Asian Journal of Information Technology 15 (17): 3339-3346, 2016
ISSN: 1682-3915

Modeling and Implementation of Matrix Converter Based Unified Power Flow Controller

[1]Gajalakshmi Purushothaman and [2]Ramesh Ramdoss
[1]Department of Electrical and Electronics Engineering,
University College of Engineering Tindivanam, Tindivanam, Tamil Nadu, India
[2]Department of Electrical and Electronics Engineering,
Anna University, Chennai, Tamil Nadu, India

Abstract: The detailed model of Unified Power Flow Controller with Matrix Converter (UPFC-MC) is derived and simulated for a sample power system to assess the suitability and functionality of the model. The modeling of this new UPFC-MC structure is controlled by space vector modulation technique. Through the presented modeling, the dynamic and steady state performance of the new structure are well investigated. The model is simulated in MATLAB by changing each system parameter.

Key words: UPFC-MC, matrix converter, steady state model, dynamic model, Space Vector Modulation (SVM)

INTRODUCTION

The FACTS devices enable the power system to transmit the maximum power and improve the transient, dynamic and voltage stability. UPFC is one of the most versatile FACTS device used in power system. The main weakness of the UPFC structure developed is its energy storage element with limited life time, hence it increases the loss, volume cost and weight of UPFC. An alternate structure of UPFC without energy storage is developed with the help of matrix converter. MC is a direct convert which converts directly ac-ac power without any intermediate stages (Geethalakshmi and Dananjayan, 2008; Geethalakshmi *et al*., 2009). The structure of the MC has many advantages such as adjustable power facer, high quality input and output variables, high operating speed etc. it also has some disadvantages that its limited voltage transfer ratio and large number of semiconductor switches leads to high frequency switching.

In UPFC-MC, structure, there are two methods direct power conversion and indirect transfer function approach (Monteiro *et al*., 2011). In general for the UPFC-MC structure indirect modulation approach is used (Iranaq *et al*., 2010). In the indirect space vector technique, MC operates as two stage transformation converter, one as rectification stage providing constant vitrtual dc link voltage and other inversion stage to produce three phase at the output terminals. As like our UPFC, structure shunt and series converter stages (Shahir and Babaei, 2013a, b) here the rectification and inversion stages performs the same operation of UPFC converter and hence, instead of two converters, single converter is enough perform the operation. This study investigates steady state and dynamic model UPFC-MC through mathematical modeling (Shahir and Babaei, 2013a, b; Babaei and Shahir, 2012). Sameeullah *et al*. (2008) has presented the Genetic algorithm based technique to solve non linear system equations.

MATERIALS AND METHODS

Structure of UPFC-MC

Topology of UPFC-MC: The UPFC-MC structure shown in Fig. 1 includes the matrix converter with nine

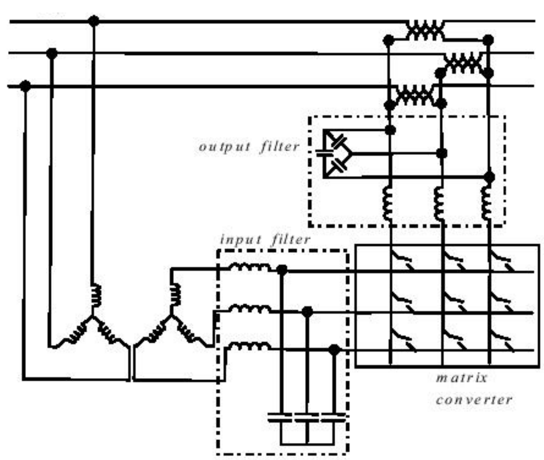

Fig. 1: UPFC-MC structure

Corresponding Author: Gajalakshmi Purushothaman, Department of Electrical and Electronics Engineering, University College of Engineering Tindivanam, Tindivanam, Tamil Nadu, India

bi-directional switches, its input and output filters, the series and shunt transformer at the transmission line side. The transformer may be star or delta connected structures. The bi-directional switches of matrix converters directly connect the each one of the input phases to the three output phases (Babaei *et al*., 2006). Filters used in the structures eliminates the high frequency components from input current because matrix converter acts as a current source at the input and also output voltage harmonics because matrix converter acts as voltage source at the output side. The UPFC-MC structure input current injected in the shunt side and fundamental component of voltage injected in series with the transmission line. The generalized equations of input current and output voltages are shown in the following Eq. 1 and 2:

$$\begin{aligned} I_{i,a} &= I_{im}\cos(\omega_i t - \varphi_i); \\ I_{i,b} &= I_{im}\cos(\omega_i t - \varphi_i - 120^0); \\ I_{i,c} &= I_{im}\cos(\omega_i t - \varphi_i - 240^0) \end{aligned} \tag{1}$$

$$\begin{aligned} V_{o,a} &= V_{om}\cos(\omega_o t - \varphi_o); \\ V_{o,b} &= V_{om}\cos(\omega_o t - \varphi_o - 120^0); \\ V_{o,c} &= V_{om}\cos(\omega_o t - \varphi_o - 240^0) \end{aligned} \tag{2}$$

Modulation technique: The UPFC-MC structure has restricted switching pattern combination which has 27 possible switching states out of $2^9 = 512$ states. This refers to the structure of MC (Hosseini and Babaei, 2003), because it should satisfy the two conditions, input phases never be short circuited to protect device from heavy in rush current. And output phases never are open circuited to avoid over voltage spikes. The space vector modulation technique of MC uses the input current as a rectifier stage of conversion and output voltage as a inverter stage of conversion (Huber and Borojevic, 1995). Hence, there are two SVM hexagons and finally they are combined to make the 27 possible combination of switching states.

Rectifier side structure: The Voltage Source Rectifier (VSR) side includes six switches with SVM technique. The reference current vector using the switching period is derived in Eq. 3 and 4. Duty cycles of the VSR switches are given in Eq. 5:

$$I_i^* = \frac{T_\gamma}{T_S} I_\gamma + \frac{T_\delta}{T_S} I_\delta + \frac{T_0}{T_S} I_0 \tag{3}$$

$$d_\gamma\, I_\gamma + d_\delta\, I_\delta + d_0\, I_0 = I_i^* \tag{4}$$

$$\begin{aligned} d_\gamma &= m_i \sin(60^0 - \delta_i); \\ d_\delta &= m_i \sin(\delta_i) \text{ and} \\ d_0 &= 1 - d_\gamma - d_\delta \end{aligned} \tag{5}$$

The VSR duty cycle is and current modulation index are calculated as follows:

$$d_{VSR} = d_\gamma + d_\delta = m_i \sin(60^0 - \delta_i) + m_i \sin(\delta_i) \tag{6}$$

$$m_i = \frac{I_{im}\sqrt{3}}{I_{dc}} \tag{7}$$

Inverter side structure: The Voltage Source Inverter (VSI) side also includes six switches with SVM technique the reference voltage vector is obtained from the duty cycle, using Eq. 8 and 9:

$$V_o^* = \frac{T_\alpha}{T_S} V_\alpha + \frac{T_\beta}{T_S} V_\beta + \frac{T_0}{T_S} V_0 \tag{8}$$

$$d_\alpha\, V_\alpha + d_\beta\, V_\beta + d_0\, V_0 = V_o^* \tag{9}$$

$$\begin{aligned} & d_\alpha = m_0 \sin(60^0 - \delta_o);\ d_\beta = m_0 \sin(\delta_o); \\ & d_0 = 1 - d_\alpha - d_\beta \end{aligned} \tag{10}$$

$$\begin{aligned} d_{VSI} &= d_\alpha + d_\beta; \\ &= m_o \sin(60^0 - \delta_o) + m_o \sin(\delta_o) \end{aligned} \tag{11}$$

$$m_o = \frac{V_{om}\sqrt{3}}{V_{dc}} \tag{12}$$

Duty ratios and the modulation index of the output side was calculated using Eq. 10-12.

State space modeling of UPFC-MC: The VSR side, the mathematical model for phase a is given by:

$$L_{i,a}\frac{dI_{i,a}}{dt} + R_{i,a} \times I_{i,a} = V_{i,t,a} - V_{i,a} \tag{13}$$

And this equation can be rewritten as:

$$L_{i,a}\frac{dI_{i,a}}{dt} = -R_{i,a} I_{i,a} + V_{i,t,a} - V_{i,a} \tag{14}$$

$$\begin{aligned} V_{i,a} &= A_i \cos(\delta_{i,a} - 30°) \\ &= \frac{m_i V_{dc}}{2}\cos(\omega_i t + \varphi_i - 30°) \end{aligned} \tag{15}$$

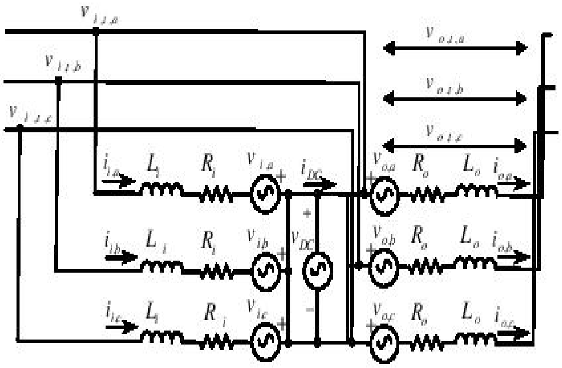

Fig. 2. Generalized equivalent circuit of UPFC-MC

$$L_{i,a}\frac{dI_{i,a}}{dt} = -R_{i,a}.I_{i,a} + V_{i,t,a} - A_i\cos(\delta_{i,a} - 30°) \quad (16)$$

From the VSI side:

$$V_{o,t,a} = A_o\cos(\delta_{o,a} - 30^0) - L_{o,a}\frac{dI_{o,a}}{dt} - R_{o,a}I_{o,a} \quad (17)$$

And finally, the virtual dc link voltage can be expressed as:

$$\frac{dV_{dc}}{dt} = \sum_{k=a,b,c} V_{i,k} - V_{o,k} \quad (18)$$

$$I_{dc} = I_{i,dc} - I_{o,dc} \quad (19)$$

$$I_{dc} = \sum_{k=a,b,c} I_{i,k}\times d_{i,k} - I_{o,k}\times d_{o,k} \quad (20)$$

The Vdc and I dc values are expressed in Eq. 18:

$$\dot{X} = AX + BU \quad (20)$$

From the above equation and generalized structure shown in Fig. 2 the state space equations for the proposed model as follows:

$$\dot{X} = AX + BU \quad (21)$$

$$X = [I_{i,a}\ I_{i,b}\ I_{i,c}\ I_{o,a}\ I_{o,b}\ I_{o,c}\ V_{dc}]T \quad (22)$$

$$U = [V_{i,t,a}\ V_{i,t,b}\ V_{i,t,c} - V_{o,t,a} - V_{o,t,b}\ V_{o,t,c}] \quad (23)$$

Steady state modeling: Ignoring the loss and resistance of the transformers assuming constant V_{dc} and I_{dc}, the per

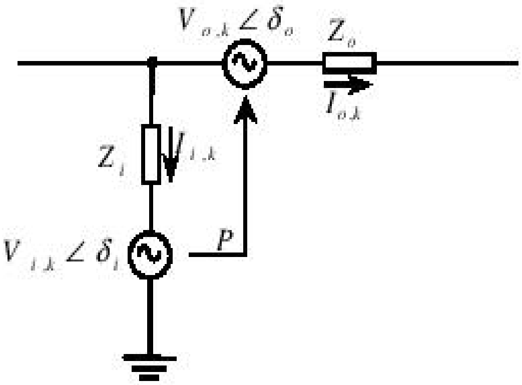

Fig. 3: Steady state equivalent circuit

phase steady state equations in VSR and VSI side are as follows. Figure 3 shows the steady state equivalent circuit of the proposed model:

$$V_{i,t,a} = \left(\frac{m_i V_{dc}}{2}\right)\cos\left(\delta_{i,a} - 30°\right) + jX_i \times I_{i,a} \quad (24)$$

$$V_{o,t,a} = \left(\frac{m_o V_{dc}}{2}\right)\cos\left(\delta_{o,a} - 30°\right) + jX_o \times I_{o,a} \quad (25)$$

Input and output terminal voltage is expressed in Eq. 24 and 25. The equations for phases b and c can be written by considering the phase difference of 120^0 and 240^0. Assuming that, ignoring loss there is no active power transferred from UPFC-MC and power system, the virtual link DC voltage and current are stable.

Dynamic modeling: Applying park transformation to (Eq. 16) and (Eq. 17) the rectifier and inverter side equations on dqo axis can be obtained as:

$$\begin{pmatrix} V_{i,t,d} \\ V_{i,t,q} \end{pmatrix} = \begin{pmatrix} \left(\frac{m_i V_{dc}}{2}\right)\cos\left(\delta_i - 30°\right) \\ \left(\frac{m_i V_{dc}}{2}\right)\sin\left(\delta_i - 30°\right) \end{pmatrix} + \begin{pmatrix} 0 & -X_i \\ X_i & 0 \end{pmatrix}\begin{pmatrix} I_{id} \\ I_{i,q} \end{pmatrix}$$

$$\begin{pmatrix} V_{o,t,d} \\ V_{o,t,q} \end{pmatrix} = \begin{pmatrix} \left(\frac{m_o V_{dc}}{2}\right)\cos\left(\delta_i - 30°\right) \\ \left(\frac{m_o V_{dc}}{2}\right)\sin\left(\delta_i - 30°\right) \end{pmatrix} + \begin{pmatrix} 0 & -X_o \\ X_o & 0 \end{pmatrix}\begin{pmatrix} I_{o,d} \\ I_{o,q} \end{pmatrix}$$

Controller design for UPFC-MC: There are number methods are available for the controller design of UPFC-MC, the basic control methods are based on maximum power transfer and minimum power factor correction. And other methods also include, linear and sliding mode controlled based on PQ decoupling controller and cross coupled methods. This study mainly uses the PQ decoupled control structure:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (26)$$

Assuming reference frame synchronized to the mains then:

$$P = V_d \times I_d \quad (27)$$

$$Q = -V_d \times I_q \quad (28)$$

Based on the relations active and reactive powers of the transmission line was calculated. The values obtained are compared with the reference value of P_{ref} and Q_{ref}. And according to the control system parameters of voltage and currents are calculated. The rectified side parameters are regulated by two PI controller and the outputs of the PI controller are modulation index and theta which is then given to the SVM pulse generator which generates the pulses for VSR side switches, similarly for inverter stage also done. There by pulses are generated for rectification and inversion stages.

RESULTS AND DISCUSSION

The parameters of the proposed UPFC-MC structure and control functions are simulated in MATLAB. The three phase balanced ac source and loads are taken to study the performance of the presented structure. Load variations are created with the help of circuit breaker block to study the performance of the given system shown in Fig. 4.

The details and parameters of the sample system was given in Table 1. The power flows of the transmission line with load variations without the FACTS devices are simulated and shown in Fig. 5.

Table 1: Power system parameters

Parameters	Values
Three phase ac voltage source 1	
Rated voltage	500 kV×1.03
Frequency	50 Hz
Short circuit level	10, 000 MVA
Base voltage	500 kV
X_g/R_g	8
Three phase ac voltage source 2	
Rated voltage	500kV×1.03
Frequency	50 Hz
Short circuit level	6500 MVA
Base voltage	500 kV
X_g/R_g	8
Transmission line parameters	
Resistance per unit length	0.01273 Ω km^{-1}
Inductance per unit length	0.9337 mH km^{-1}
Capacitance per unit length	12.74 nF km^{-1}
Length 1	100 km
Length 2	200 km
Length 3	180 km
Shunt transformer ratings	
Nominal power	150 MVA
Frequency	50 Hz
Nominal voltage	500 kV/21 kV
Magnetization reactance and resistance	500 pu
Series transformer ratings	
Rated voltage	42kV/21kV
Rated power	150 MVA
Magnetization reactance and resistance	500 pu
GBT switching parameters	
Internal resistance	0.001 Ω
Snubber resistance	0.1M Ω
Snubber capacitance	Infinite

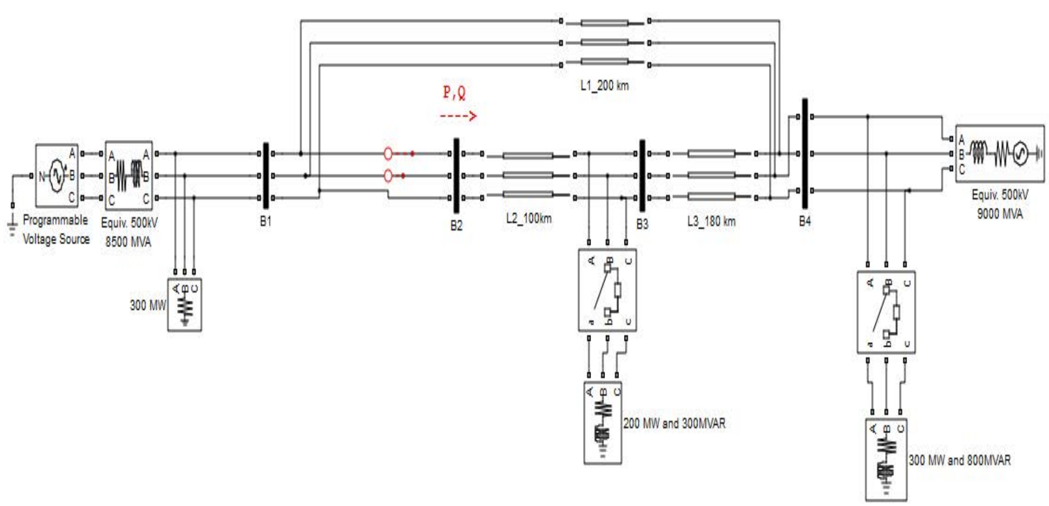

Fig. 4: Sample power system model

The load voltage and current variations are shown in Fig. 6. The UPFC-MC is connected between the buses B1 and B2 via the shunt transformer and series transformer. The dynamic load is applied through circuit breaker. Various loads of 200 and 500 MW, 300 MVAR at 0.04 sec and 400 MW, 800M VAR 0.1sec are applied to the power system. The voltage profile with the UPFC-MC is shown in Fig. 7 and it clearly shows improved the regulated output voltage profile. The power flow variations are also noted down and shown in Fig. 8.

It can be seen from Fig. 8 the active and reactive power flows are increased with the proposed structure. Finally, the input variation at the matrix converter input side without and with filter connections is also measured and plotted in Fig. 9 and 10.

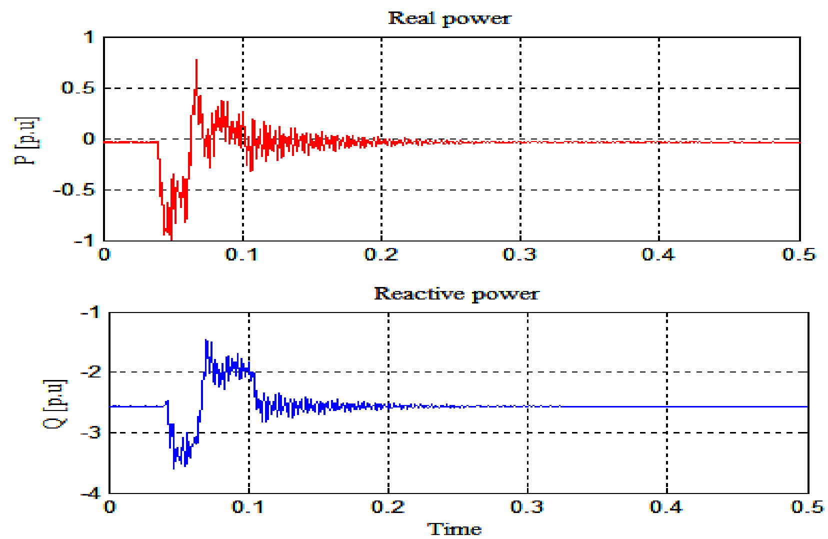

Fig. 5: Real and reactive power flows without FACTS device

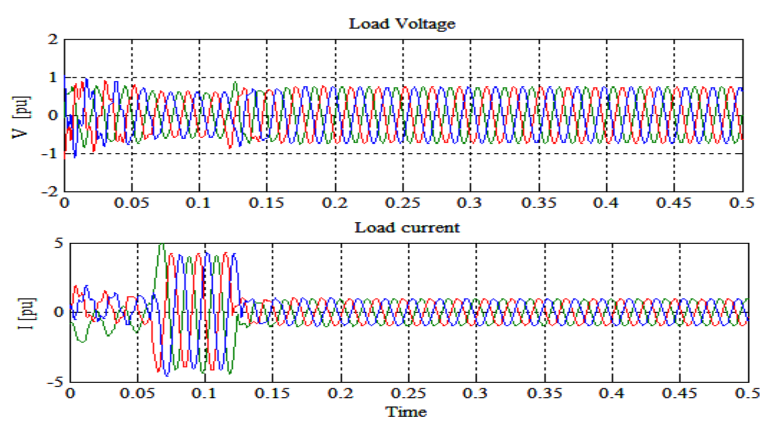

Fig. 6: Load voltage and current variation without FACTS

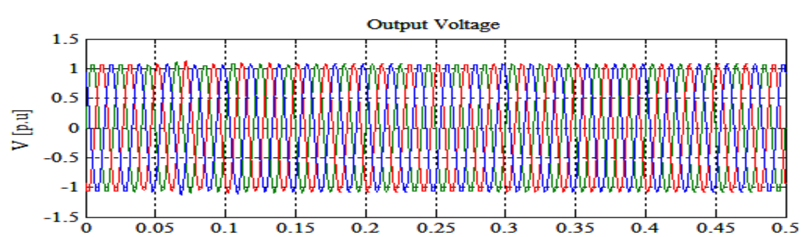

Fig. 7: Continue

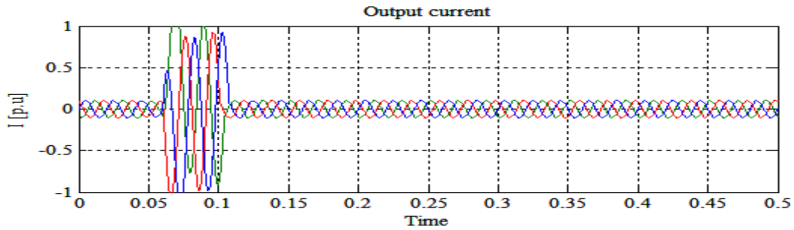

Fig. 7: Load voltage and current variations with UPFC-MC

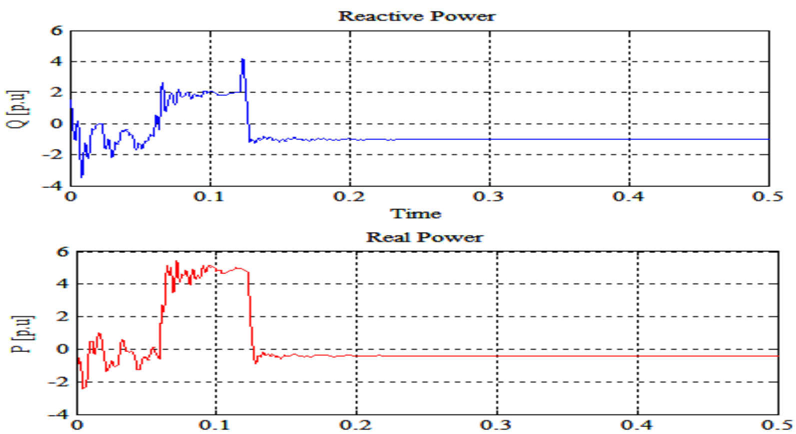

Fig. 8: Real and reactive power flows of UPFC-MC structure at the receiving end bus

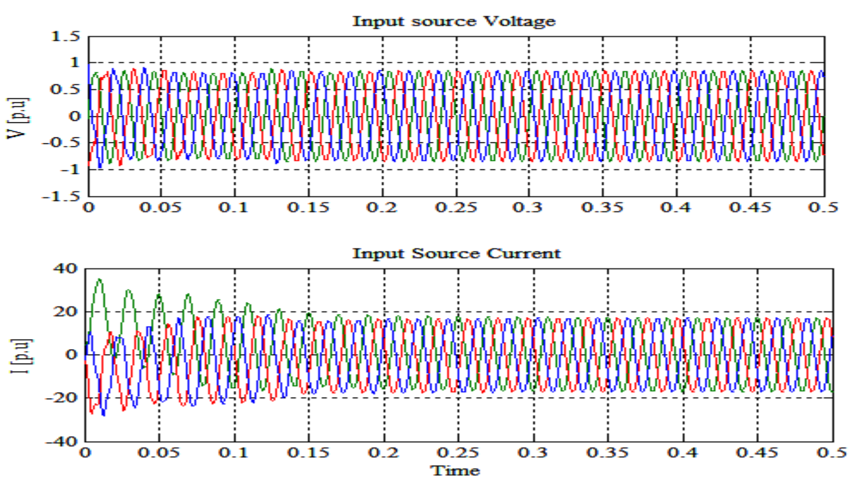

Fig. 9: Input voltage and current variations with matrix converter without filter

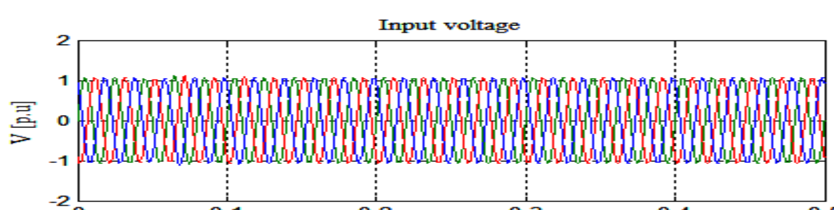

Fig. 10: Continue

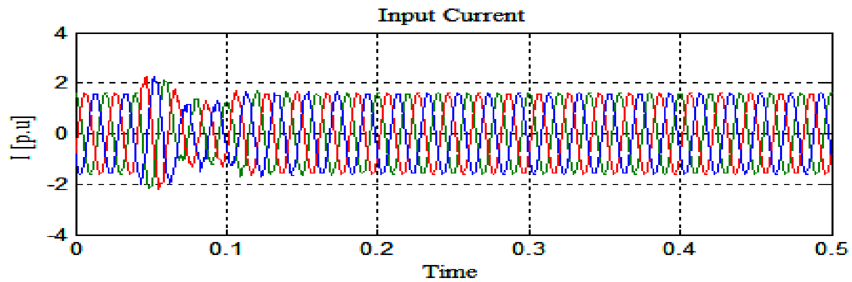

Fig. 10: Input voltage and current variations with matrix converter with filter

CONCLUSION

In this research, the generalized UPFC-MC structure was designed and developed. The dynamic and steady state model of the structure was analyzed with the help of mathematical functions. Matrix converter is connected to the transmission line as UPFC and the simulated results shows that active and reactive power flows were effectively controlled using this structure. By proper design of control parameters and high frequency filter there was no steady state error found and power factor correction was also achieved.

Finally this new structure reduces the line losses by improving the power factor, increases the reliability and protection level of power system and improves the voltage profile active and reactive power flows. The simulation system defined in this paper was a simple power system model composed of generator, bus and loads. The system was not complicated. The power flow adjustment is easy. Future discussion relies on how to control power flows in complex multi input multi output system.

NOMENCLATURE

Inde 1	=	Index to show input side quantities
Index o	=	Index to show output side quantities
$m_b b = i, o$	=	Modulation index
δ_b b = i, o	=	Phase angle
ω_b b = i, o	=	Switching angular frequency
ϕ_b b = i, o	=	Phase difference
I_{im}	=	Peak value of input current
V_{om}	=	Peak value of output voltage
$I_{i,k}$ k = a,b,c	=	Input current of phase k
$V_{o,k}$ k = a,b,c	=	Output voltage of phase k
I_{i*}	=	Reference of input current vector
Vo^*	=	Reference of output voltage vector
T_S	=	Switching time in a period
$T_{\gamma\_}, T_{\delta\_}, T_{\alpha\_}, T_{\beta}$	=	Switching times in adjacent vectors
$d_{\delta\_}, d_{\delta\_}, d_{\alpha\_}, d_{\beta}$	=	Duty cycles in adjacent vectors
$d_{b,0}$ b = i,o	=	Zero duty cycle
$T_{b,0}$b = i, o	=	Zero switching time

REFERENCES

Babaei, E. and F.M. Shahir, 2012. Evaluation of power system stability by UPFC via two shunt voltage-source converters and a series capacitor. Proceedings of the 20th Iranian Conference on Electrical Engineering (ICEE) 2012, May 15-17, 2012, IEEE, Tehran, Iran, ISBN: 978-1-4673-1149-6, pp: 318-323.

Babaei, E., S.H. Hosseini, G.B. Gharehpetian and M. Sabahi, 2006. A new switching strategy for 3-phase to 2-phase matrix converters. Proceedings of the International Joint Conference on SICE-ICASE 2006, October 18-21, 2006, IEEE, Busan, South Korea, pp: 3599-3604.

Geethalakshmi, B. and P. Dananjayan, 2008. Investigation of performance of UPFC without DC link capacitor. Electr. Power Syst. Res., 78: 736-746.

Geethalakshmi, B., G. Devanathan and P. Dananjayan, 2009. A novel structure of UPFC with matrix converter. Proceedings of the International Conference on Power Systems 2009, December 27-29, 2009, IEEE, Kharagpur, India, ISBN: 978-1-4244-4331-4, pp: 1-6.

Hosseini, S.H. and E. Babaei, 2003. A new control algorithm for matrix converters under distorted and unbalanced conditions. Proceedings of 2003 IEEE Conference on Control Applications (CCA) 2003, June 23-25, 2003, IEEE, New York, USA., ISBN: 0-7803-7729-X, pp: 1088-1093.

Huber, L. and D. Borojevic, 1995. Space vector modulated three-phase to three-phase matrix converter with input power factor correction. IEEE Trans. Ind. Applic., 31: 1234-1246.

Iranaq, A.R.M., M.T. Haque and E. Babaei, 2010. A UPFC based on matrix converter. Proceedings of the 1st Conference on Power Electronic Drive Systems and Technologies, February 17-18, 2010, Tehran, Iran, pp: 95-100.

Monteiro, J., J.F. Silva, S.F. Pinto and J. Palma, 2011. Matrix converter-based unified power-flow controllers: advanced direct power control method. Power Delivery IEEE. Trans., 26: 420-430.

Sameeullah, A.M., B. Palaniappan and S.D. Devi, 2008. Genetic algorithm based method to solve linear fractional programming problem. Asia J. Inform. Technol., 7: 83-86.

Shahir, F.M. and E. Babaei, 2013a. Dynamic modeling of UPFC by Two shunt voltage-source converters and a series capacitor. Int. J. Comput. Electr. Eng., Vol. 5, 10.7763/IJCEE.2013.V5.757

Shahir, F.M. and E. Babaei, 2013b. Evaluating the dynamic stability of power system using UPFC based on indirect matrix converter. J. Autom. Control Eng., 1: 279-284.