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RESEARCH ARTICLE

Reduction of THD using three level twenty-four pulse VSI based STATCOM

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Abstract

This study deals with digital simulation of STATCOM based on three level twenty-four pulse VSI using SPWM control strategy to support bus bar voltage as well as harmonic reduction of the voltage and current across different types of load. Multilevel VSI is extremely fast in response to reactive power change. In keeping with the need to implement very high-power inverters, switching frequencies is restricted to line frequency. The system stability can be improved when the shunt FACTS devices (like STATCOM) are controlled by some auxiliary signals superimposed over its voltage control signals. While the power marketers are focusing on fully utilizing the transmission system. Researchers are concerned with the transmission system security as any power transfers over the limit might result in system instability. The proposed control strategy improves the STATCOM output side harmonic spectrum and also enables balancing voltages of the DC capacitors.

Keywords: STATCOM, reactive power change, high-power inverters, auxiliary signals, DC capacitors.

Introduction

In recent decades, the electric distribution systems are suffering from various problems. Amongst them, the important one is power quality problems which are characterized by poor voltage regulation, voltage flickering, voltage sag/swell, load unbalancing, low p.f. etc. As a result, many Power quality standards were proposed in IEEE std. 141-1993, IEE std. 1159-1195, IEC 1000-3-2 etc. FACTS devices are used in power distribution systems in a large scale to improve both the static and dynamic performances of the power system.

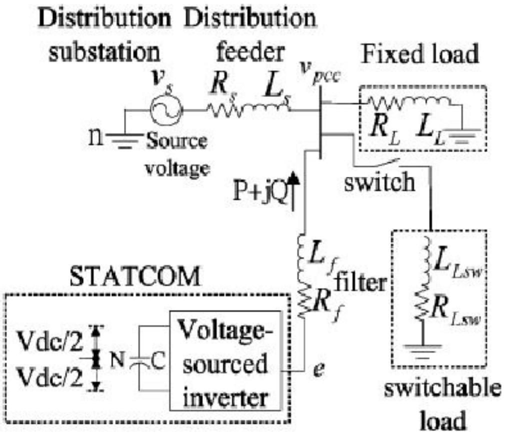
A static synchronous compensator (STATCOM) is one of the important member of the FACTS devices that is connected in shunt with the distribution system. STATCOM is used mainly to support bus bar voltage by injecting or absorbing fundamental frequency reactive power component into (or from) the system. This device has the capability to improve both the transient as well as steady-state stability of a power system by maintaining full capacitive output current at low system voltage as well as by controlling the voltage regulation for grid voltage at the common coupling point. High-performance and cost-effective high-power inverters are prerequisite for the realization of FACTS controllers such as Static Shunt compensators (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC) and the interline power flow controller (IPFC). In this regard, it should be mentioned that due to limitations of the power semiconductor devices, implementations of such inverters may be difficult in some cases. Typical voltage ratings are between 2.7-6 kV and are a small fraction of those required. Thus, in FACTS Controllers design, series connection of those devices is normally done. Compared with the SVC, the STATCOM has advantages such as fast, constant reactive power output ability, high efficiency and low harmonic distortion in the output current (Larsen *et al.,* 1992). STATCOM is composed of either VSI (or CSI) with a capacitor (or inductor) in its DC side, coupling transformer and a control system. The inverters (VSI) are switched with a single pulse per period and the transformers are connected in order to provide harmonic minimization. STATCOM has also ability to enhance the ‘Available Transfer Capability’ (ATC) of a transmission system which is basically a measure of unutilized capability of the system at a given time. For evaluation of a transmission system security as well as market forecasting, computation of ATC is very important role in power system particularly time variant power flow conditions. FACTS devices also have the capability to reduce the power flows in heavily loaded lines resulting in an increased load ability of network and thus, improving voltage stability. Although, a large nonlinear interconnected power network can exhibit very complex dynamic phenomenon when the system is disturbed from a steady-state operating conditions to complicate things even more, power systems are becoming more heavily loaded as the demand for electric power rises, while economic and environmental concerns limit the construction of new transmission and generation capacity (Rao *et al.,* 2007). In this study, digital simulation of Three Level Twenty-four pulse VSI based STATCOM has the improved effect of damping low frequency oscillations of power systems and supplying regulated voltage.

This study also presents the mathematical model for a Six-pulse VSC based STATCOM configuration in the radial system as well as three level twenty four pulse VSI based STATCOM .This model provides a tool to properly design a controller for the proposed STATCOM based on the proposed control strategy.

STATCOM operating principle

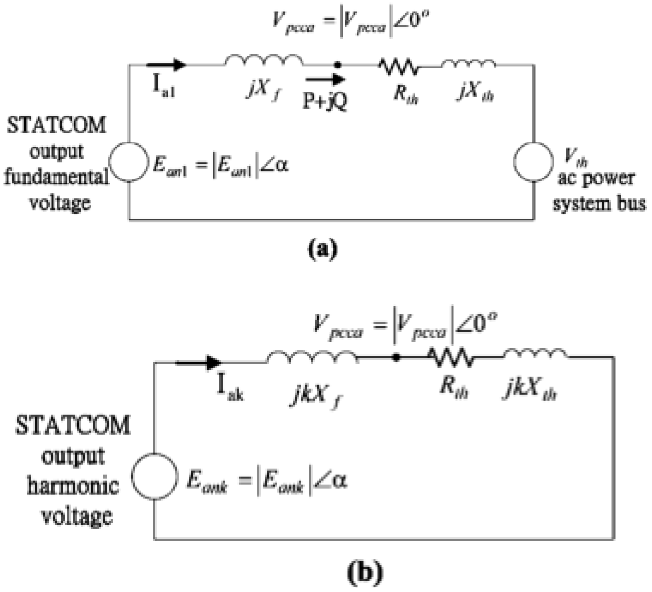
As shown in Fig. 1, two impedance loads (one is fixed and the other is connected to the point of common coupling (PCC) through a switch) are supplied power from a distribution sub-station with source voltage Vs through a distribution feeder with the impedance (Rs+jωLs). To regulate the PCC bus voltage, a STATCOM, which is composed of a VSI and a dc capacitor, is included (Chen and Jan, 2007). The STATCOM is connected to the PCC through a coupling transformer and a filtering inductor which can be represented by the series impedance (R_f+jωL_f).

Fig. 1. Single-line diagram of a STATCOM connected to a power system.



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 and the resultant reactive power (Pal and Dalapati, 2012). Figure 1 shows the schematic configuration 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 governed bydc capacitor voltage which is controlled by varying the phase difference between output voltage of VSI and system voltage at bus. The magnitude and phase difference of q-axis current determine the magnitude and phase difference between output voltage of VSI and system voltage at bus, which in turn controls reactive power flow. Figure 2 shows the single-phase equivalent circuit of a STATCOM connected to a power system.

Fig. 2. Single-phase equivalent circuit of a STATCOM connected to a power system. (a) At fundamental frequency. (b) For harmonic analysis. (E*an1*: the Fundamental component of the STATCOM per phase output voltage V*pcca*: PCC line-to neutral voltage V*th*: Thevenin-equivalent line to neutral voltage of the power system R*th* + jkX*th*: the Thevenin-equivalent impedance of the power system I*a1*: the fundamental component of the phase-A ac current I*ak*: the *k*th harmonic component of the phase-A ac current).



(a)

(b)

Materials and methods

STATCOM dynamic analysis

A. Modelling OF STATCOM based on six-pulse VSC:

An example radial system with STACOM is shown in Fig. 3a. Rd is included to represent small losses in the switching devices of VSC. R and L represent the equivalent circuit of the tie-transformer between bus U and V.

The complex voltage vectors and complex current vector can be expressed in the stationary reference frame (αβ-axis) as (Voraphonpiput and Chatratana, 2005):

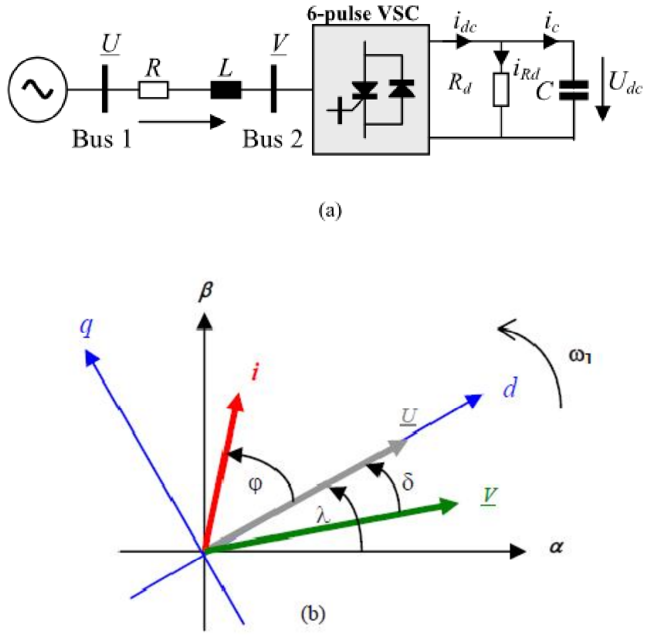
$$\underline{U} = u_1 + u_2\, e^{j\gamma} + u_3\, e^{j2\gamma} = u\, e^{j\gamma} \tag{1}$$

$$\underline{V} = v_1 + v_2\, e^{j\gamma} + v_3\, e^{j2\gamma} = v\, e^{j(\lambda-\delta)} \tag{2}$$

$$\underline{i} = i_1 + i_2\, e^{j\gamma} + i_3\, e^{j2\gamma} = v\, e^{j(\phi+\lambda)} \tag{3}$$

Where $\gamma = \frac{2\Pi}{3}$ and δ is the VSC firing angle.

Fig. 3. STATCOM configuration in the radial system (3a) and the Space-Vector Diagram (3b). The u_1, u_2 and u_3 are defined as instantaneous phase voltages at bus 1; V_1, V_2 and V_s are instantaneous phase voltages at bus 2; and i_1, i_2 and i_3 are instantaneous line currents.



The space vector diagram for voltages and current is shown in Fig. 3b, where αβ-axes represent stationary reference frame and dq-axes represent synchronous rotating reference frame. The d-axis is assigned to coincide with the space vector U̲. The circuit equation on stationary reference frame can be written as equation (4)

$$L\frac{d}{dt}(\underline{i}) + R\underline{i} = \underline{U} - \underline{V} \qquad (4)$$

The complex vectors from stationary reference frame are transformed to synchronously rotating reference frame by multiplying them with a unit space vector $e^{-j\lambda}$.

$$\underline{U}\, e^{-jy} = u_d + ju_q = u \qquad (5)$$

$$\underline{V}\, e^{-j\lambda} = V_d + jV_q = V\, e^{-j\delta} = V\cos\delta - jv\sin\delta \qquad (6)$$

$$\underline{i}\, e^{-j\lambda} = i_d + j\, i_q \qquad (7)$$

$$Le^{-j\lambda}\frac{d}{dt}(\underline{i}) + R\, e^{-j\lambda}\, \underline{i} = \underline{U}\, e^{-jy} - \underline{V}\, e^{-j\lambda} \qquad (8)$$

Substituting (5), (6), (7) into (8) and rearrange, voltage equations for real part in d-axis and for imaginary part in q-axis are

$$L\frac{di_d}{dt} + Ri_d = u_d - m\, U_{dc}\cos\delta + L\,\omega_1\, i_q \qquad (9)$$

$$L\frac{di_q}{dt} + Ri_q = u_d + mU_{qc}\sin\delta + L\,\omega_1\, i_d \qquad (10)$$

Where ω_1 is system frequency.

The magnitude of phase voltage at bus 2 (V) is directly proportional to the DC voltage across the capacitor U_{dc}, and therefore can be expressed as

$$v = mU_{dc} \qquad (11)$$

Where m is a proportional value. The value of *m* depends on the type of VSC. If the dc current (i_c) is defined as the sum of capacitor current (ic) and resistor current (i_{rd}), then the power flows into VSC can be described as

$$P = U_{dc}\, i_{dc} = \frac{3}{2}(v_d i_d + v_q i_q) \qquad (12)$$

With the help from (6) and (12) and (13), the dc current is

$$i_{dc} = \frac{3}{2}m(i_d\cos\delta - i_q\sin\delta) = C\frac{dUdc}{dt} + \frac{Udc}{R_d} \qquad (13)$$

Equation (9), (10) and (13) form a state equation for STATCOM

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix} = = \begin{bmatrix} -\frac{1}{T_1} & \omega_1 & -\frac{m}{L}\cos\delta \\ -\omega_1 & -\frac{1}{T_1} & \frac{m}{L}\sin\delta \\ \frac{3}{2}\frac{m}{C}\cos\delta & -\frac{3}{2}\frac{m}{C}\sin\delta & -\frac{1}{T_2} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix} \qquad (14)$$

Where $T_1 = \frac{L}{R}$, $T_2 = R_dC$

Linearization of (14) around the operating firing angle δ_0, gives a set of linear equations as shown in (15).

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ u_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_1} & \omega_1 & -\frac{m}{L}\cos\delta_0 \\ -\omega_1 & -\frac{1}{T_1} & \frac{m}{L}\sin\delta_0 \\ \frac{3}{2}\frac{m}{C}\cos\delta_0 & -\frac{3}{2}\frac{m}{C}\sin\delta_0 & -\frac{1}{T_2} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ u_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & \frac{m}{L}u_{dc0}\sin\delta_0 \\ 0 & \frac{1}{L} & \frac{m}{L}u_{dc0}\cos\delta_0 \\ 0 & 0 & -\frac{3}{2}\frac{m}{C}(i_{d0}\sin\delta_0 + i_{q0}\cos\delta_0) \end{bmatrix}\begin{bmatrix} u_d \\ u_q \\ \delta \end{bmatrix} \qquad (15)$$

The characteristic equation of the system described by (15) is

$$s^3 + \left\{\frac{2}{T_1} + \frac{1}{T_2}\right\}s^2 + \left\{\frac{2}{T_1T_2} + \frac{1}{T_1^2} + K + \omega_1^2\right\}s + \left\{\frac{1}{T_1^2T_2} + \frac{K}{T_1} + \frac{\omega_1^2}{T_2}\right\} = 0 \qquad (16)$$

Where $K = \frac{3}{2}\frac{m^2}{LC}$

The characteristic equation is not a function of firing angle. Hence, firing angle does not affect to the position of characteristic roots on the complex plane.

The stability of STATCOM can be tested with Routh-Hurwitz criterion. By assigning p, q and r to represent the coefficients of s^2, s^1 and s^0, respectively, (16) becomes $s^3+ ps^2+qs+r=0$ and the Routh's Array is

s^3	1	q
s^2	p	r
s^1	$q - \frac{r}{p}$	
s^0	r	

Substitute p, q and r to determine the element in the s^1 row

$$q- \frac{r}{p} = \frac{4}{T_1} + \frac{2}{T_2} + \frac{2T_2}{T_1^2} + KT_2 + KT_1 + 2\omega_1^2 T_2 \geq 0$$

Examination of all elements in the first column of Routh's array reveals that all elements are positive, and the STATCOM is a stable system. Therefore, the values of resistors, inductors and capacitors in the STATCOM equivalent circuit have no effect on stability.

B. Mathematical modelling OF STATCOM based on 3-level 24-pulse VSC:

The schematic of STATCOM has already shown in Fig.1. In the power circuit of a STATCOM, the converter has either a multi-pulse and/or a multilevel configuration. With three-level converter topology the magnitude of ac output voltage of the converter can be changed by varying dead angle β with fundamental switching frequency. The time period in a cycle during which the converter pole voltage is zero is $\frac{4\beta}{\omega_0}$. The three-level converter topology greatly reduces the harmonic distortion on the ac side. Here the STATCOM is realized by a combination 24-pulse three level configuration. The detailed three-phase model of a STATCOM is developed by modeling the converter operation by switching functions. The modeling of three-level VSC based on switching functions is as follows:

In three level bridge, the phase potentials can be modulated between three levels instead of two. Each phase can be connected to the positive dc terminal, the midpoint on the dc side or the negative dc terminal. The switching function $P_a(t)$ for phase ' *a* ' is shown in Fig. 4. The switching functions of phase *b* and *c* are similar but phase shifted successively by 120^0 in terms of the fundamental frequency. Assuming that the DC capacitor voltages $V\,d\,c1 = V\,d\,c2 = \frac{Vdc}{2}$.

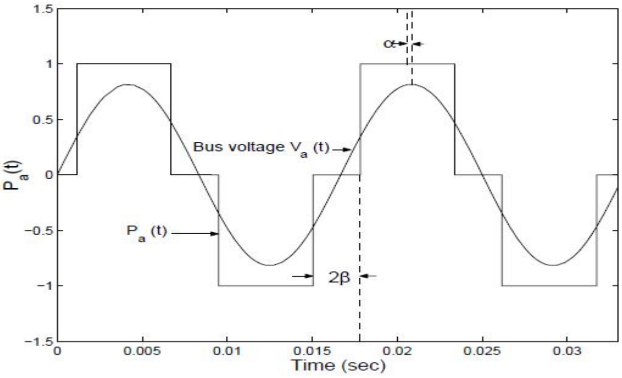


Fig. 4. Switching function for a three level converter.

The converter terminal voltages with respect to the midpoint of dc side ' *N* ' can be obtained as (Prabhu *et al.*, 2008):

$$\begin{bmatrix} V_{aN}^i \\ V_{bN}^i \\ V_{cN}^i \end{bmatrix} = \begin{bmatrix} P_a(t) \\ P_b(t) \\ P_c(t) \end{bmatrix} \frac{V_{dc}}{2} \qquad (17)$$

The converter terminal voltages with respect to the neutral of transformer can be expressed as,

$$\begin{bmatrix} V_{an}^i \\ V_{bn}^i \\ V_{cn}^i \end{bmatrix} = \begin{bmatrix} S_a(t) \\ S_b(t) \\ S_c(t) \end{bmatrix} V_{dc} \qquad (18)$$

Where, $S_a(t) = \frac{P_a(t)}{2} - \left[\frac{P_a(t)+P_b(t)+P_c(t)}{6}\right]$

$S_a(t)$ is the switching function for phase '*a*' of a 6-pulse 3-level VSC and V_{dc} is the dc side capacitor voltage. Similarly for phase '*b*'**,** $S_b(t)$ and for phase '*c*', $S_c(t)$ can be derived. The peak value of the fundamental and harmonics in the phase voltage V_{an}^i are found by applying Fourier analysis on the phase voltage and can be expressed as

$$V_{an}^i = \frac{2}{h\pi} V_{dc} \cos(h\beta) \qquad (19)$$

Where, *h* =1, 5, 7, 11, 13 and β is the dead angle (period) during which the converter pole output voltage is zero. We can eliminate the 5th and 7th harmonics by using a twelve-pulse VSC, which combines the output of two six-pulse converters using transformers.

The switching functions for first twelve-pulse converter are given by

$$S_{1a}^{12}(t) = S_{1a}(t) + \frac{1}{\sqrt{3}}\left(S_{1a}^{1}(t) - S_{1c}^{1}(t)\right),$$

$$S_{1b}^{12}(t) = S_{1b}(t) + \frac{1}{\sqrt{3}}\left(S_{1b}^{1}(t) - S_{1a}^{1}(t)\right),$$

$$S_{1c}^{12}(t) = S_{1c}(t) + \frac{1}{\sqrt{3}}\left(S_{1c}^{1}(t) - S_{1b}^{1}(t)\right),$$

Where

$$S_{1x}^{1}(t) = S_{1x}\left[t + \frac{2\pi}{\omega_0}\frac{1}{12}\right]$$

$$S_{1x}(t) = S_{x}\left[t + \frac{\pi}{\omega_0}\frac{1}{24}\right],$$

x=a, b and c (20)

The switching functions for second twelve-pulse converter are given by

$$S_{2a}^{12}(t) = S_{2a}(t) + \frac{1}{\sqrt{3}}\left(S_{2a}^{1}(t) - S_{2c}^{1}(t)\right),$$

$$S_{2b}^{12}(t) = S_{2b}(t) + \frac{1}{\sqrt{3}}\left(S_{2b}^{1}(t) - S_{2a}^{1}(t)\right),$$

$$S_{2c}^{12}(t) = S_{2c}(t) + \frac{1}{\sqrt{3}}\left(S_{2c}^{1}(t) - S_{2b}^{1}(t)\right),$$

Where

$$S_{2x}^{1}(t) = S_{2x}\left[t + \frac{2\pi}{\omega_0}\frac{1}{12}\right]$$

$$S_{2x}(t) = S_{x}\left[t - \frac{\pi}{\omega_0}\frac{1}{24}\right]$$

x=a, b and c (21)

The switching functions for a twenty-four pulse converter are given by

$$S_{a}^{24}(t) = S_{1x}^{12}(t) + S_{2x}^{12}(t),$$

x=a, b and c (22)

If the switching functions are approximated by their fundamental components (neglecting harmonics) for a 24-pulse three-level converter, we get

$$V_{an}^{i} = \frac{8}{\pi}V_{dc}\cos(\beta)\sin(\omega_0 t + \alpha + \theta_s) \qquad (23)$$

and V_{bn}^{i}, V_{cn}^{i} are phase shifted successively by 120°.

The line current is given by, $i_a = \sqrt{\frac{2}{3}}I_a \sin(\omega_0 t + \theta_s)$

i_b, i_c are phase shifted successively by 120°.

Neglecting converter losses the DC capacitor current is given by

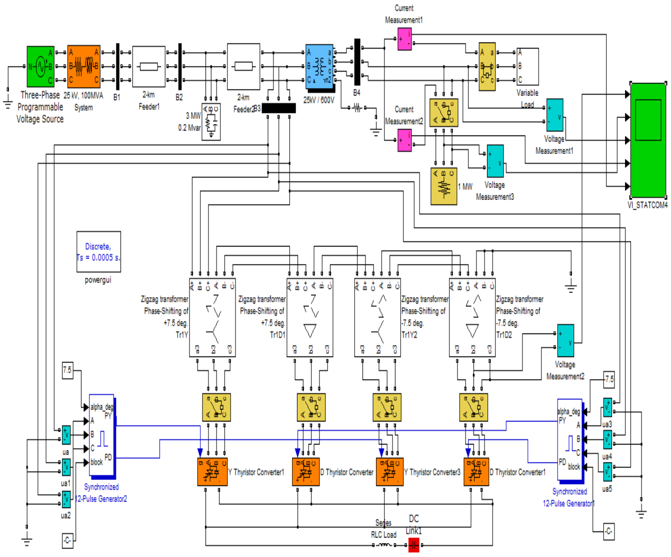
$$[i_{dc}] = \begin{bmatrix} S_a^{24}(t) & S_b^{24}(t) & S_c^{24}(t) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (24)$$

A particular harmonics reaches zero, when 2β = $\frac{180^0}{h}$. At $\beta_{optimum} = 3.75^0$ a three level 24-pulse converter behaves nearly like a two level 48-pulse converter as 23rd and 25th harmonics are negligibly small.

Simulation of the STATCOM with system description using three-level twenty four pulse VSI-based STATCOM:

In our proposed system (Fig. 5), the three level STATCOM is connected to bus through four zigzag transformer respectively. In the Power circuit diagram of the STATCOM, the converter has multi-pulse or a multilevel configuration. With twenty four 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. This model consists of two pairs of 6-pulse STATCOM-cascaded to form 24-pulse STATCOM, connected in parallel in the circuit with two sets of fixed load of the same type and merges to a single variable load. Power to this system is supplied from a 25 kV, 60 Hz, 100 MVA programmable voltage source.

Fig. 5.Simulink diagram for three-level twenty-four pulse VSI-based STATCOM in a distribution system.



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 STATCOM output is coupled on parallel with the network. A 12,000 µF 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, SPWM Control 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. The Total Harmonic Distortion found in all the cases is within the permissible limits. Therefore it can be concluded that the model will operate in a proper manner.

Results

In Figure 6, we have shown the output waveforms of different voltages and currents across the output port of STATCOM and different load end. The first graph represents the output voltage waveform of STATCOM. The second and third graph represents the output voltage waveform across the Fixed Load (1MW) and Variable Load respectively. From these two graphs, the effect of STATCOM during its operating period can be observed for improving the voltage profile across the load end. From Figure 7, the quality of these voltage (and current also) profile also been observed by checking the value of THD. The fourth and fifth graph of Fig. 6a represents the output current profile across the fixed load and variable load respectively. In Fig. 7a and b and c, FFT analysis of output voltage across STATCOM (THD=1.45%), Fixed Load (THD=4.10%) and Variable Load (THD=0.60%) have been shown. In Fig.7d and e, FFT analysis of current across the Fixed load (THD=0.54%) and Variable Load (THD=3.38%) has also been shown. Employing turn-off-capable semiconductor devices, switching power converters have been able to operate at higher switching frequencies and to provide a faster response. This makes the VSC an important part in the FACTS controllers. Thus, we obtain an effective result from the system as shown in Fig. 5.

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

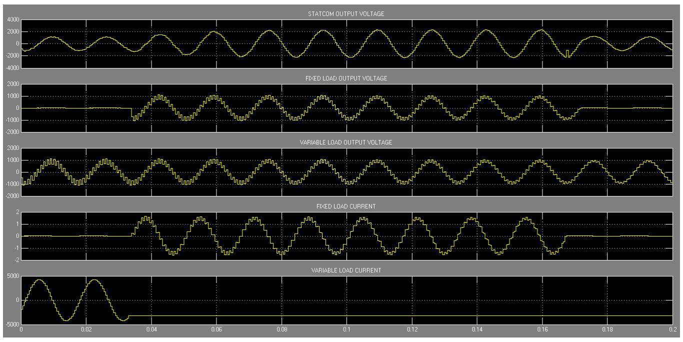
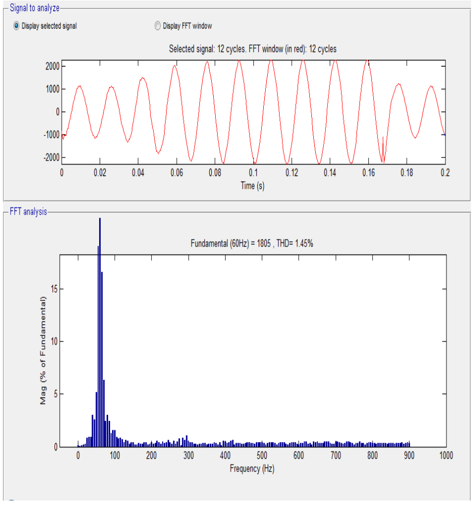


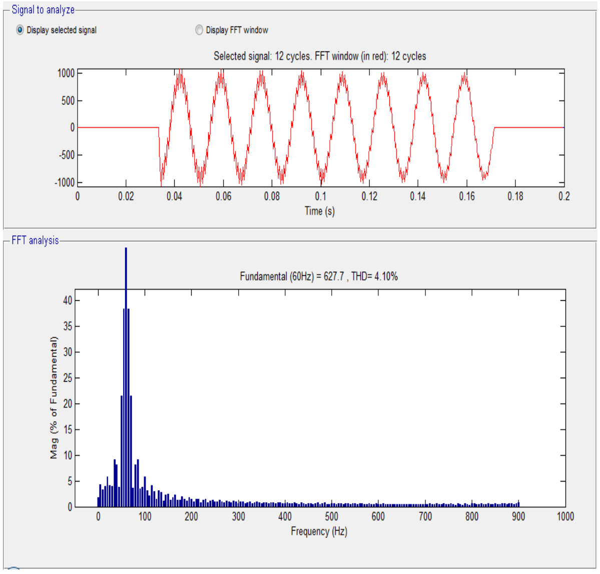
Fig. 7a. FFT analysis of output voltage across STATCOM (THD=1.45%).



Selected signal: 12 cycles. FFT window (in red): 12 cycles

Fundamental (60Hz) = 1805 , THD= 1.45%

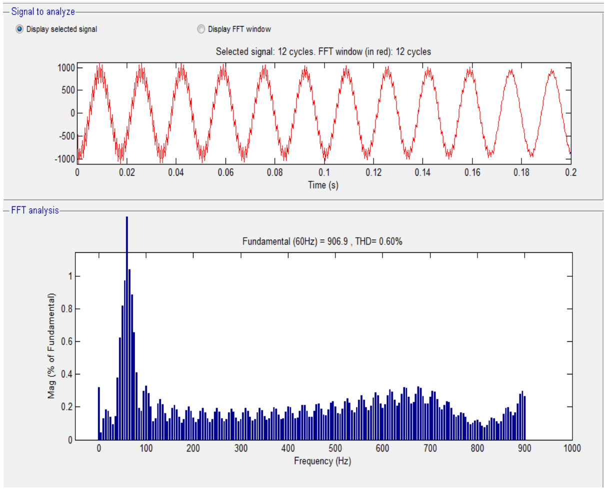
Fig. 7b. FFT analysis of output voltage across STATCOM Fixed Load (THD=4.10%).



Selected signal: 12 cycles. FFT window (in red): 12 cycles

Fundamental (60Hz) = 627.7 , THD= 4.10%

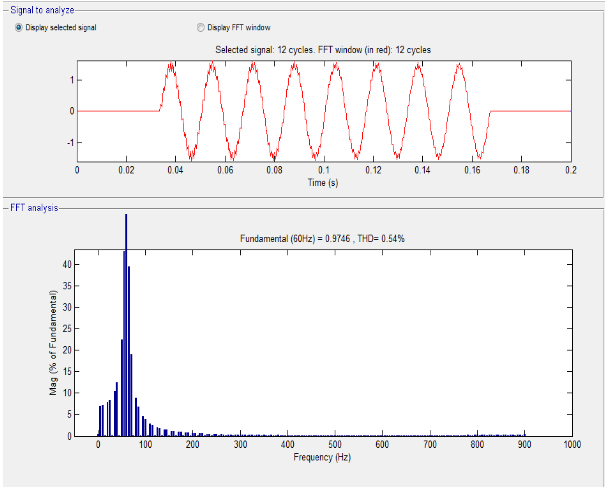
Fig. 7c. FFT analysis of output voltage across STATCOM Variable Load (THD=0.60%).



Selected signal: 12 cycles. FFT window (in red): 12 cycles

Fundamental (60Hz) = 906.9 , THD= 0.60%

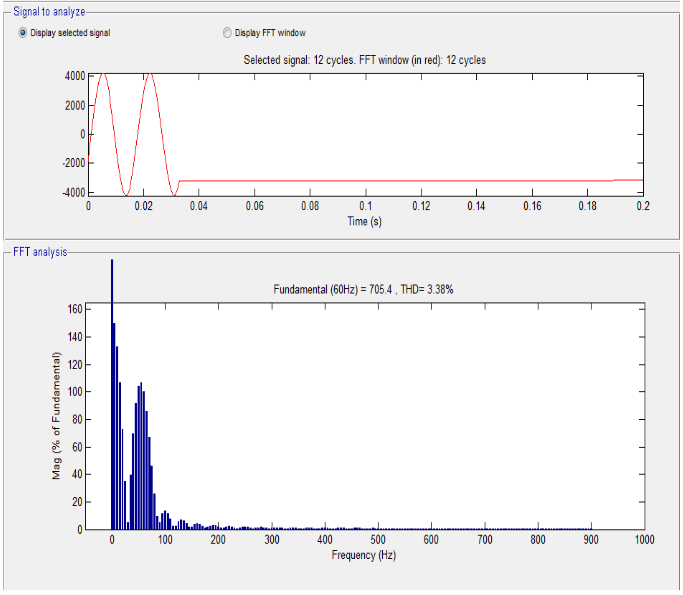
Fig. 7d. FFT analysis of current across the Fixed load (THD=0.54%).



Selected signal: 12 cycles. FFT window (in red): 12 cycles

Fundamental (60Hz) = 0.9746 , THD= 0.54%

Fig. 7e. FFT analysis of current across the Variable Load (THD=3.38%).



Discussion

The STATCOM is a shunt power electronic device used to help in improving the voltage profile in the transmission system. The simplest configuration of the STATCOM is the six-pulse (Two-level) converter. However, multipulse and or multilevel configuration is able to generate voltage waveforms with a reduced harmonic content and thus the value of THD will be much lesser. The control strategy of dc-link voltage can quickly increase system stability and decrease electric impulsion. The proposed model is feasible and will be helpful to the design and development of the high power STATCOM. Due to improved dynamic performance, extended operating range, increased availability, reduced line harmonics and an adjustable power factor at the point of common coupling, multilevel VSIs are used as VSC within the STATCOM. So it is more suitable for the power electronic system with the high voltage and large capacity.

Conclusion

In this study, three level twenty four pulse VSI based STATCOM has been applied in a distribution system for checking its effect on voltage profile across the load. The results are showing that the value of THD across different load voltages and current are within the acceptable limits. Thus Simulation results are in line with the predictions. The increase of the converter power of multilevel VSCs will enable replacement of thyristor based CCVs and LCIs in the near future.

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