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DIGITAL SIMULATION OF A STATCOM BASED ON TWELVE PULSE VSC FOR VOLTAGE CONTROL APPLICATION IN POWER SYSTEM

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ABSTRACT

The Static Synchronous Compensator (STATCOM) using GTOS and Square-wave Voltage Source Converter (VSC), is one of the recent FACTS device used for static shunt reactive power compensation in high power (Several hundreds of MVARs) application. Improving the system's reactive power handling capacity is a remedy to prevent voltage instability.The VSI is extremely fast in response to reactive power change. A state-space representation on a d-q framework is presented here and twelve-pulse VSC based STATCOM is simulated (for harmonic reduction on the AC side) here by MATLAB and the results are presented. It is found that these controllers can increase the loadability margin of power systems.

KEYWORDS: SVC, FACTS, STATCOM, VSC, Voltage regulation

Nowadays with the increase in peak load demand & power transfer between utilities has elevated concerns about system voltage security. Voltage collapse has been deemed responsible for several major disturbances in power system.

A flexible AC Transmission system (FACTS) is an AC transmission system incorporating power electronic-based or other static controllers which can be used for better power flow control, loop-flow control, voltage regulation, better controllability, enhancement of transient stability & damping of power oscillation by control of one or more ac transmission system parameters (voltage, phase angle & impedance), FACTS devices can be used as series controllers to regulate the line impedance, as shunt controllers to regulate the voltage magnitude or as series/shunt combination to regulate several signals (Hadjeri et a1.,2008).

Voltage instability is mainly associated with reactive power imbalance, as reactive power (VARs) is required to maintain the voltage to deliver active power (Watts) thru transmission lines. The loadability of a bus in a power system also depends on the reactive power support that the bus can receive from the system when the system approaches the maximum loading point (MLP or voltage collapse point), both real & reactive power losses increase rapidly. Thus, the reactive power supports should be local & adequate, otherwise the voltage sags down & it is not possible to push the power demanded by loads thru the lines. Static VAR generators(SVG's) using voltage-source-inverters have been widely accepted as the next generation reactive power controllers of power systems to replace the conventional VAR compensators such as TSC's & TCR's (Peng et al.,1996).

As with all static FACTS devices the STATCOM has the potential to be more reliable & has capability to

(a) sustain constant reactive current (by producing reactive power at lower voltages.)
(b) increase relocatability
(c) be used as voltage & frequency support and provide improved quality of supply.
(d) minimize magnetic impact as it uses encapsulated electronic converters.
(e) respond linearly to voltage, (as STATCOM are current limited) as opposed to the voltage squared relationship of SVC.
(f) block low order harmonics.
(g) respond faster.

Currently there are several manufacturers that offers diverse DSP architectures to help developers choose the device that best suits their applications.The main

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advantage of using DSPs lies in their software implementation which makes the design flexible, extensible and easy to use(Dinavahi et al.,2004).

Principle of Operation

The STATCOM is a solid state shunt device that generates or absorbs reactive power by means of electronic processing of the voltage & current waveforms in a VSC & it was self-commutated power electronics to synthesize the reactive power output.

Figure 1, shows the single line STATCOM power circuit (basic scheme of a STATCOM connected to a bus of the transmission system). The STATCOM mainly consists of a step-down transformer with a leakage reactance, a three phase GTO voltage source converter (VSC) and a DC capacitor (Iswaran,2005). In fig.1, a VSC is connected to a utility bus thru magnetic coupling.

The exchange of reactive power between the VSC & the AC system can be controlled by varying the amplitude of the 3-phase output voltage (E_s) of the converter(VSC). If this voltage, E_s is increased above that of the utility bus voltage, E_t, then a current flows from the VSC to the ac system (i.e. Q is positive), the capacitive reactive power is generated by VSC and supplies to the ac system. If E_s is decreased below E_t, then the current flows from the ac system to the VSC & the inductive reactive power is absorbed by VSC from the ac system (i.e. Q is negative).

This reactive current is calculated as follows (Hingorani and Gyugyi,2000):

$$I = \frac{U_{acs} - U_{vsi}}{\bar{X}} \qquad \ldots\ldots\ldots\ldots\ldots..(1)$$

Where U_{acs} and U_{vsi} are the ac power system & VSI output voltages,respectively and $\bar{X}$ is the leakage reactance of the transformer. In the case of equal secondary and primary voltage, interchange of the reactive power is equal to zero.

The reactive power supplied by the STATCOM is given by the following equation

$$Q \qquad \frac{E_S \quad E_t}{X} \quad E_t \qquad \ldots\ldots\ldots\ldots\ldots..(2)$$

Where X is the equivalent impedance between STATCOM & the ac system. The STATCOM's output reactive power is controlled thru firing angle change.

We can also control the real power exchanges between the VSC & the ac system by creating a phase shift (by applying the phase angle of the modulating signal) between the output voltage of VSC & the ac system voltage.

A small amount of real power should be always supplied to the STATCOM to compensate the component loss so that the dc capacitor voltages can be maintained. If the real power delivered to the STATCOM is more than its total component loss, the dc capacitor voltage will rise and vice-versa.

The exchange of real power between the STATCOM & the ac system can be written as:-

$$P \qquad \frac{E_S \quad E_t}{X} \quad \sin \qquad \ldots\ldots\ldots\ldots\ldots..(3)$$

where, is the phase angle difference between E_s and E_t.

Figure 2, shows the typical V-I characteristic of STATCOM. STATCOM can supply both the capacitive & the inductive compensation & can control its output current independently over the rated maximum capacitive or inductive range irrespective of the amount of ac system voltage. Fig.2, also shows that the STATCOM has an increased transient rating in both the capacitive & inductive operating regions.

Voltage equation of STATCOM can be written as,

$$V=V_{ref}+ X_s I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where,

V= positive sequence voltage (in p.u. system)

V_{ref}= reference voltage

I= reactive current

and X_s= droop reactance.

As long as the reactive current lies in between maximum & minimum values, the voltage is regulated at the reference voltage, V_{ref}.

As the modulating signal for the VSCs are same, the fundamental component of the STATCOM output voltage (E_s) is N times of that of each VSC if the voltage across the dc capacitor of each VSC is same. Thus STATCOM output voltage can be controlled by varying the amplitude modulating index (m_a) and thus STATCOM has fast dynamic response to system reactive power demand. $E_s \propto m_a$, when each VSC is in the linear modulating region.

MATERIALS AND METHODS

Modeling 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.3.

Here the resistance, r_s is the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance l_s represent 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 voltage 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 (Schauder et a1.,1993)

$$\frac{d}{dt} i_{abc} \qquad \frac{r_s}{l_s} i_{abc} \qquad \frac{1}{l_s}(e_{abc} \qquad v_{abc}) \quad .... (5)$$

The phase voltage of bus a can be written as:

$$V_s \qquad \sqrt{2} V_{s\,(rms)} \cos(\quad _s t \qquad _s) \qquad .... (6)$$

Where, $\;_s$ 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:

$$e_{ad} \qquad k_m V_{dc} \sin(\quad _s t \qquad) \qquad ....(7)$$

$$e_{aq} \qquad k_m V_{dc} \cos(\quad _s t \qquad) \qquad ....(8)$$

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)

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \\ V'_{dc} \end{bmatrix} = A_s \begin{bmatrix} i'_d \\ i'_q \\ V'_{dc} \end{bmatrix} - \frac{\omega_s}{L'_s}\begin{bmatrix} V_s \cos\theta_s \\ V_s \sin\theta_s \\ 0 \end{bmatrix} \qquad \ldots\ldots\ldots\ldots\ldots(9)$$

Where ,

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

$$\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

and

$$M_k = -\frac{3}{2}k\omega_s C' \qquad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Note that, equation (9) 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 nonlinear responses in the STATCOM states i_d , i_q and V_{dc} .

The nonlinear power system may be represented as:

$$\dot{x} = g1(x,z) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(12)$$

$$\dot{y} = g2(y,z) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

$$\dot{v} = g3(x,y,z) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(14)$$

where the states x represents the generator states of the system (say, generator rotor angle and speed, d-q axis voltages, excitation system states, etc.) and equation (12) represents the n sets of dynamic models corresponding to the generators. The states y represents the STATCOM states and equation (13) represents the STATCOM dynamic model given in equation (8). The states z will denote the bus voltage magnitude and angle of the system buses.

The above system can be linearized as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} A_{gen} & 0 & B_{xz} \\ 0 & A_{stat} & B_{yz} \\ C_{zx} & C_{zy} & D \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} 0 \\ E \\ 0 \end{bmatrix} \alpha \qquad \text{..........(15)}$$

Where, E for each STATCOM is given by,

$$E_i = \begin{bmatrix} -\frac{\omega_s k_i}{L_{si}} \sin(\alpha_i + \theta_i)\, V_{dc_i} \\ \frac{\omega_s k_i}{L_{si}} \cos(\alpha_i + \theta_i) V_{dc_i} \\ \frac{3}{2} k_i \omega_s C'_i(\sin(\alpha_i + \theta_i) i_{d_i} - \cos(\alpha_i + \theta_i) i_{q_i} \end{bmatrix} \qquad \text{............ (16)}$$

Assuming that the network equations are solvable and invertible, then a reduced order linear system can be found:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} \\ A_{yx} & A_{yy} \end{bmatrix} + \begin{bmatrix} 0 \\ E \end{bmatrix} \alpha \qquad \text{.........(17)}$$

Where,

$$\begin{aligned} A_{xx} &= A_{gen} - B_{xz} D^{-1} C_{zx} \\ A_{yy} &= A_{stat} - B_{yz} D^{-1} C_{zy} \\ A_{xy} &= -B_{xz} D^{-1} C_{zy} \\ A_{yx} &= -B_{yz} D^{-1} C_{zx} \end{aligned} \qquad \text{...............(18)}$$

The linearization given in equation (16) may be used to design and compare various state feedback controllers of the form:

$$y_i = -K\alpha_i \qquad \text{..........(19)}$$

which yields the following controlled system:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} \\ A_{yx} & A_{yy} - EK \end{bmatrix} \qquad \text{..........(20)}$$

Since the only states that are required for feedback are the local STATCOM states, state feedback control may be used for this type of power system control.

Utility of Using 12-Pulse VSC Inside STATCOM

In 6-pulse phase controlled converters, current harmonics are generated on the ac side & voltage ripples are produced on the dc side of the converter used in transmission system. To reduce this voltage ripples as well as current harmonics, twelve pulse VSC is used in our proposed STATCOM configuration. Here, we use two six pulse converters fed from delta-delta and delta-star transformers.

The two transformers secondaries, one in star and the other in delta, cause a displacement of in the two six pulse output voltages so that a twelve pulse voltage is obtained at the output of VSC.

The average output voltage of the VSC (i.e. the dc link voltage) is given by (Bimbhra,2010)

$$V_{0()av} \quad \frac{6}{}[V_{ml} \cos \qquad L_s I_d] \text{ .... } (21)$$

Where,

V_{ml} = Maximum value of line to line input voltage to each of the six-pulse converters.

= Triggering angle

L_s = Transformer leakage inductance (per phase)

I_d = DC current

RESULTS AND DISCUSSION

Simulink Diagram and Results

In Figure 4, an operation methodology of a STATCOM (static synchronous compensator) is proposed with constant dc link voltage. Here, 12 pulse VSC (voltage source converter) based STATCOM (Static synchronous compensator) maintaining the constant voltage of the bus. For achieving this objective, two sets of 6-pulse VSCs are used which are operated at the fundamental frequency switching. The reactive power is controlled by the phase angle difference between the two sets of 6-pulse VSCs. The converter utilization in the proposed configuration of STATCOM is improved as it is working at a constant dc link voltage. The proposed model of the STATCOM is connected to a 25kv, 60 Hz system and simulation results are presented for demonstrating its steady state and dynamic performance.

For the time domain simulations, the load is modelled as constant impedance characteristics for the fast (transient) portion and as constant MVA for the slow (steady state) portion.

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).

STATCOM output voltage and voltage across the load are shown in Fig.5.

The frequency spectrum for the voltage across the load is shown in Fig.6.

From the output, it is seen that voltage across the load reaches normal value due to injection of voltage by STATCOM & thus the value of THD is within acceptable range.

CONCLUSION

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 are able to generate voltage waveforms with a reduced harmonic content and thus the value of THD will be much lesser.

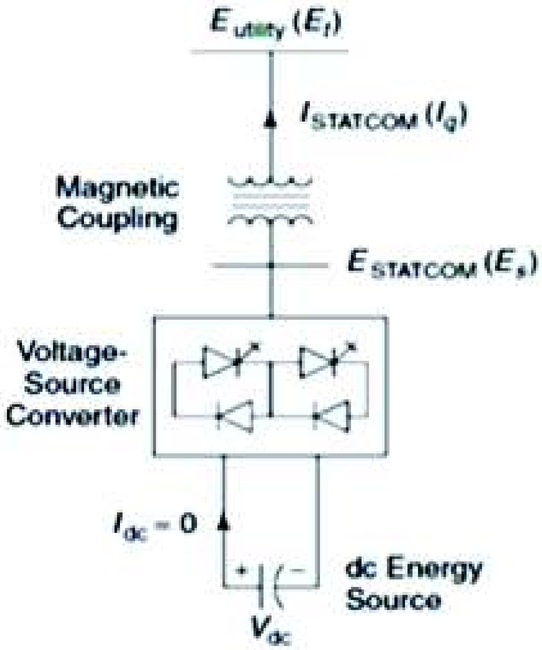

Fig.1: Single line STATCOM power circuit

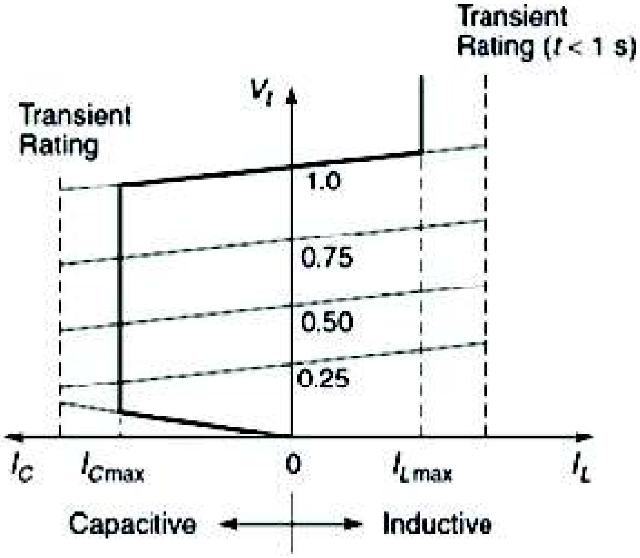

Fig.2: Typical V-1 characteristics of STATCOM

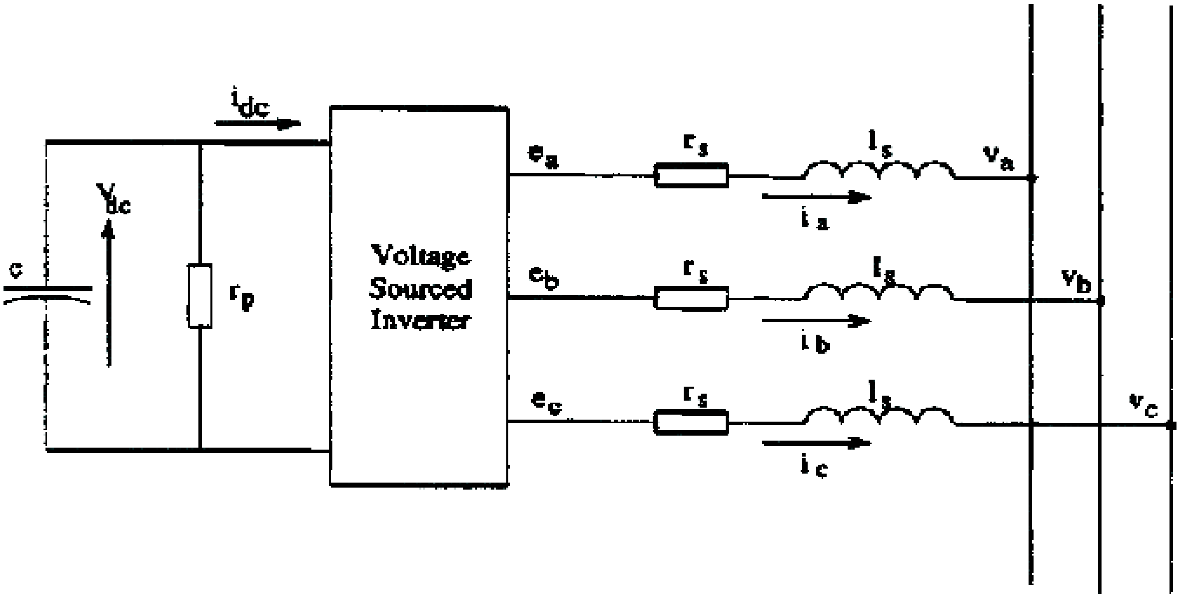

Fig.3: Equivalent circuit of STATCOM

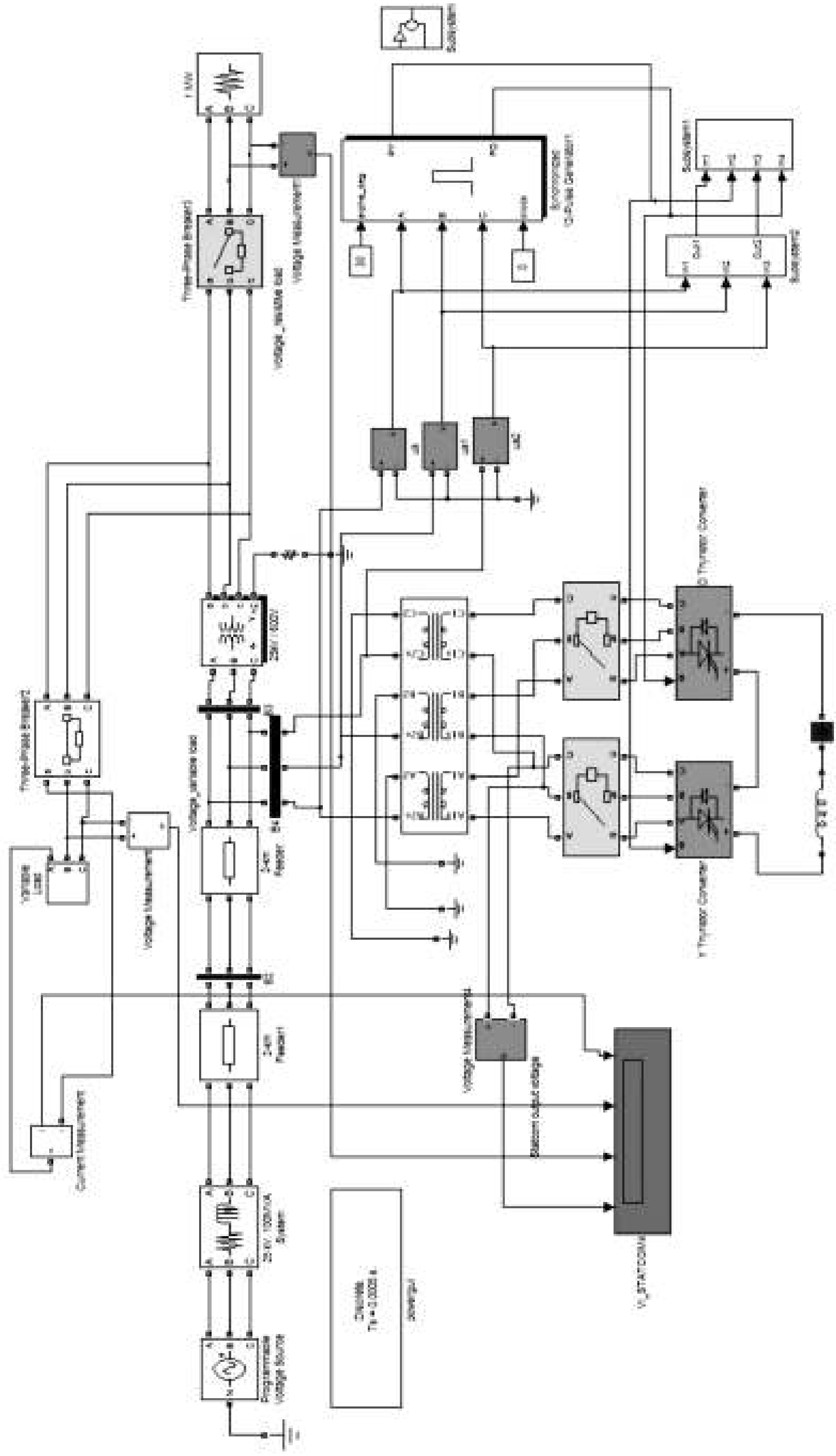

Fig.4: Proposed Simulink model of STATCOM in 3-phase system using 12-pulse VSC

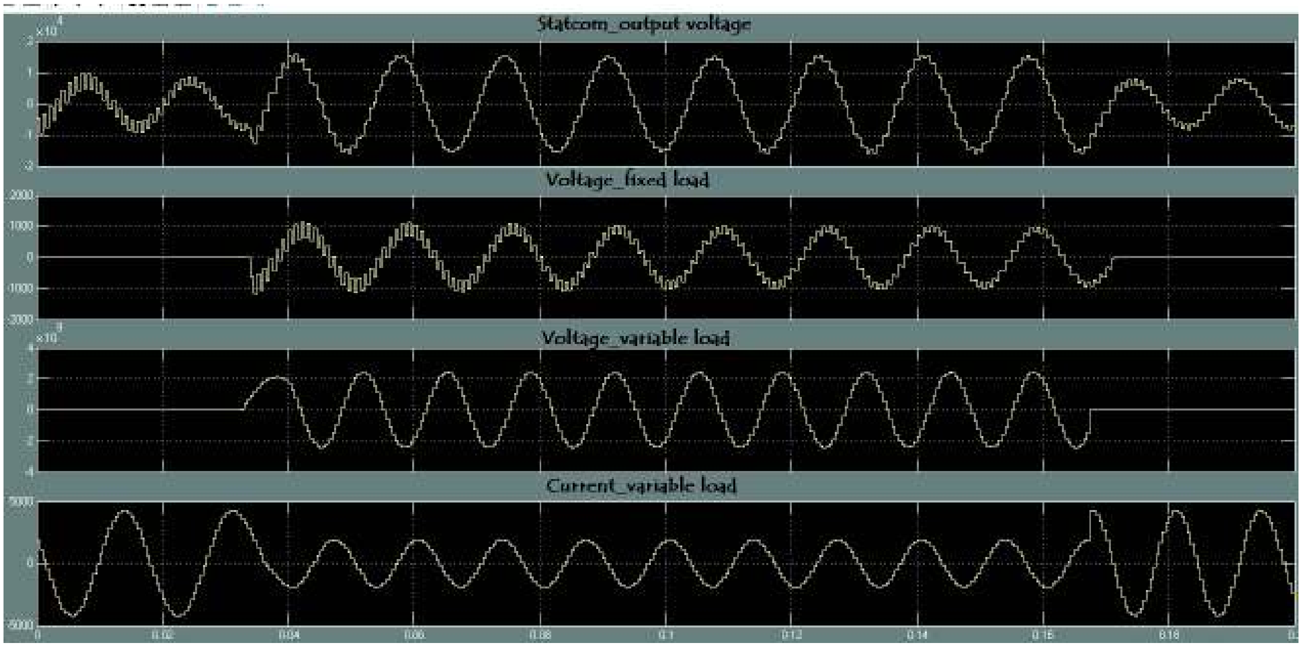

Fig.5: Output Voltage and Current Response Curve

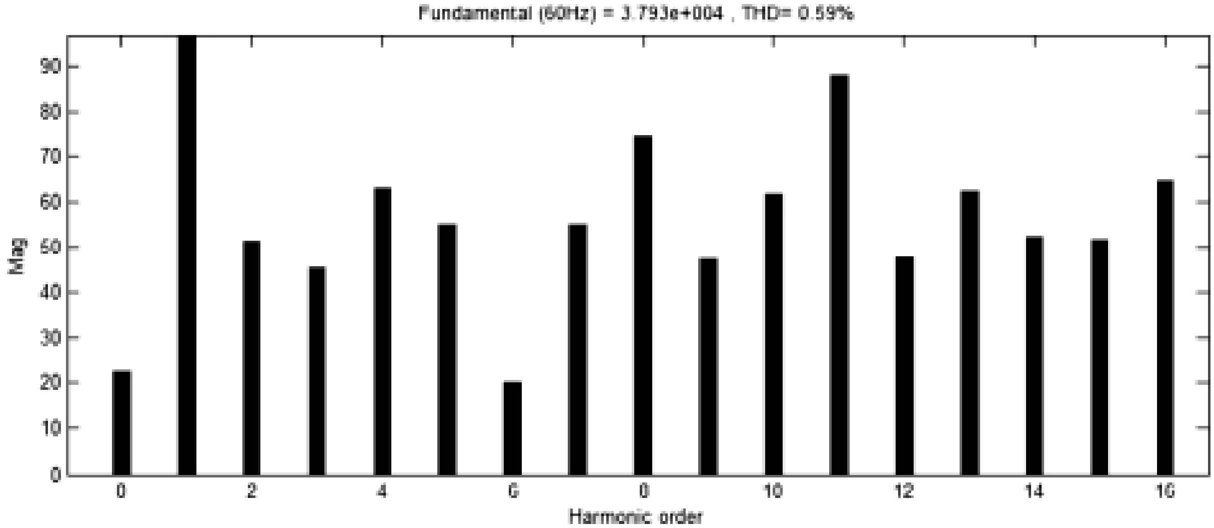

Fig.6: Frequency Spectrum for the Voltage across the resistive load

In our proposed work, a STATCOM model has been developed with all the necessary components and controllers in order to demonstrate its effectiveness in maintaining simple and fast voltage regulation at any point in the transmission line.12-Pulse VSC based STATCOM is modelled and simulated using the power system blocksets of Simulink. This work has proposed a statcom for the reduction of harmonics in the receiving end voltage. The simulation is based on the assumption of both balanced load as well as variable load. Three phase circuit model is considered here for simulation studies. It has been clearly shown in simulation results that voltage level has improved satisfactorily when statcom is operating.

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