. 3. Control system of series inverters.

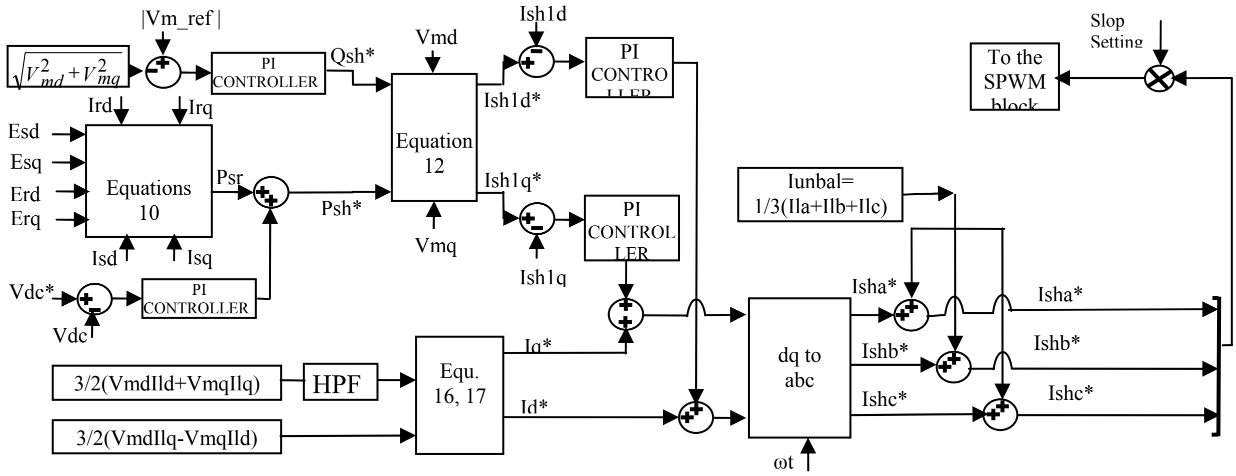

Fig.4. Control system of shunt inverter.

4 Simulation Results

The tow machine test system, whish is simulated by PSCAD/EMTDC [15], is shown in Fig.5. The inverters consist of IGCT based three phase voltage source converters. The transmission line configuration is illustrated in Fig. 6 and the parameters of this system are listed in tables 1 and 2.

TABLE 1: POWER SYSTEM PARAMETERS

	V(KV)	MVA	f(Hz)	R+jLw(pu)	Phase(deg.)
Gen. 1	230	800	50	.066+j.4	0
Gen. 2	230	800	50	.066+j.4	-10

TABLE 2: PARAMETERS of C_UPFC

Ccp	Lcp	Rcp	Ccs, Ccr	Lcs, Lcr	Rcs, Rcr	C
10 µf	2 mh	5Ω	10 µf	1 mh	5Ω	470 µf

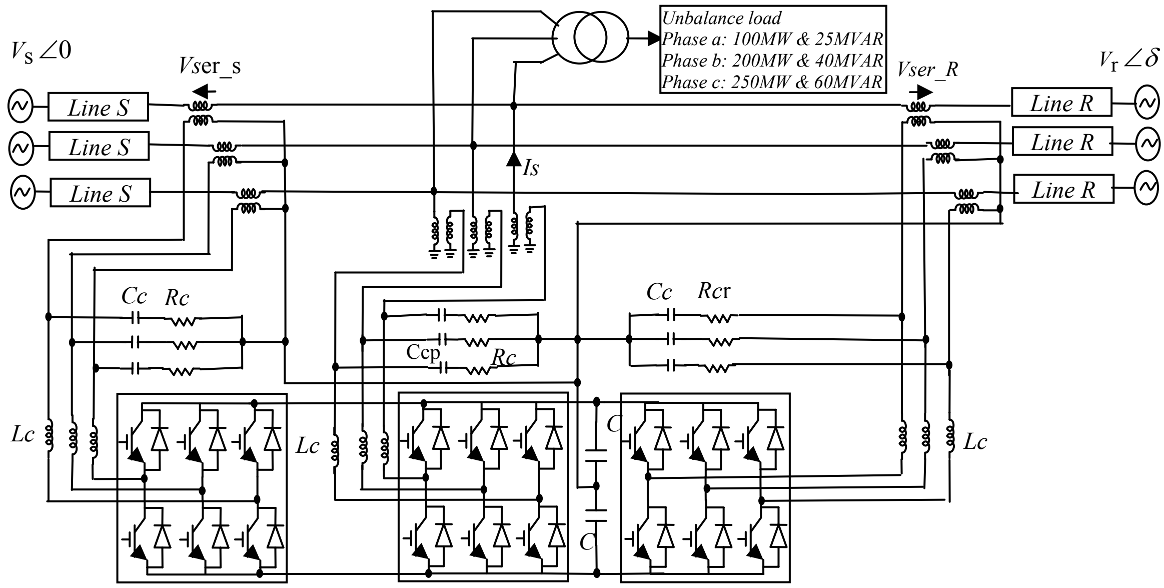

Fig.5. Configuration of simulation system.

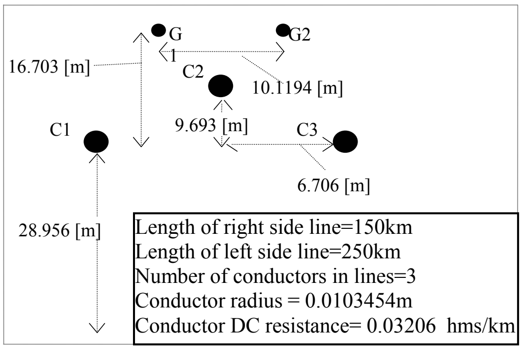

Fig.6. Transmission lines configuration.

As mentioned earlier, the C-UPFC can control system active and reactive power flows in steady state and transient conditions. Fig. 7 shows the reference and line active power flows. As it can be seen the line power flow follows the step changes of reference. To compare the capability of UPFC and C-UPFC, the Fig. 8 a and b show the reactive powers of receiving and sending ends, respectively. In this case the conventional UPFC has been simulated. The same variables are illustrated in Fig. 9 a and b, but in this case C-UPFC shown in Fig. 5 has been simulated. In both simulations the reference points are the same. As it can be seen, during transient conditions C-UPFC can limit the receiving and sensing ends reactive power flows much better than UPFC. For example, receiving end reactive power flow is limited about 30MVAR in Fig.8-a to 10 MVAR in Fig.9-a and the sending end reactive power is limited about 130MVAR in Fig.8-b to 30MVAR in Fig.9-b. These figures show the reactive power of both ends when the reference point of reactive power is zero and the active power changes as Fig.7. To show the capability of C-UPFC for reactive power flow control, step changes of reactive power reference point have been applied to the designed control system. The simulation results are presented in Fig. 10 a and b for reactive power flows of receiving and sending ends.

Now we set the line active and reactive power flow reference points to 380 MW and 0 MVAR, respectively. This time the load angle of generator No.2 has been changed as shown in Fig. 11. The simulation results are presented in Fig. 12 a and b. It is obvious that C-UPFC can easily regulate and compensate line active and reactive power flows. The Fig.13 shows the DC link capacitors voltages when the line active power flow is changed as Fig. 7.

An attractive application of C-UPFC is load current balancing. The control system shown in Fig.4 has added this capability to the conventional UPFC. The unbalance load has been modeled as shown in Fig.5. The simulation results are illustrated in Fig. 14. As it can been seen the sending end generator currents are balanced. Table 3 lists the harmonics and THD of line current when the active and reactive powers are changed as step.

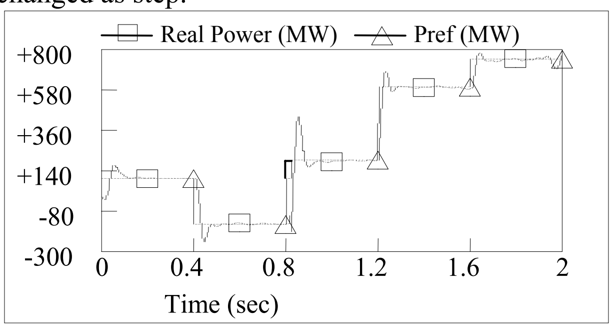

Fig.7. Reference and active power flow, Qref=0, C_UPFC installed.

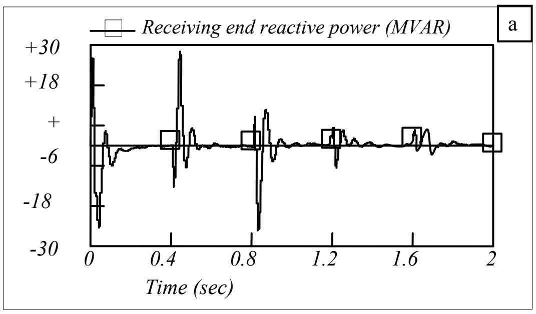

Fig.8-a. Reactive power of receiving end, Qr_ref=0, UPFC installed.

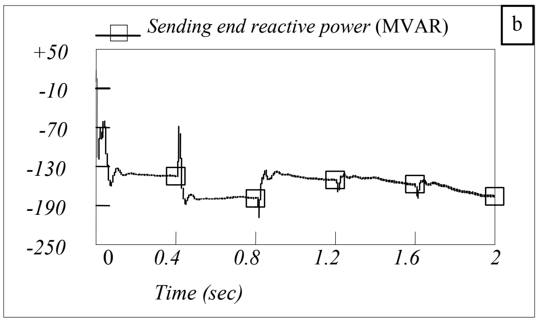

Fig.8-b. Reactive power of sending ends, Qs_ref, UPFC installed.

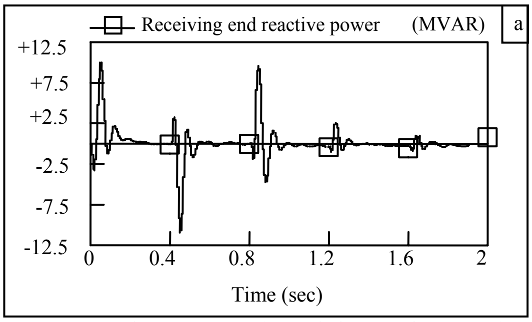

Fig.9-a. Reactive power of receiving end, Qr_ref=0, C_UPFC installed.

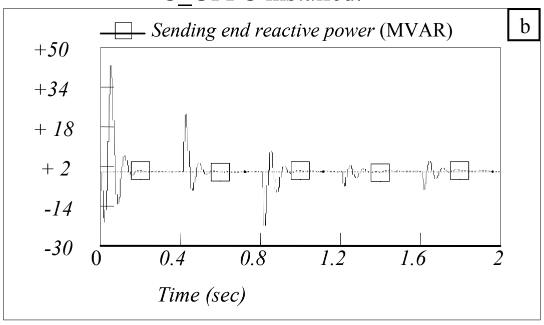

Fig.9-b. Reactive power of sending end, Qs_ref , C_UPFC installed.

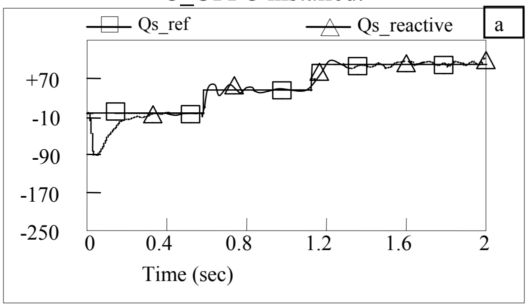

Fig.10_a. Reference and reactive power flows (MVAR) of sending ends, C_UPFC installed.

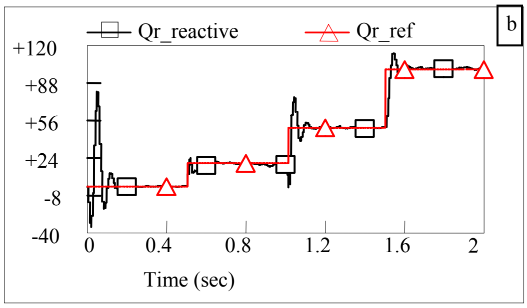

Fig.10_b. Reference and reactive power flows (MVAR) of receiving C_UPFC installed.

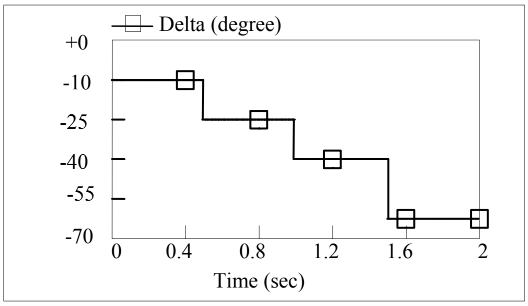

Fig.11. Step changes of load angle of Gen.2.

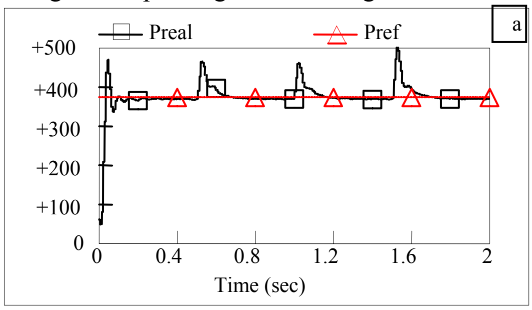

Fig. 12-a. Reference and line active power flow, when load angle of generator 2 has been changed.

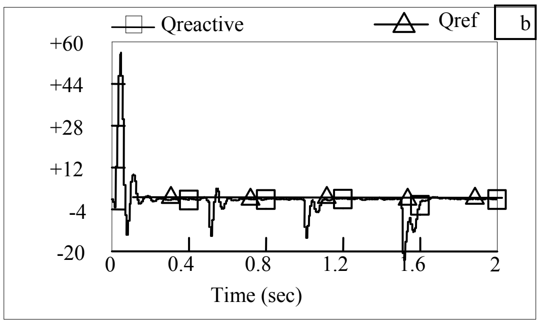

Fig. 12-b. Reference and line reactive power flow, when load angle of generator 2 has been changed.

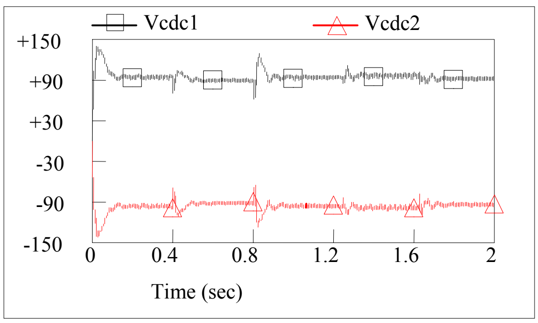

Fig.13. DC link capacitors voltage.

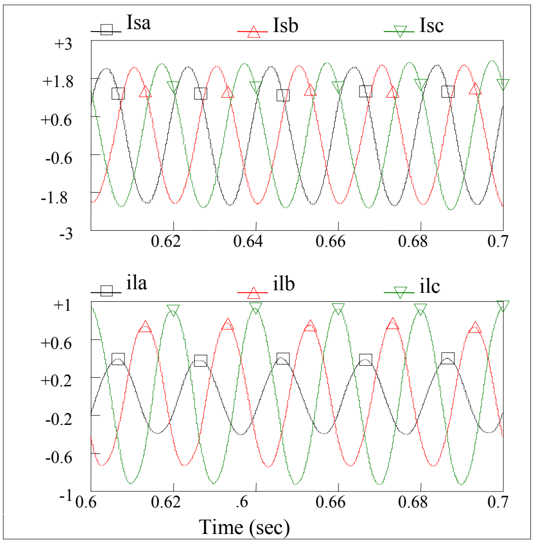

Fig.14. Sending end and load side currents (KA).

TABLE 3: Harmonics of line current

Harmonics order	3th	5th	7th	11th	13th	THD
Values (%)	2	1.6	1	.5	.05	2.79

5 Conclusion

This paper presents the transient model and control system of a new FACTS device, the center node unified power flow controller (C_UPFC), installed at the midpoint of a transmission line. The presented C_UPFC control system can regulate line active and reactive power flow and voltage at midpoint of the transmission line. The presented control system of C_UPFC not only responses to the step changing in the active and reactive power, but also is able to exchange the direction of line active power flows. In this paper a supplementary control system is added to the shunt inverter control system to compensate unbalance load current. The simulation results indicate the fast dynamic response, validity and effectiveness of the presented device and its control scheme.

References:

[1] L. Gyugi, A Unified Power Flow Control Concept for Flexible AC Transmission Systems, IEE Proceedings, Vol.139, No.4, July 1992, pp. 323-331.

[2] Narain G. Hingorani, L. Gyugyi, Understanding FACTs: Concept and Technology of Flexible AC Transmission Systems, IEEE Press, New York, 1999.

[3] C.A. Canizares, Z. Faur, Analysis of SVC and TCSC Controllers in Voltage Collapse, IEEE Transactions on PWRS, Vol.14, No.1, Feb. 1999, pp. 1-8.

[4] Y.Sumi, Y.Harumoto, T.Hasegawa, M.Yano, K.Lkeda, T.Matsuura, New Static VAR Control Using Force Commutated Inverters, IEEE Transactions on Power Apparatus and System, Vol. 100, No. 9, Sept. 1981, pp.4216-4226.

[5] L. Gyugyi, C.D. Schauder, K.K. Sen, Static Synchronous Series Compensator: A Solid-State Approach to the Series Compensation of Transmission Lines, IEEE Transactions on Power Delivery, Vol. 12, No. 1, 1997, pp. 406-413.

[6] K.K.Sen, SSSC- Static Synchronous Series Compensator: Theory, Modeling Control, IEEE Trans. On Power Delivery, Vol. 10, No. 2, April 1995, pp. 1085-1097.

[7] L. Gyugyi, C.D. Schauder, et al, The Unified Power Flow Controller: A New Approach to Power Transmission Control, IEEE Transactions on Power Delivery, Vol. 10, No. 2, April 1995, pp. 1085-1093.

[8] H. Fujita, Y. Watanabe, H. Akagi, Control and Analysis of a Unified Power Flow Controller, IEEE Transactions on Power Electronics, Vol.14, No.6, November 1999, pp. 1021-1027.

[9] S. Round, Q. Yu, et al, Performance of a Unified Power Flow Controller Using a d-q Control System, AC and DC Transmission Conference, April 1996.

[10] D.G. Cho, E. Ho. Song, A Simple UPFC Control Algorithm and Simulation on Stationary Reference Frame, ISIE Conference, Pusan, Korea, 2001, pp.1810-1815.

[11] B. Ooi, B. Lu, C-UPFC: A New FACTs Controller for Midpoint Sitting, Conference Record of the International Power Electronics Conference, April 2000, Tokyo, Japan, pp. 1947-1952.

[12] Pranesh Rao, L.M. Crow, Zhiping Yang, STATCOM Control for Power System Voltage Control Applications, IEEE Trans. On Power Delivery, Vol. 15, No. 4, October 2000, pp. 1311-1317.

[13] S.H.Hosseini, A. Ajami, Voltage Regulation and Transient Stability Enhancement of a Radial AC Transmission System Using UPFC, IECON04, Pusan, Korea.

[14] A.Ajami, S.H.Hosseini, Line Current Balancing Using Unified Power Flow Controller, TENCON04, Chiang Mai, Thailand.

[15] PSCAD/EMTDC V4.1, Power System Simulation Software User Manual, Manitoba HVDC Research Center, CANADA, 2003.