Digital simulation of forty eight pulse STATCOM for reduction of voltage instability and improvement of power quality

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Abstract

With the trend of progression of distributed generation within a bulk power system, there is a need to support bus bar voltage by injecting appropriate reactive power, which can also improve the dynamic behaviour of a power system. Static Synchronous Compensators (STATCOMs) is a power electronic based synchronous voltage generator (SVG), which provides embedded control of transmission-line voltage and power flows. The paper represents the internal structure of the forty eight pulse STATCOM-based on two24-pulse GTO-based converters, phase-shifted by 7.5 º from each other for reduction in THD at the output voltage of the load in power systems. The integration of energy storage with a STATCOM can extend traditional STATCOM capabilities to four quadrant power flow control and transient stability improvement. The proposed model of the STATCOM is connected to a 25kv, 60 Hz system and simulation (in MATLAB) results are presented for demonstrating its steady state and dynamic performance. Fast Fourier Transform (FFT) analysis has also been carried out and the results showing the value of THD within acceptable limit and fast control of the reactive current. Thus the STATCOM shows excellent transient response to step change in the reactive current reference.

Keywords: FACTS,STATCOM,VSI,FFT,THD.

1. Introduction

With the trend of deregulating power industry and more distributed generators, the modern power system needs to provide stable, sufficient, secure, economic and high quality electric power to various load centers. This situation has spurred interest in providing already existing power system with greater operating flexibility and better utilization, thus having led to the concept of FACTS. The main purpose of introducing FACTS to the power system is to increase stability and transmission capability as stated by Hingorani&Gyugyi (2000). For transmission networks, one of the major consequence of the non discriminatory open access requirement is a substantial increase of power transfers, which demand adequate ATC, to ensure all economic transactions. Sufficient ATC should be generated to support free market trading and maintain an economical and secure operation over a wide range of system of condition as stated by Xiao *et al.* (2003). FACTS devices are also used for ATC enhancement, fast dynamic control of voltage, impedance, and phase angle in high voltage AC transmission system and they need a considerably smaller amount of real estate for their installation. The main drawback of using FACTS device is switching and conduction loss. Also voltage rating of switching devices is not enough. For high voltage application, we mostly use GTO (~ 6 KV rating max) as switching devices. To increase the voltage rating of power converter and so of the overall FACTS controllers, different multilevel topologies have been proposed by Lai and Peng (1996). The hardware of a STATCOM is similar to the shunt branch of the Unified Power Flow Controller (UPFC) and and can be controlled to provide concurrent real and reactive compensation with an external electric energy source adding to the DC bus as shown by Ma (2011). The series and shunt compensation has the purpose of handling reactive power to maintain bus voltage nearer to their nominal values, reduce line currents and system losses. By regulation of the STATCOM's output voltage magnitude, the reactive power exchanged between the STATCOM and the transmission system can be controlled, as expressed by Hingorani&Gyugyi (2000). The circulating power in the grid that does no useful work which results from energy storage elements in the power grid has a strong effect on the system voltage collapse and current distortion is mainly generated by non linear loads (electronic load). This current distortion affects the power system stability and distribution equipment. By adjusting terminal voltage of generators and tap changing of OLTC, particularly rescheduling generator outputs are considered as major control measures for ATC boosting. This paper presents the design of eighty-four-pulse VSC based STATCOM for satisfactory performance in performing various reactive power flow control function during steady-state and transient operations of power systems. Sood (2004) expresses how multi-purpose circuit configurations are employed to reduce the harmonic generation and to produce practically sinusoidal current. The digital signal processor (DSP) control implementation should incorporate to take the voltage levels needed for the ADC to detect the signals with appropriate precision and must refresh the output data before to take new samples in order to be considered real time. The proposed STATCOM is modelled using MATLAB/SimPower System (SPS) toolbox and the results of various power flow control are presented to show the effectiveness of the proposed control strategy.

2. Working Principle of STATCOM

The essential component in a VSC based STATCOM are GTO-VSC bridge (s), DC capacitor (c), working as an energy storage device, interfacing magnetic forming the electrical coupling between the VSC bridge circuit, AC mains system and controller generating gating signals, as presented by Singh and Saha (2006). The reactive power exchange between the AC system and the compensator is controlled by varying the fundamental component magnitude of the inverter voltage, above and below the AC system level. The compensator control is achieved by small variations in the semiconductor devices switching angle, so that fundamental component of the voltage generated by the inverter is forced to lag or lead the AC system voltage by a few degrees causing the flow of active power into or out of the VSI & the resultant reactive power. Fig. 1 shows the schematic configuration and power exchange of STATCOM. The controlled output voltage is maintained in phase with the line voltage, and can be controlled to draw either capacitive or inductive current from the line rapidly. STATCOM has the ability to maintain full capacitive output current at low system voltage, which improves the transient stability output voltage of VSC bridge (E_s) is governed bydc capacitor voltage which is controlled by varying the phase difference between(E_s) and (E_t) (system voltage at bus). The magnitude and phase difference of $I_q$determine the magnitude and phase difference between E_s and E_t across the transformer leakage inductance, which, in turn, controls reactive power flow.

The basic objective of a good VSI-converter scheme is to produce a near sinusoidal ac voltage with minimal wave form distortion or excessive harmonics content. Three basic techniques can be used for reducing the harmonics produced by the converter switching. Harmonic neutralization using magnetic coupling (multi pulse converter configurations), harmonic reduction using multilevel converter configurations, and novel pulse-width modulation (PWM) switching techniques. The 24- and 48-pulse converters are obtained by combining two or four (12-pulse) VSI, respectively, with the specified phase shift between all converters. For high-power applications with low distortion, the best option is the 48-pulse converter, although using parallel filters tuned to the 23th–25th harmonics with a 24-pulse converter could also be adequately attentive in most applications, but the 48-pulse converter scheme can ensure minimum power quality problems and reduced harmonic resonance conditions on the interconnected grid network.

3. Mathematical Modelling of the STATCOM

We have already seen that STATCOM (or D-STATCOM) is a power electronic system with a complex control system. We have already seen the equivalent circuit of STATCOM as shown in Fig.-2. Here the resistance, $r_s$is the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance $l_s$represents the leakage inductance of the transformer. The resistance $r_p$denotes the sum of the switching losses of the inverter & the power loss in the capacitor (which acts as an energy storage device).The voltages e_a, e_b&$e_c$are the inverter ac side phase voltages suitably stepped up.
The loop equations for the circuit may be written as:

$$\frac{d}{dt} i_{abc} = -\frac{r_s}{l_s} i_{abc} + \frac{1}{l_s}\left(e_{abc} - v_{abc}\right) \tag{1}$$

The phase voltage of bus acan be written as:

$$V_s = \sqrt{2} V_{s(rms)} \cos\left(\omega_s t + \theta_s\right) \tag{2}$$

Where, θ_s is the phase angle between V_s and V_{dc}.

The output of the STATCOM (neglecting harmonics) may be expressed in the d-q frame of reference as:

$$e_{ad} = k_m V_{dc} \sin\left(\omega_s t + \alpha\right) \tag{3}$$

$$e_{aq} = k_m V_{dc} \cos\left(\omega_s t + \alpha\right) \tag{4}$$

where,
V_{dc} is the DC-side voltage,
α is the phase angle of the voltage between and output voltage of VSI
k_m is the modulation index that relates the DC voltage to the peak voltage on the AC side.
Transforming the system to a synchronous reference frame (using Kron's transformation) and scaling the equations (where the primed quantities indicate per unit) results in the following model (Rao*et a1*., 2000)

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \\ V'_{dc} \end{bmatrix} = A_s \begin{bmatrix} i'_d \\ i'_q \\ V'_{dc} \end{bmatrix} - \frac{\omega_s}{L'_s}\begin{bmatrix} V_s \cos\theta_s \\ V_s \sin\theta_s \\ 0 \end{bmatrix} \tag{5}$$

Where,

$$A_s = \begin{bmatrix} \frac{-R'_s w_s}{L'_s} & w_s & \frac{W_s k}{L'_s}\cos(\alpha+\theta) \\ -w_s & \frac{-R'_s w_s}{L'_s} & \frac{W_s k}{L'_s}\sin(\alpha+\theta) \\ M_k \cos(\alpha+\theta) & M_k \sin(\alpha+\theta) & \frac{-C' w_s}{R'_p} \end{bmatrix}$$

and

$$M_k = \frac{3}{2} k w_s C' \tag{7}$$

Note that, equation (5) is a nonlinear equation. The nonlinearity of the STATCOM is manifested by the inclusion of the state equation for the control angle α. Changes in the control angle α will results in non-linear responses in the STATCOM states i_d ,i_q and V_{dc}.

4. Two Level 48 Pulse STATCOM Model

Fig.1 depicts the simpler and basic representation of the six-pulse Statcom.
R: is the series resistance representing the transformer windings resistances plus the converter conduction losses.
L: is the transformer's leakage inductance.
C: is the capacitance of the DC side.
The mathematical model of such STATCOM is developed in [10] and it is given by:

$$e_{an}(t) - v_{an}(t) = L\frac{d}{dt} i_a(t) + R\, i_a(t) \tag{8}$$

$$e_{bn}(t)-v_{bn}(t)= L\frac{d}{dt} i_b(t)+R i_b(t) \quad (9)$$

$$e_{cn}(t)-v_{cn}(t)= L\frac{d}{dt} i_c(t)+R i_c(t) \quad (10)$$

where $v_{an}(t)$ is the converter output voltage determined by the gating signals and the DC voltage.
The STATCOM state space model at fundamental frequency is given by

$$\dot{x} = A_s x(t) + B_s u(t)$$

Where $x(t) = [i_a^0(t), i_b^0(t)\ i_c^0(t), v_{DC}^0(t)]^T$

And $u(t) = [e_{an}(t), e_{bn}(t), e_{cn}(t)]^T$

$$A_s = \begin{bmatrix} \frac{-R}{L} & 0 & 0 & -k_1 \sin(wt+\alpha) \\ 0 & \frac{-R}{L} & 0 & -k_1 \sin(wt+\alpha-120) \\ 0 & 0 & \frac{-R}{L} & -k_1 \sin(wt+\alpha-240) \\ -k_1 \sin(wt+\alpha) & -k_1 \sin(wt+\alpha-120) & -k_1 \sin(wt+\alpha-240) & \end{bmatrix}$$

$$B_s = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & \frac{1}{L} \end{bmatrix}$$

$k_1 = 2/\pi L$, $k_2 = 2/\pi C$ for a 6 pulses converters

$k_1 = 4/\pi L$, $k_2 = 4/\pi C$ for a 12 pulses converters

$k_1 = 8/\pi L$, $k_2 = 8/\pi C$ for a 24 pulses converters

$k_1 = 16/\pi L$, $k_2 = 16/\pi C$ for a 48 pulses converters

The Park's transformation ratio has been used so that the Statcom's model in the dq0 reference frame becomes:

$$\dot{x} = A_{dq0}x_{dq0} + B_{dq0}u_{dq0} ,$$

Where:

$$x_{dq0} = [\, i_d ,\ i_q ,\ i_0 ,\ v_{DC}]^T$$
$$u_{dq0} = [e_d ,\ e_q ,\ e_0 ,\ 0]^T$$

$$A_{dqo} = \begin{bmatrix} \frac{-R}{L} & w & 0 & -k_1 \sin(x) \\ -w & \frac{-R}{L} & 0 & -k_1 \cos(x) \\ 0 & 0 & \frac{-R}{L} & 0 \\ \frac{3}{2} k_1 \cos(x) & \frac{3}{2} -k_1 \cos & 0 & \frac{1}{C} \end{bmatrix}$$

$$B_{dqo} = \begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & \frac{1}{C} \end{bmatrix}$$

Fig.1. *STATCOM schematic and power exchange with AC system*

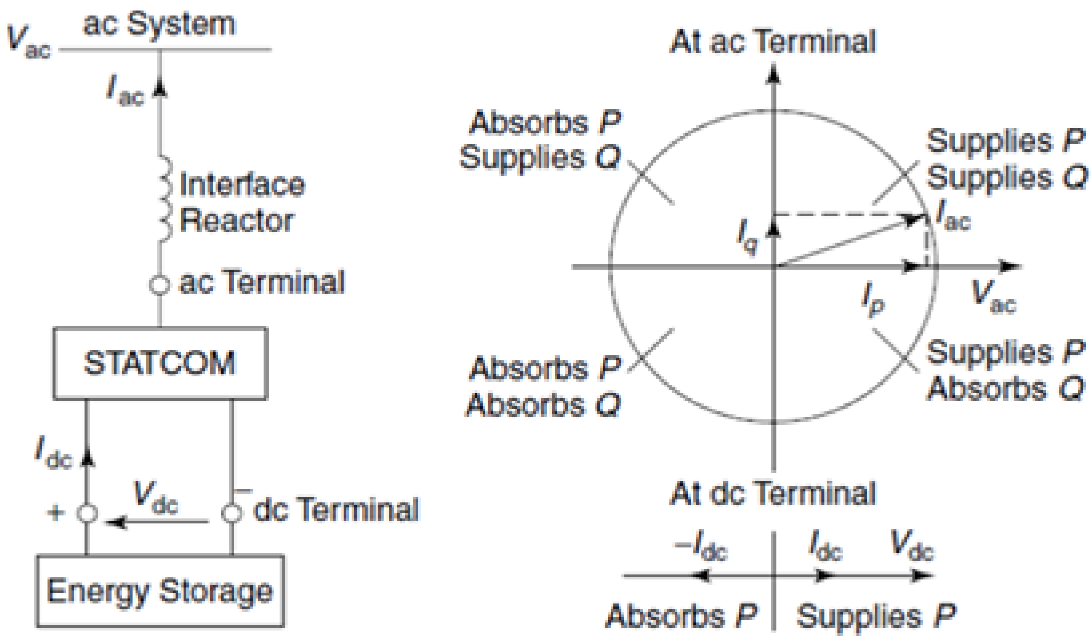


Fig.2. *Equivalent circuit of STATCOM*

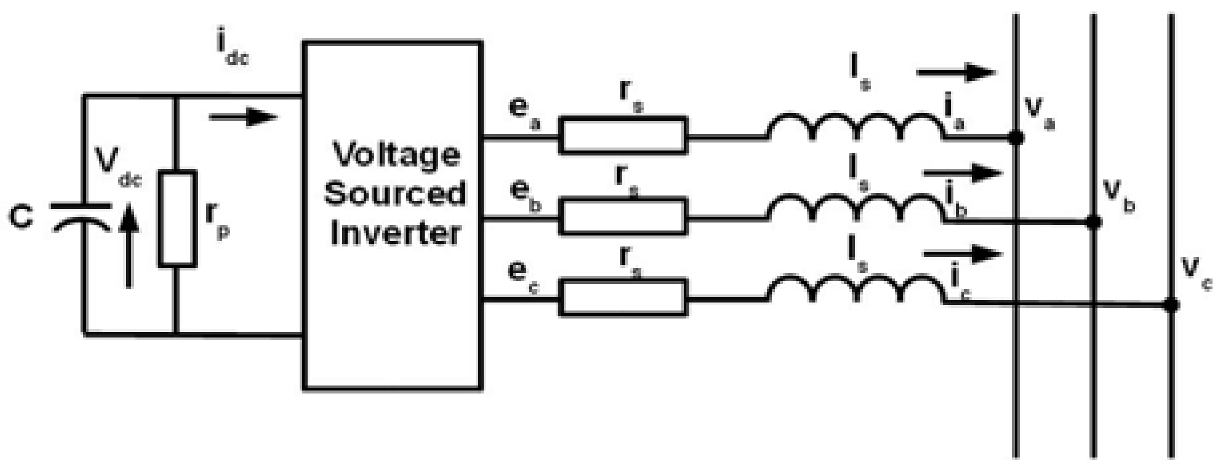
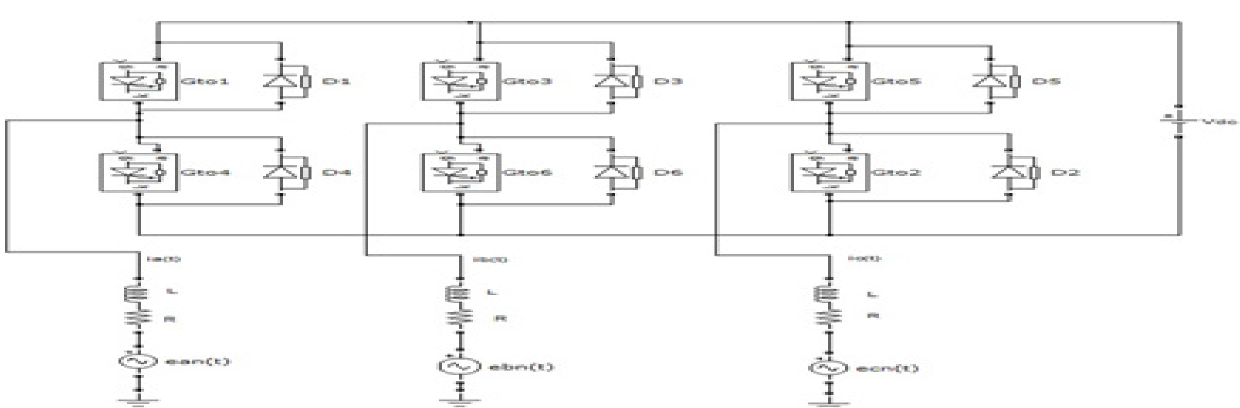


Fig.3. *Basic representation of the six-pulses STATCOM*



5. Control of STATCOM

We can control the output voltage of STATCOM by the following two methods.

1. Indirect control:- By controlling the dc capacitor voltage, reactive output current can be controlled.

2. Direct control:- When dc voltage is kept constant, this type of control can be obtained by internal voltage mechanism of the multilevel VSI. In case of indirect vector control method, three phase currents are transformed to direct and quadrature axis, which are then synchronized with the ac system (3 phase) voltage via a phase locked loop (PLL). The d-axis and q-axis voltages generated by vector control are then transformed to three phase quantities and converted into line voltages by multilevel VSI. By increasing or decreasing the capacitor voltage by using control system block, we can obtain the correct amplitude of VSI output voltage for the required reactive power. A frequently used measure of harmonic level of VSI output voltage is total distortion (THD) or distortion factor (DF). THD is the ratio of RMS value of the harmonics (except fundamental) to the RMS value of the fundamental, times 100%.

$$THD = \sqrt{\frac{1}{V_1^2}\sum_{k=2,3...}^{\infty} V_k^2} \ X\ 100\%$$

$$DF = \sqrt{\frac{1}{V_1^2}\sum_{k=2,3...}^{\infty}\left(\frac{V_k^2}{k^4}\right)}$$

The power factor of the system is affected with THD and hence if THD is controlled, power factor of the system is controlled. The eighty four pulse signal value depends on the injection transformer turns ratio. However a strict re-injection transformer's turns-ratio is not needed to get a THD within a stringent condition.

6. Simulation of the STATCOM with System Description Using Forty Eight Pulse VSI

In our proposed system (Fig.5), the STATCOM is connected to bus through a coupling transformer with resistance and reactance respectively. In the Power circuit diagram of the STATCOM, the converter has multi-pulse or a multilevel configuration. With Forty Eight pulse converter topology, the magnitude of the ac output voltage of VSI can be changed by varying the dead angle with fundamental switching frequency. This higher level topology of the VSI greatly reduces the THD much more than two-level VSI. Here, the STATCOM is connected to a 25 KV, 60 Hz. System, where fixed load and variable loads are existing in different buses.

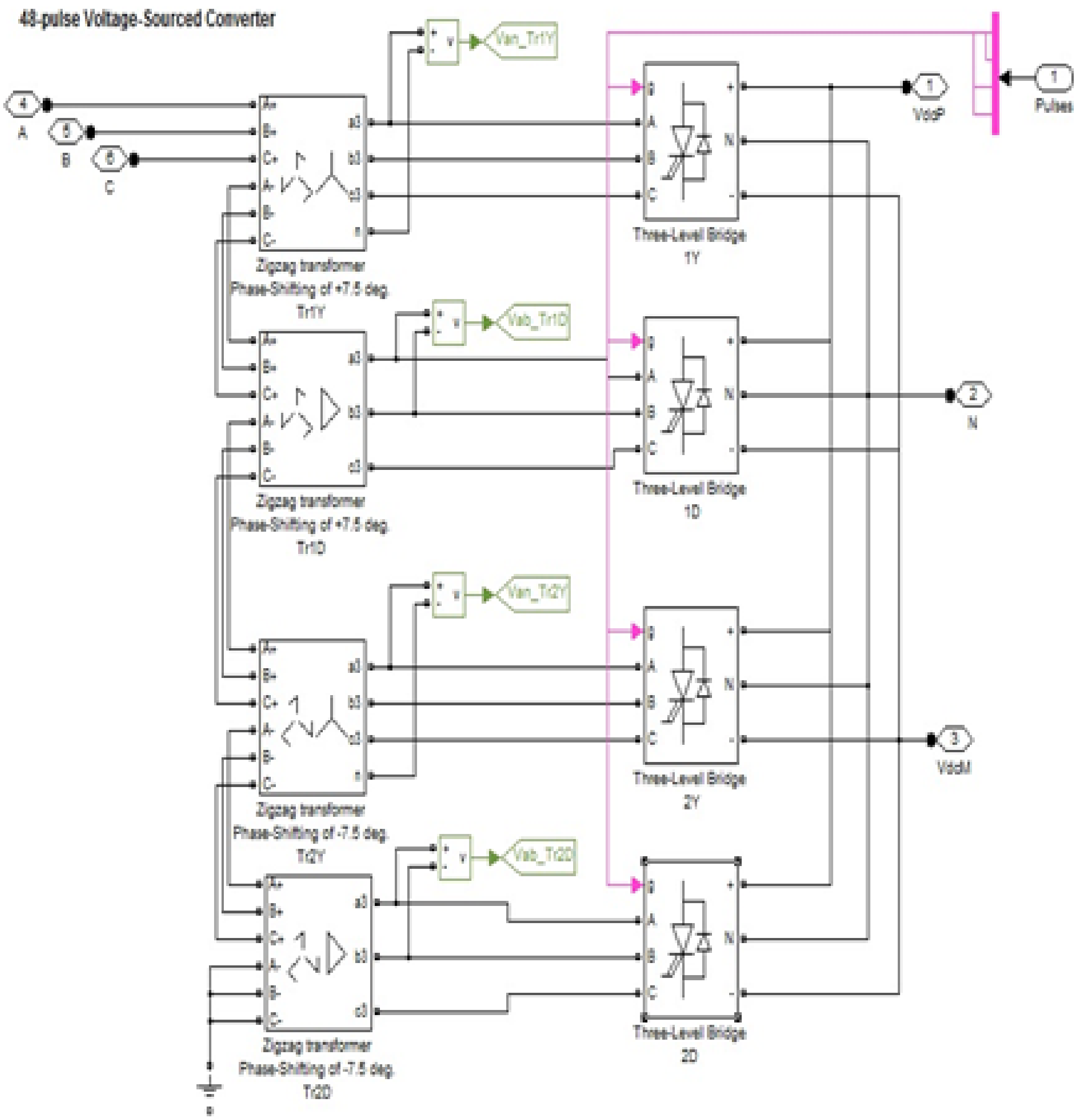
The basic building block of the STATCOM is the full 48-pulse converter-cascade implemented using the MATLAB/Simulink software it was shown in the Fig.4(Ref:Appendix). The control process is based on a novel decoupled current control strategy using both the direct and quadrature current components of the STATCOM. The operation of the full STATCOM model is fully studied in both capacitive and inductive modes in a power transmission system and load excursion. The use of full 48–pulse STATCOM model is more accurate than existing low-order or functional models.

The STATCOM output is coupled on parallel with the network. A 12,000µF capacitor is used as dc voltage source for the inverter. The standard response time is typically chosen to be of the order of a hundred microseconds (i.e. 0.2s). To control the output voltage of VSI,PWM Strategy has been used not only for fast communications to reach a lower THD but also it can be effectively used during unbalanced operation of the system.

Appendix:

Internal diagram of 48-pulse generation block and VSC are shown in the following figure:

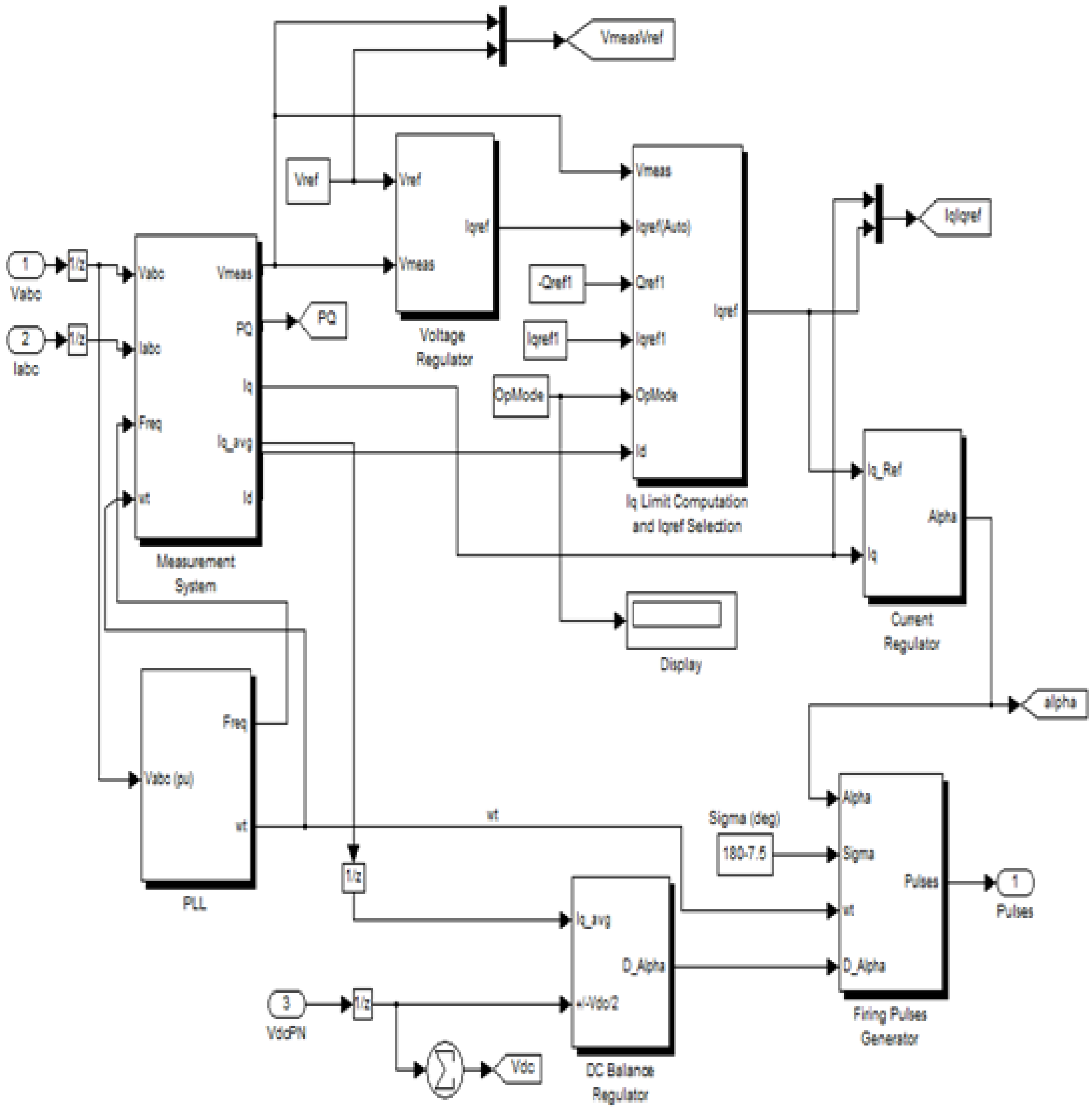
Fig.4(a). Forty-eight-pulse (GTO based) voltage source converter(VSC).



Two 24-pulse GTO-converters, phase-shifted by 7.5 º from each other, can provide the full 48-pulse converter operation. Using a symmetrical shift criterion, the 7.5 º are provided in the following way: phase-shift winding with ---3.75º on the two coupling transformers of one 24-pulse converter and +3.75º on the other two transformers of the second 24-pulse converter. The firing pulses need a phase-shift of +3.75º, respectively. The 48-pulse converter model comprises four identical 12-pulse GTO converters inter-linked by four 12-pulse transformers with phase-shifted windings. Fig. 3 depicts the schematic diagram of the 48-pulse VSC (GTO based) model. The transformer connections and the necessary firing-pulse logics to get this final 48-pulse operation are also modelled. The 48-pulse converter can be used in high-voltage high-power applications without the need for any ac filters due to its very low harmonic distortion content on the ac side. The output voltage have normal harmonics n=48± 1 , where r=0,1,2,……, i.e., 47^{th} ,49^{th} ,95^{th} ,97^{th} ,…. , with typical magnitudes (1/47^{th} ,1/49^{th} , 1/95^{th} ,1/97^{th} ,….), respectively, with respect to the fundamental; on the dc

side, the lower circulating dc current harmonic content is the 48th.
STATCOM output voltage and voltage across the load are shown in Fig. 6.The frequency spectrum are shown in Fig.7& Fig8.

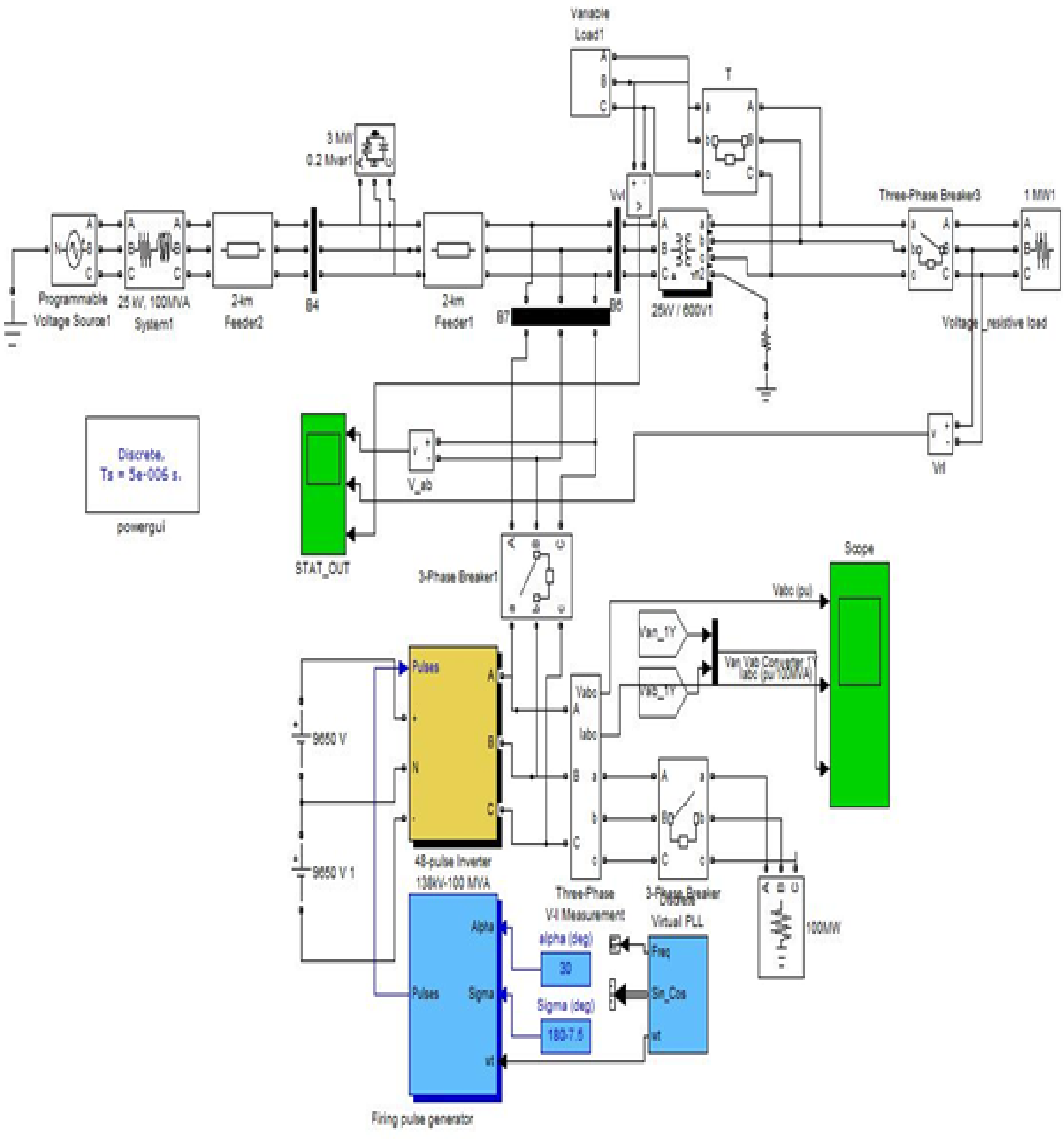
Fig.4(b). 48-pusle generation block



7. Results and Conclusion

The forty eight pulse digital simulation of the STATCOM with PWM switching Strategy is very attractive and effective configuration for High voltage application. In our system, each phase has to respond individually with its own voltage. Two 24-pulse GTO-converters, phase-shifted by 7.5º from each other, can provide the full 48-pulse converter operation. The performance of the proposed STATCOM with the optimized control parameters results in excellent transient response. It is also clearly seen that the STATCOM improves the voltage magnitude considerably across the different types of load & thus reduces the problem of voltage instability. This phenomenon has been verified by comprehensive digital time domain 'MATLAB' simulations. The harmonic content of the STATCOM current is also

Fig. 5. *SIMULINK Model of the proposed 3-Phase system with STATCOM*



found good enough within specified IEEE-519 standard & thus shows its excellent effectiveness in Power quality improvement.

Fig. 6. *Output voltage response curve of STATCOM and Load*

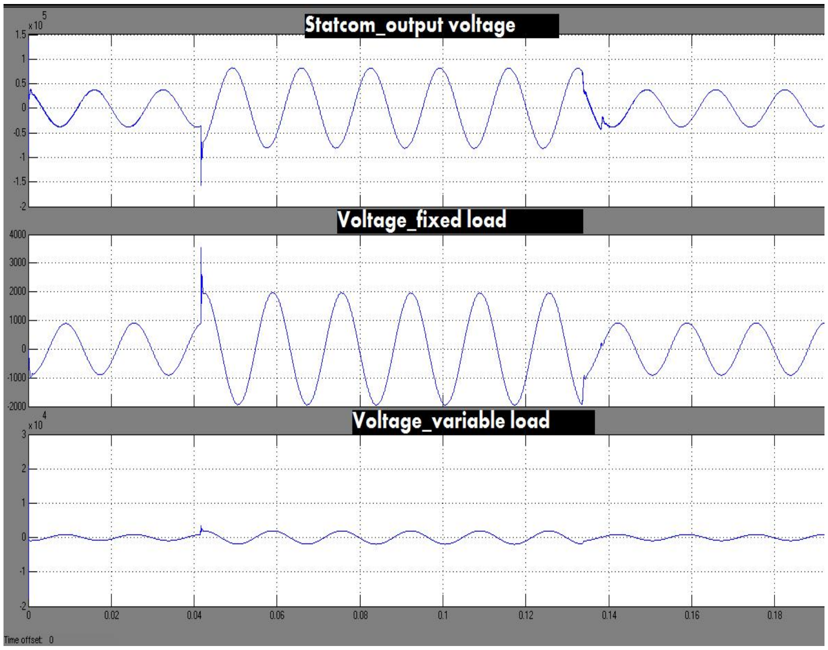


Fig. 7(a). *FFT analysis of voltage with fixed load*

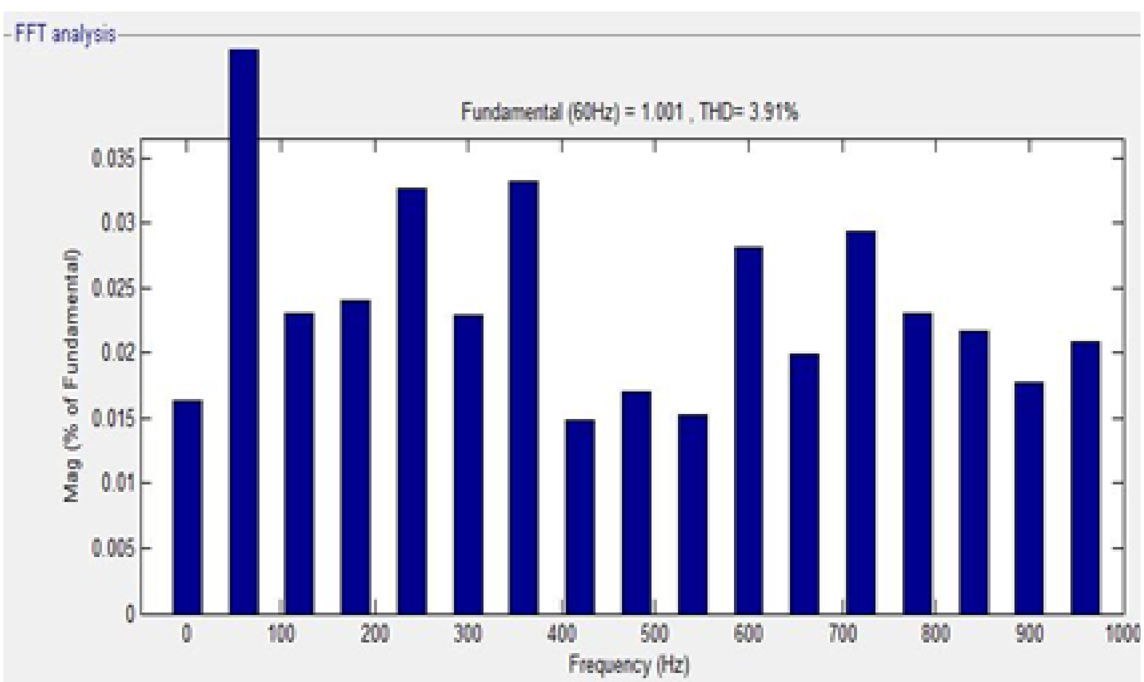


Fig. 7(b). *FFT analysis of voltage with variable load*

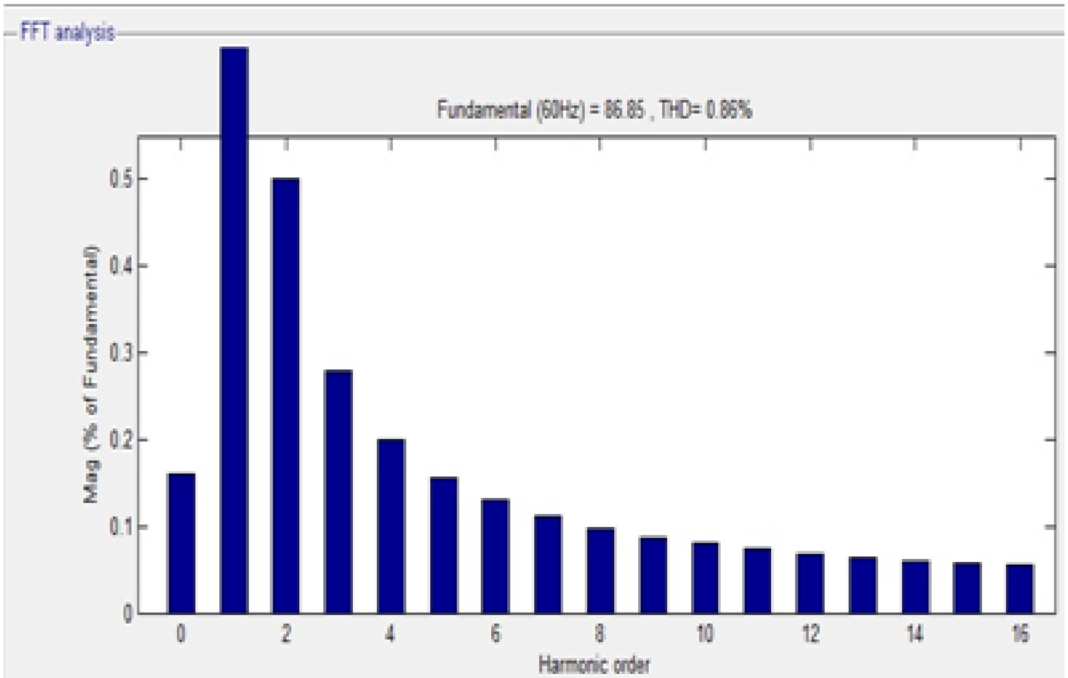
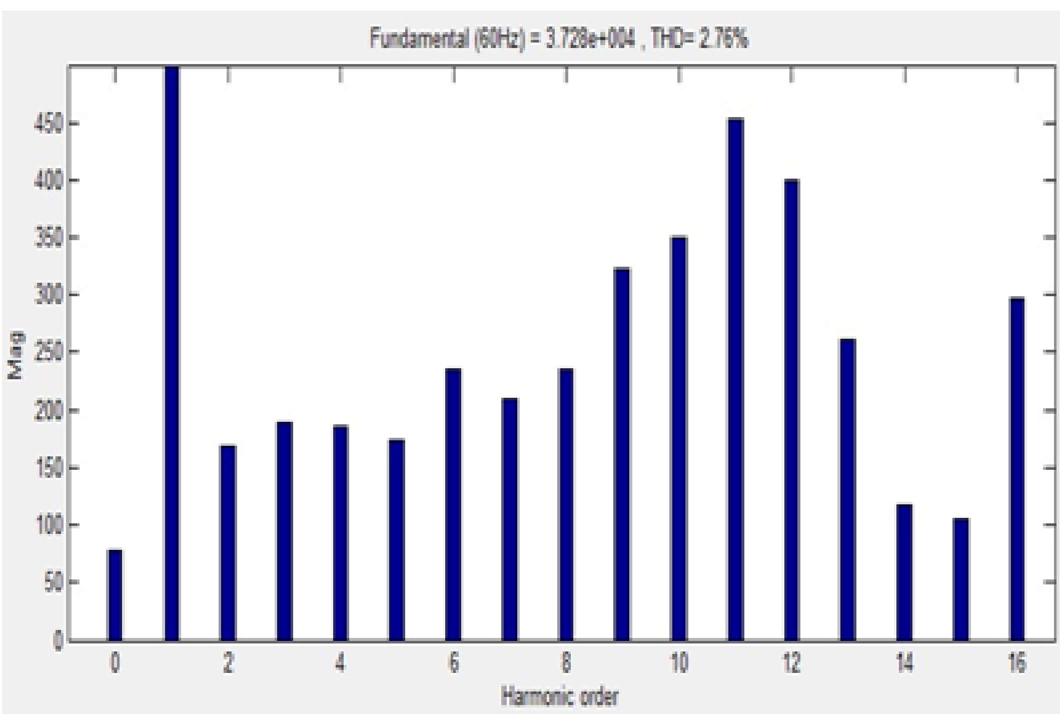


Fig. 8. *FFT analysis of output voltage of Statcom*



8. References

1• Hingorani NG and Gyugyi L (2000)Understanding FACTS: Concepts and technology of flexible AC transmission systems. Institute of Electrical and Electronic Engineer, New York.

2• Lai JS and Peng FZ(1996)Multilevelconverters: A new breed of power converters.*IEEE Trans.Ind.Appl*.32 (3), 509-517.

3• Ma TT (2011)New control strategies for a Two-Leg Four Switch STATCOM.*Proc. Int. Multi Conf.Eng.*Vol II,IMECS-2011,Hongkong.

4• Sood VK(2004) HVDC and FACTS Controllers: Applications of Static Converters in Power Systems.Kluwer Academic Publishers, USA.

5• Singh B and Saha R(2006) A New 24-pulse STATCOM for voltage Regulation.*Int. Conf. on Power Electronics, Drives and Energy Systems,PEDES*. pp:1-5.

6• IEEE Standard 519-1992(1992) IEEErecommended practices and requirements for harmonic control in electrical power systems.*IEEE Inc.,* New York.

7• Xiao Y, Song YH, Liu CC and Sun YZ(2003) Available transfer capability enhancement using FACTS devices.*IEEE Transaction on Power Systems*.Vol.18,No.1.

8• Rao P, Crow ML and Yang Z (2000) STATCOM control for power system voltage control applications. *IEEE transactions on Power Delivery.* 15 (4), 1311-1313.

9• Lee CK, Leung JSK, Ron-Hui SY and Chung HSH (2003) Circuit level comparison of STATCOM technologies. *IEEE Trans. Power Electronics.* 18 (4), 1084-1092.

10• Ricardo DM (2003) Detailed analysis of a multi-pulse STATCOM, Pre-doctoral thesis.