Advanced Research in Electrical and Electronic Engineering
Print ISSN: 2349-5804; Online ISSN: 2349-5812 Volume 2, Number 4 January-March (2015) pp. 325-330

http://www.krishisanskriti.org/areee.html

Vector Analysis and Current Control Strategy Used for STATCOM

S.S. Pavagadhi[1] and A.R. Patel[2]

[1]P.G. Student, (E.P.S.) Electrical Engineering department B.V.M Engineering, V.V. Nagar, Gujarat
[2]Electrical Engineering department B.V.M Engineering, V.V. Nagar, Gujarat
E-mail: [1]pavagadhisonal@yahoo.com, [2]ashish.patel@bvmengineering.ac.in

Abstract—*This paper presents the modeling and controlling strategy for STATCOM, also known as advanced VAR compensator, uses a high power self commutating inverter that draws the reactive current from transmission line. Type-I inverter is employed for this purpose, in this work which provides control of output voltage magnitude and phase angle. The STATCOM is modeled using the d-q transformation and SPWM technique used to generate gate pulses for three phase inverter. This model is used to design an efficient control strategy based on the control of reactive current of transmission system. Simulated results obtained using matlab are presented and discussed for validity of model.*

1. INTRODUCTION

In recent years, the rapid growth of power semiconductor switching devices has made it possible to design forced commutation converters for reactive power compensation. Static inverter can be connected between three phase A.C. power lines and an energy storage devices like batteries or capacitor and can be controlled to draw mainly reactive current from transmission lines. These devices are successfully used for voltage regulation, power factor correction and increasing transient stability margin. The operating principle of STATCOM is based on that of exact equivalent of conventional rotating synchronous compensator.

The proposed model represents an optimal power circuit configuration based on voltage source inverter, and includes the control that can be applied to full power installation. The inverter system is able to compensate lagging and leading reactive power supplied by the load connected to supply. The control system is designed on the base of instantaneous reactive current drawn from the transmission line in a way to achieve fast dynamic control.

This paper presents a simplified mathematical model of STATCOM which is used to derive the transfer function needed for control system synthesis. The resulting control system designs are presented in brief and computer simulation results are obtained with matlab are provided and discussed for validity of performance of the proposed STATCOM model with change in programmed instantaneous reactive current.

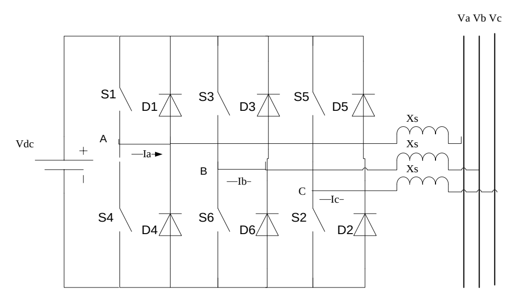

Fig. 1: Power circuit of STATCOM

2. MAIN OPERATING PRINCIPLE OF STATCOM

2.1 Main Circuit Configuration

The three phase inverter is connected to the A.C. mains through a first order low pass filter, which is used to minimize the damping of current harmonics on utility lines. The D.C. side of the converter is connected to a D.C. capacitor which is the main reactive current storage element. This capacitor provides a constant D.C. voltage and also contributed in real power exchange, which is required to compensate the losses took place in the system. The proposed model of STATCOM uses a programmed SPWM switching pattern for converter of the voltage source type shown in Fig. 1.

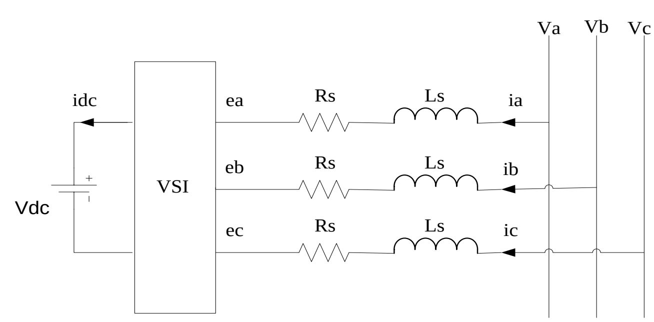

Fig. 2: Main circuit of the STATCOM

The operating principle of STATCOM can be explained by Fig. 2., where a voltage source inverter is connected to the A.C. mains through reactor Xs, which is composed of Ls and Rs which represents leakage inductance of the transformer and losses of inverter and transformer respectively. C is D.C. side capacitor, Ea and Va are the magnitude of the fundamental output voltage of the converter and phase voltage respectively.

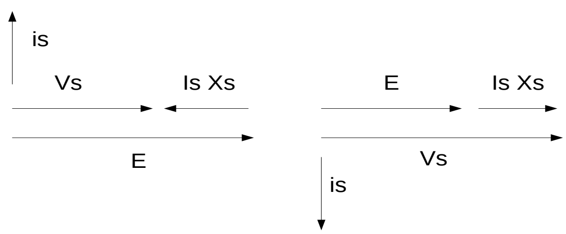

Fig. 3: Phasor diagram for leading and lagging mode

2.2 Operating Principle

As shown in Fig. 3., the STATCOM when operating in steady state condition will generate a leading reactive current when the magnitude of the inverter output voltage E is higher than the magnitude of supply voltage Vs, and it will draw a lagging current from the lines when E is smaller than Vs.

3. MATHEMATICAL MODEL OF STATCOM

3.1 Instantaneous Reactive Current

STATCOM is mainly used to regulate the voltage level of transmission line where it is connected. This is achieved by drawing reactive current from lines n controlling it. STATCOM also has the ability to exchange real power with the transmission line. The real power must be actively controlled to zero on average as the absence of sizable power source or sinks associated with the inverter or DC side component, which departs from zero only to compensate for the losses in the system.

At the point on the line the instantaneous real power is given by

$$\boldsymbol{p = v_a i_a + v_b i_b + v_c i_c} \quad (1)$$

The instantaneous reactive current can be defined conceptually as that part of the three-phase current set that could be eliminated at any instant without altering *P.*

3.2 Vector Representation Of Instantaneous 3- Phase Quantities

As illustrated by Fig. 4. a sum of three instantaneous phase variable equal to zero can be uniquely represented by a single point in a plane. The vector contains all the information on the three phase set, which contains harmonic waveform distortion, steady-state unbalance, and transient components. As per the definition, the vector drawn from the origin to this point has vertical projection onto each of three symmetrically disposed phase axes which corresponds to the instantaneous value of the associated variables. These transformation of phase variable to instantaneous variable can be applied to voltage as well as current. associated vector moves around the plane and describes different trajectories, depending on the change in the value of phase variable.

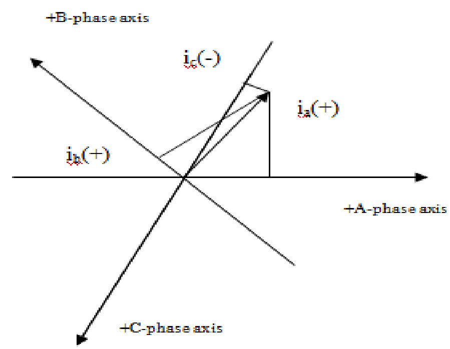

Fig. 4: Vector representation of instantaneous 3-phase variables

As shown in Fig. 5. each vector is presented in form of ds- and qs- components, this is done by introducing an orthogonal co-ordinate system. The transformation from phase variables to ds and qs co-ordinates is as follows:

$$[\boldsymbol{c}] = \frac{2}{3}\begin{bmatrix} \mathbf{1} & -\mathbf{1}/_\mathbf{2} & -\mathbf{1}/_\mathbf{2} \\ \mathbf{0} & \sqrt{\mathbf{3}}/_\mathbf{2} & -\sqrt{\mathbf{3}}/_\mathbf{2} \\ \mathbf{1}/_{\sqrt{\mathbf{2}}} & \mathbf{1}/_{\sqrt{\mathbf{2}}} & \mathbf{1}/_{\sqrt{\mathbf{2}}} \end{bmatrix}$$

$$\begin{bmatrix} \boldsymbol{i_{ds}} \\ \boldsymbol{i_{qs}} \\ \mathbf{0} \end{bmatrix} = [\boldsymbol{c}]\begin{bmatrix} \boldsymbol{i_a} \\ \boldsymbol{i_b} \\ \boldsymbol{i_c} \end{bmatrix}, \begin{bmatrix} \boldsymbol{v_{ds}} \\ \boldsymbol{v_{qs}} \\ \mathbf{0} \end{bmatrix} = [\boldsymbol{c}]\begin{bmatrix} \boldsymbol{v_a} \\ \boldsymbol{v_b} \\ \boldsymbol{v_c} \end{bmatrix} \quad (2)$$

Fig. 5. shows the vector representation of instantaneous reactive current. In Fig. 5. two vectors are drawn, one represents the line voltage of transmission line at the point which it is connected and the second one represents the current in the STATCOM lines. The instantaneous power is given by equation 1 using equation 2 in terms of ds and qs components which is as follow:

$$\boldsymbol{P} = \frac{3}{2}\left(\boldsymbol{v_{ds} i_{ds} + v_{qs} i_{qs}}\right), \boldsymbol{P} = \frac{3}{2}|\boldsymbol{v}||\boldsymbol{i}|\,\mathbf{cos}(\emptyset) \quad (3)$$

where the angle $\emptyset$ is the angle between the voltage and the current vectors. The constant 3/2 is taken so that under balanced steady state condition the definition coincides with the classical phasor definition.

As shown in the Fig. the only component of current vector which is in phase with the instantaneous voltage vector contributes to the instantaneous power. The current component other than that can be removed without changing the power, and this component is therefore the instantaneous reactive current.

These can be extended to define the instantaneous reactive power:

$$Q = \frac{3}{2}\left(v_{ds} i_{qs} - v_{qs} i_{ds}\right),\ Q = \frac{3}{2}|v||i|\sin(\emptyset) \tag{4}$$

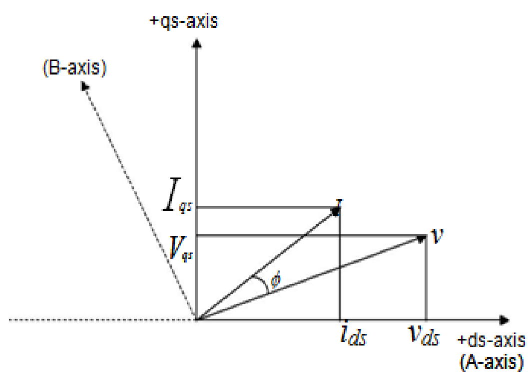

Fig. 5: Definition of orthogonal co-ordinates

The separation of variables for power control purpose is done by manipulating the vector co-ordinate frame is shown in Fig. 6. A new co-ordinate system is defined here, where the d-axis is always coincide with the instantaneous voltage vector and the q-axis is in quadrature with it The d and q axes are not stationary in the plane in fact they follow the trajectory of the voltage vector, and the d and q co-ordinates within this synchronously rotating reference frame.

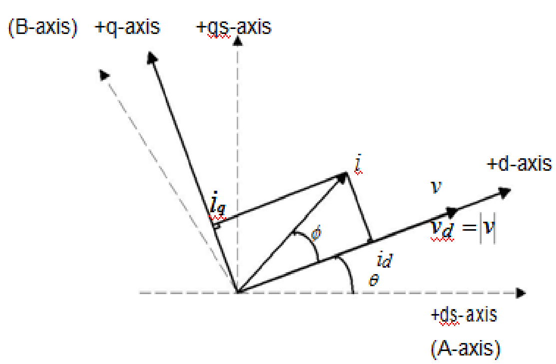

Fig. 6: Definition of rotating reference frame

The d-axis current component i_d represent the instantaneous power and the q-axis current i_q represents the instantaneous reactive current. Under balanced steady-state conditions, the co-ordinates of the voltage and current vectors in the synchronous reference frame are constant quantities. This feature is useful for the analysis and for control of decoupled two current components.

The Synchronously rotating reference frame are given by the time varying transformation given below:

$$[c_1] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$$[c_1]^{-1} = \frac{3}{2}[c_1]_t\ ,\ \ \theta = \tan^{-1}\left(\frac{v_{qs}}{v_{ds}}\right)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = [c]^{-1}\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix},\ \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = [c]^{-1}\begin{bmatrix} |v| \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

and substituting in equation 1, we obtain the real and reactive power as follow:

$$P = \frac{3}{2}|v| i_d\ \ ,Q = \frac{3}{2}|v| i_q \tag{6}$$

3.3 Equivalent Circuit And Equations

The simplified representation of the STATCOM with a DC-side capacitor, an inverter, and series inductance in the three lines connecting to the transmission lines, is shown in Fig. 7.

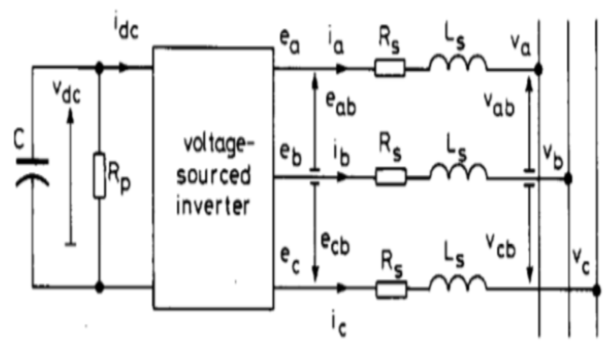

Fig. 7: Equivalent circuit of STATCOM

The inductance represents the leakage of the actual power transformers. Resistance in shunt with the capacitor represents the switching losses took place in the inverter, and resistance in series with the AC lines represents the losses due to the inverter and transformer conduction. The inverter block is treated as an lossless power transformer. The AC-side circuit equations can be written in terms of instantaneous variables as follow:

$$p\begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} = \begin{bmatrix} \frac{-R_s\omega_b}{L'} & 0 & 0 \\ 0 & \frac{-R_s\omega_b}{L'} & 0 \\ 0 & 0 & \frac{-R_s\omega_b}{L'} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{\omega_b}{L'} \begin{bmatrix} (e'_a - v'_a) \\ (e'_b - v'_b) \\ (e'_c - v'_c) \end{bmatrix} \quad (7)$$

where p=d/dt and per unit system has been adopted according to the following definition:

$$L' = \frac{\omega_b L_s}{Z_{base}}, C' = \frac{1}{C\omega_b Z_{base}}, R'_s = \frac{R_s}{Z_{base}}, R'_p = \frac{R_p}{Z_{base}}$$

$$i'_x = \frac{i_x}{i_{base}}, V'_x = \frac{v_x}{v_{base}}, e'_x = \frac{e_x}{e_{base}}, Z_{base} = \frac{V_{base}}{i_{base}} \quad (8)$$

Equation 7 can be transformed to the synchronously rotating reference frame, using the transformation of variables defined in equation 5, as follows:

$$p\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s\omega_b}{L'} & \omega \\ \omega & \frac{-R_s\omega_b}{L'} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \frac{\omega_b}{L'} \begin{bmatrix} (e'_d - |v'|) \\ (e'_q) \end{bmatrix} \quad (9)$$

The AC-side circuit vectors in the synchronous frame is defined in Fig. 8. When i_q' is positive, the STATCOM is drawing inductive power from line, and for negative i_q' it supplies capacitive power.

By neglecting the voltage harmonics produced by the inverter, we can write a pair of equations for e'_d and e'_q.

$$e'_d = kv'_{dc}\cos(\alpha) \quad (10)$$

$$e'_q = kv'_{dc}\sin(\alpha) \quad (11)$$

where k is a factor for which relates the DC-side voltage to the peak of the phase-to-neutral voltage at the inverter AC-side terminals, and α is the angle by which the inverter voltage vector leads the line voltage vector.

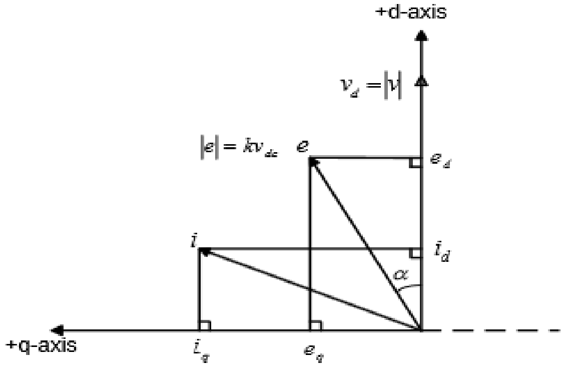

Fig. 8: STATCOM vectors in synchronous frame

Inverter type *I* is used which allows the instantaneous values of both α and k to be varied for control purpose. Provided that reference Vdc is kept sufficiently high, e'_d and e'_q can be controlled independently. This capability can be achieved by various Pulse-Width-Modulation (PWM) technique but that have a negative impact on the efficiency, harmonic content, or utilization of the inverter.

3.4 Inverter type I control system

Equation 9 leads directly to a rule that will provide decoupled control of i'_d and i'_q. The inverter voltage vector is controlled as follows:

$$e_d' = \frac{L'}{\omega_b}(x_1 - \omega i_q') + |v'| \quad (12)$$

$$e_q' = \frac{L'}{\omega_b}(x_2 + \omega i_d') \quad (13)$$

Substituting equation 12 and 13 into equation 9 yields,

$$p\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s\omega_b}{L'} & 0 \\ 0 & \frac{-R_s\omega_b}{L'} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (14)$$

From equation 14 it can be seen that i'_d and i'_q responds to x_1 and x'_2 respectively, through a simple first-order transfer function, with no cross-coupling. The control rule for equation 12 and 13 is thus achieved by defining the feedback loops and proportional plus integral compensation as follows:

$$x_1 = \left(k_a + \frac{k_b}{p}\right) + (i'^{*}_d - i'_d) \quad (15)$$

$$x_2 = \left(k_a + \frac{k_b}{p}\right) + (i'^{*}_q - i'_q) \quad (16)$$

The control is achieved by using the feedback variables in the synchronous reference frame. The reference reactive current i_q*, is supplied from the STATCOM outer loop voltage control system, and the real power is regulated by varying i'^{*}_q according to the difference in DC-link voltage via a proportional plus integral compensation. A block diagram of the control scheme is presented in Fig. 9.

4. IMPLEMENTATION OF STATCOM

4.1. Description

A 0.5 kVA STATCOM using a three phase supply, line to line voltage is 190V. The sensed voltage and current given to the controller. The controller then generates the reference voltage waveform. This reference voltage waveform is compared with triangular wave in SPWM technique, thereby generating the gate pulses for inverter card switches. The coupling transformer is used for isolation between the STATCOM and grid.

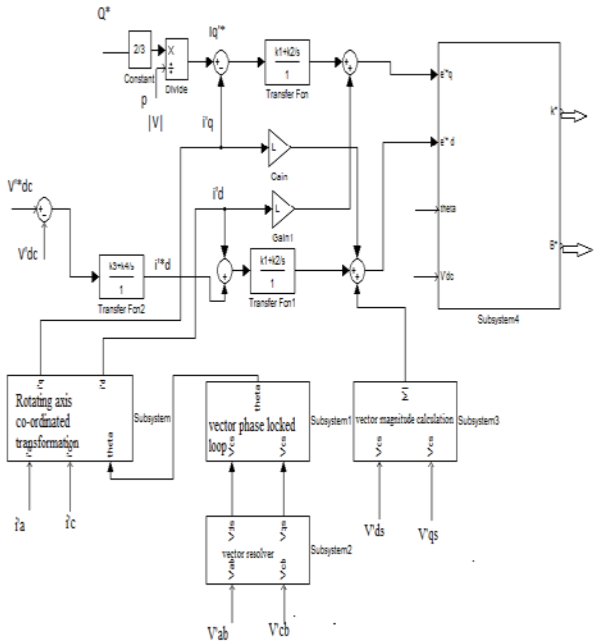

Fig. 9: Block diagram of Inverter type I control

4.2. Simulation Parameter

Sr. No	PARAMETER	VALUES
1	Phase voltage	110 volt
2	Line voltage	190 volt
3	Current	3.2 A
4	Fundamental frequency	50 Hz
5	Switching frequency	2250 Hz
6	Capacitor	220 □F
7	Coupling Transformer	0.5kVA
8	Coupling Transformer resistance	1.6 ohms

5. RESULTS FROM STATCOM PROPOSED MODEL

1. Phase angle

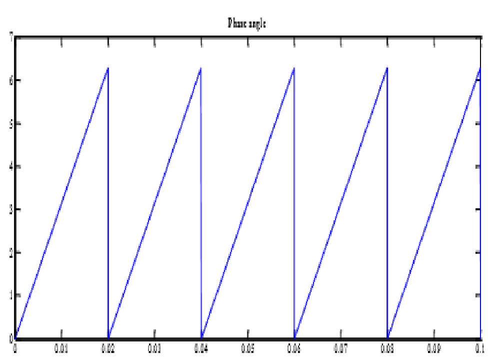

Fig. 10: Phase angle

A Phase-Locked Loop (PLL) is a control system that generates a signal that has a fixed relation to the phase of a reference signal. A phase-locked loop circuit responds to both the frequency and the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase as shown in Fig. 10.

2. Reactive current

For grid voltage regulation, reactive current is observed. When load is capacitive then reactive current is increased and when load is inductive reactive current decreases while, in balanced condition reactive current is zero as shown in Fig. 11. When there is change in reactive current, references signal changes accordingly.

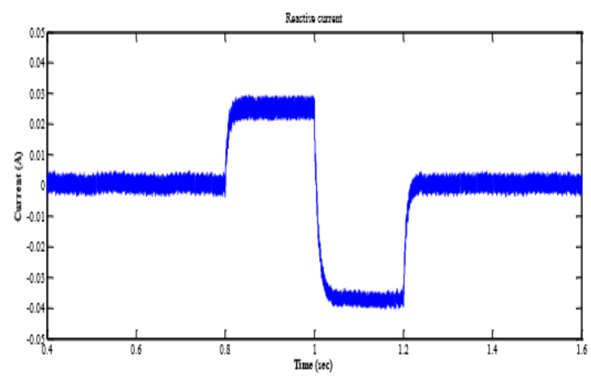

Fig. 11: Reactive current I_q

3. Reference Signal

Fig. 12. shows the controller reference signals generated from the controller. It can be seen from the Fig. that when load is capacitive within time interval 0.8 to 1.0 then the reference voltage is increasing and when load is inductive within time interval 1.0 to 1.2 then reference voltage is decreasing. For the inverter used in this thesis, SPWM technique is used for generating the gate pulse for inverter.

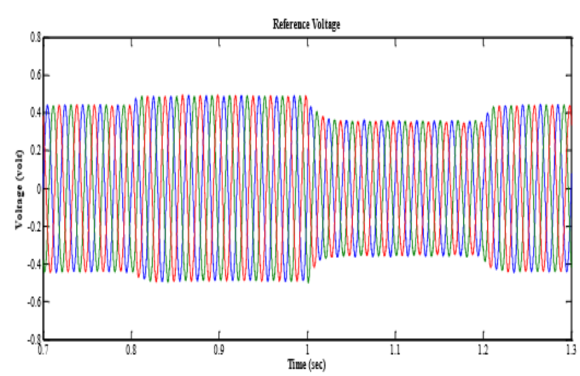

Fig. 12: Controller reference voltage

4. Capacitor voltage

Reactive power changes are observed by capacitor voltage. Fig. 13. shows the variation in capacitor voltage. When load is capacitive, reactive power is absorbed by the STATCOM. On the other hand, when the load is inductive reactive power flows from the STATCOM. In balanced condition, there is no change in capacitor voltage.

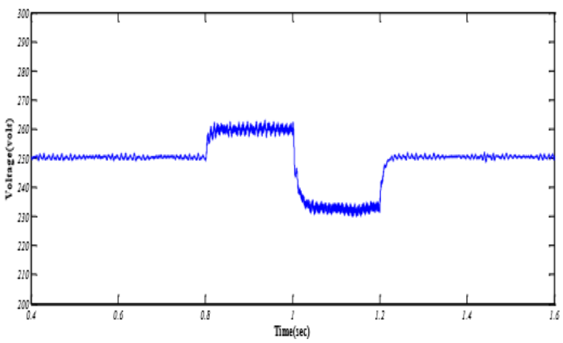

Fig. 13: Capacitor voltage

5. Phase current and voltage

A sinusoidal alternating voltage applied to a purely resistive load results in an alternating current that is fully in phase with the voltage. However, in practical applications reactive component in the system exists due to capacitive or inductive load. These electrical properties cause the current to change phase with respect to the voltage, capacitance tending the current to lead the voltage in phase and inductance to lag it.

The line current flowing into or out of the VSI is always at 90 , to main voltage due to reactive coupling. When there is change in reactive current the phase shift in line current for both capacitive mode and inductive mode is shown in Fig. 14.

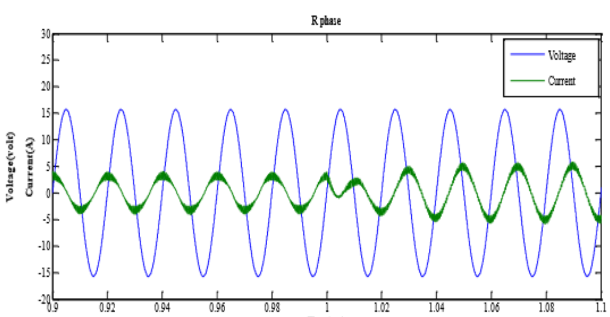

Fig. 14: For R-Phase

6. CONCLUSION

Nowadays STATCOM is an important part of power transmission system. The proposed system has thoroughly been modeled and analyzed. The mathematical model derived in this report is the key of the development of the decoupled control scheme and an important contribution for future power transmission systems studies.

Programmed PWM switching pattern is used as a means of reducing the size of reactive components and to have a high quality reactive power in compensation. Simulated results obtained have confirm the applicability of the proposed scheme and have led to a proper design of a simple and fast controller for reactive power applications. Detailed simulation studies are carried out to demonstrate the effectiveness of the control scheme.

REFERENCES

[1] C. Schauder, H. Mehta, "Vector analysis and control of advanced Static VAR compensators", *IEEE Proceedings*, vol. 140, pp. 299-306, 1993.

[2] P. S. Sensarma, K. R. Padiyar, V. Ramanarayanan, "Analysis and Performance Evaluation of a Distribution STATCOM for Compensating Voltage Fluctuations", *IEEE Transactions on Power Delivery*, vol. 16, no. 2, 2001.

[3] Nitus Voraphonpiput, Somchai Chatratana, "STATCOM Analysis and Controller Design for Power System Voltage Regulation", *IEEE/PES Transmission and Distribution Conference*, vol. 5, no. 4, pp. 114-119, 2005.

[4] Deepika Masand, Shailendra Jain, Gayatri Agnihotri, "Control Algorithms for Distribution Static Compensator", *IEEE ISIE*, vol. 5, no. 6, pp. 1830-1834, 2006.

[5] Pablo Garcia Gonzalez, Aurelio García-Cerrada, "Control System for a PWM-Based STATCOM", *IEEE Transactions on Power Delivery*, vol. 15, no. 4, pp. 1811-1817, 2000.

[6] Dong Shen, Xu Liang, Yingduo Han, "A Modified Per-unit STATCOM Model and Analysis of Open Loop Response Time", *IEEE Transactions on Power Delivery*, vol. 6, no. 8, pp. 2624-2629, 2000.

[7] K. R. Padiyar, "Facts Controllers in Power Transmission and Distribution", 2009, New Age International Publishing.

[8] L Gyugi, N G Hingorani, P R Nannery, N Tai, "Advanced static VAR compensator using gate turn-off thyristors for utility applications", *CIGRE*, vol. 4, no.5, pp. 253-258, 1990.

[9] Tahri, A. Draou, M. Benghanem, "A Fast current control strategy of a PWM Inverter used for Static VAR Compensator", *IEEE*, vol. 7, no. 8, pp. 512-519, 1998.

[10] HINGORANI, N.G., "High power electronics and flexible AC transmission system", *IEEE Power Eng. Rev*., vol. 31, no. 5, pp. 1561-1566, 1988.

[11] H.F.Wang, "Application of damping torque analysis to STATCOM control", *IEEE Electrical Energy and Power System*, vol. 22, no. 14, pp. 197-204, 2000.