POWER SYSTEM PERFORMANCE ENHANCEMENT STUDY, USING A SINGLE PHASE MULTI-LEVEL CASCADE INVERTOR BASED STATCOM

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ABSTRACT: *This paper is attempting to implement self-commutated VAR compensators, single phase multi-level STATCOM for compensating the demandable amount of reactive power while connecting reactive consumers in power system. For harmonic elimination approach, Cascade H bridge converter based STATCOM is examined with different levels and resulted a THD in range of (18.1%-4.4%). Phase shifted pulse width modulation is used to generating control signals that triggering the invertors. Independent DC voltage source (capacitor) in reach unit of inverter is configured to produce 10.5 V and controlled by PI controller ($I_{direct\ reference}$), the reactive power generated by STATCOM is moderated by inner-loop of the controller. Results are shown that power factor is improved significantly (0.99) and system performance is enhanced.*

Keywords: PI, DQ, CHB, THD, PCC, FACTS, PWM, PLL, IGBTs, P, Q.

I. INTRODUCTION

The reactive power is the amount of power consumed by reactive elements such as inductors and capacitors, inductive load expansion is forcing the generator to produce larger amount of current and hence the current flow through transmission line will be increased. Load in power system may be reactive, inductive or capacitive, reactive power is absorbed by reactive elements whereas resistive load are consuming active power only (P), [1]. Applying voltage across inductive load is building a magnetic field in this element so current will hang for specific period of time before reaching to the maximum value, that make current legging voltage in phase. In other hand, current passing through capacitive load is initiating of electrical field and this make voltage legging in phase with current. The growth of power networks and deployment of non-linear load such as power electronic components, coils and extra are significantly impacting the performance of power system. Compensation techniques term to the methods in with producing the required reactive power demanded by the load from another source close to load side, this may mitigate the reactive power generation by the source and hence decreases the current flow through transmission lines.

Compensators falls in two groups; VAR generators such as fixed switched capacitors, combined thyristor controlled reactor (TCR) and synchronous condensers; self-commutated VAR compensator such as static synchronous series compensators (SSSCs) and static synchronous compensators (STATCOMs). Many other types are discussed in [2]. STATCOM is flexible AC transmission systems (FACTs) that connecting in shunt with transmission system at the points experiencing high demand of reactive power. The majority of this device is to stabilize the potential at the point of common coupling (PCC) while absorbing or injecting the same with power grid. The internal process of STATCOM is to effectively control the currents of multilevel invertors with zero steady state error [3,4,5]. There are many types of multilevel inverter are proposed throughout the literature which include Diode-clamped inverter or Neutral clamped inverter [7], Cascaded H-bridge inverter [9], Flying Capacitor Inverter [8] and Hybrid multi-level Inverter [10]. Unbalanced voltage across DC link capacitor is comprises big challenges at the time of employing such invertors.

In [11], various techniques of sensor are used to measure the DC-link voltage across the capacitor.

STATCOMs significance is about their ability to link the high power grid since STATCOM is underlying of IGPT power electronic device that can cop with such operations [12].

Decoupling control, non-linear control strategies are demonstrated in [13, 14].

In this paper, single phase cascaded multilevel inverter based STATCOM is implemented. The proposed STATCOM works in both capacitive as well as inductive mode. Direct current vector control method along with the phase shift carrier sinusoidal pulse width modulations are used to acquire a fixed switching frequency. The PI controller is used along with the DQ transformation in order to generate a fixed voltage which remains constant even with a varying load conditions or input voltage.

II. HARMONICS MITIGATION SCHEME

For reactive power compensation STATCOM is employing DC invertor to generate a voltage signal, multi-level H-bridge convertor such as five levels (N=5) is being used to produce (2N+1) output phase voltage. Invertor is composed of number of cells (single phase H-bridges) in which connecting of independent DC source on the left side and AC system on the right side, To synthesize a multilevel waveform, the AC output of each different level H-bridge cells are connected in series figure (1), multiple H-bridge are interfaced in cascade form at the output to perform voltage operations and low harmonic distortion. Harmonics are coming into picture as ripple appears in output signal hence in order to eliminate harmonics, the DC source has to be controlled effectively as well as higher levels must be adopted.

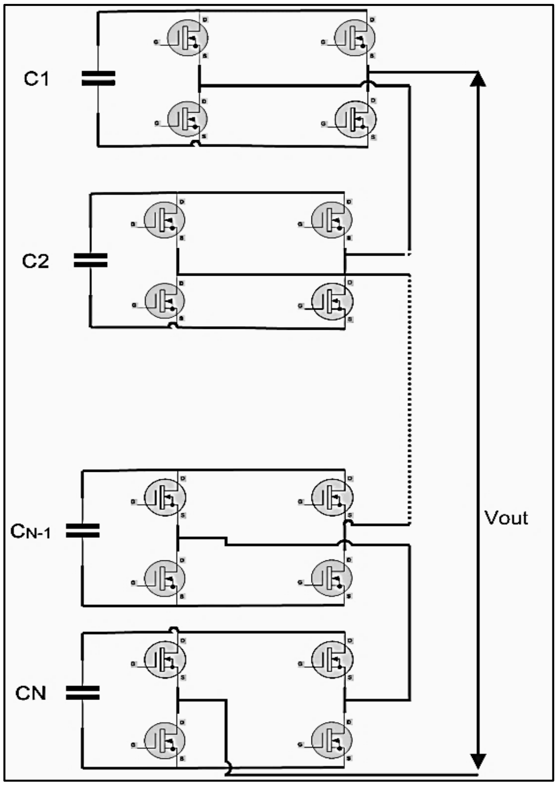

Figure (1): Multi-level single phase convertor.

In this paper, harmonics are being monitored with the use of different number of levels by connecting a different numbers of single phase H-bridge units with independent DC sources, the switching operations of each unit is performed by phase shift carrier pulse width modulator in which producing a control signals for each cell with particular phase shift. Simulation is begun with seven levels convertor (three H-bridge) and hence total harmonic distortion was found closer to 18.1 %. Hereafter simulation is adopted higher number of levels in every further experiment and it was found alike higher of levels, lesser of harmonics. The results of each simulation are tabulated in the table (1).

Table (1): Total harmonic distortion study.

No. of H-Bridge	No. of Levels	THD Value (%)
3	7	**18.1**
6	13	**9.8**
9	19	**6.4**
12	25	**5.3**
15	31	**4.4**

It is clear that, using of thirty-one levels convertor results significant harmonic elimination (4.4%). The waveforms of seven-levels and thirty-one levels are graphically compared as figure (2) depicts.

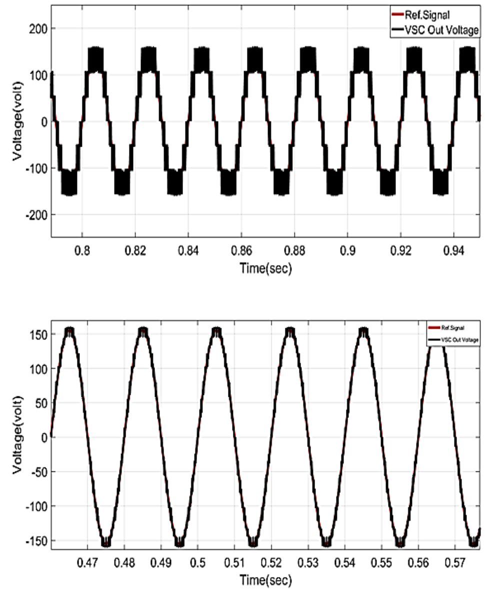

Figure (2): Convertor output waveforms.

The results explicitly reveal that thirty-one levels convertor is resulting a waveform with minimum ripple (harmonics) as in figure (2) and hence it will be adopted by further STATCOM process.

III. PHASE SHIFTED CARRIER PULSE WIDTH MODULATOR

To generate gate signals for each unit (H-bridge), PSCPWM is used. This method involves comparing the amplitude of reference signal of (50 Hz) frequency with amplitude of higher frequency signal known as carrier. The comparison produces pulse to be used for gate triggering in each arm of H-bridge. Figure (3) depicts the model of PWM.

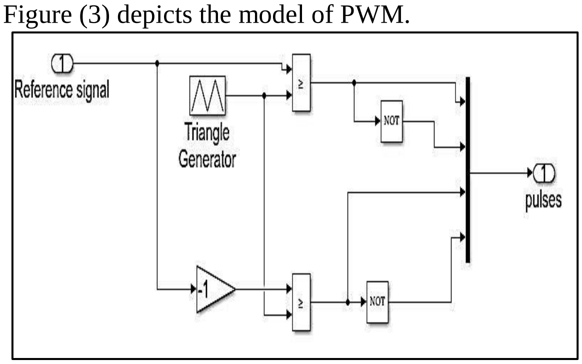

Figure (3): PSCPWM.

Each block as in this figure, shows generating a rectangular pulse with specific phase, herein for thirty-one level a (N-1) pulses are required (30 signals), each pulse is segregated by 90° phase angle so that phase of first pulse may be zero and next in pulse will be 90° similarly with all the pulses (180° ,270° etc.). Amplitude of reference signal can be adjusted by external controllers; figure (4) depicts the modulated signal and carrier signal.

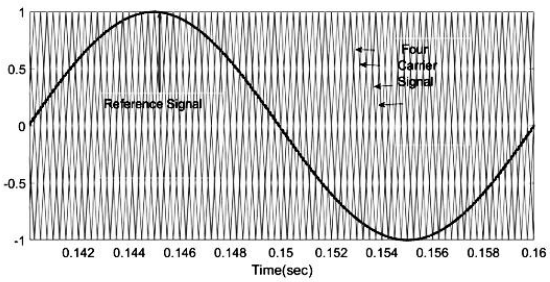

Figure (4): Modulated signal and carriers in PWM.

IV. STATCOM MODEL

A single phase STATCOM is implemented in Simulink and composed of multilevel voltage invertor which is connecting with capacitor as DC voltage source and the combination is interfaced with a single phase power grid by means of coupling transformer. The major of designed system is to compensate reactive power upon the load consumption. Exchanging of power is initiating due to potential difference at the point of common coupling (PCC). Power is flowing between STATCOM and grid in bidirectional way hence STATCOM can inject power into the grid one the voltage of grid is going blow the SATCOM voltage. On the other hand, STATCOM may absorb the power from the grid if voltage in grid is the higher. Figure (5) shows SATCOM structure and interfacing with AC power grid.

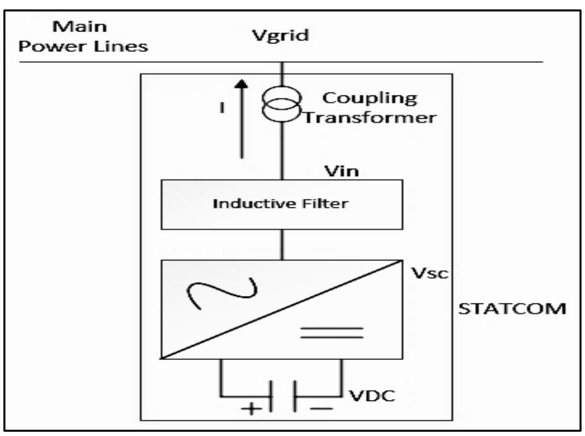

Figure (5): STATCOM general architecture.

The phase angle between the grid voltage and STATCOM output voltage can be adjusted by varying the gate signals in PWM model. This project is adopted a 31 level H-bridge invertor and hence 15 DC capacitors as independent voltage sources. In order to perform the proper control of invertor's output voltage and hence governing the STATCOM functions, the STATCOM current is transformed in DQ frame, generally, DQ transformation is simplifying the computational cost specially when three phase system is proposed, in our case, (single phase power system) DQ transformation can be performed with ease as matrix of DQ transformation is not involved hereby the imaginary part of current signal can be derived by performing π/2 phase shift on same copy of current signal by this current signal in αβ co-ordinates is resulted as figure (5) depicts.

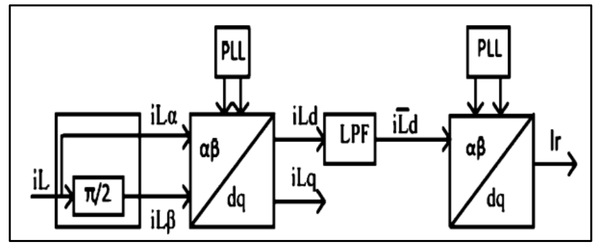

Figure (6): DQ transformation.

By rotating the αβ frame at a specified frequency resulting current signal in DQ format.

V. MATHEMATICAL MODEL

Figure below is depicting a single line representation of STATCOM, the resistor R_p connected in shunt with capacitor and stands for losses of switching in inverter. Resistor R_s and inductor L_s are representing the impedance of transmission line, whereas R_{st} stands for the conduction losses of transformer and invertor, L_{st} is the coupling reactor.

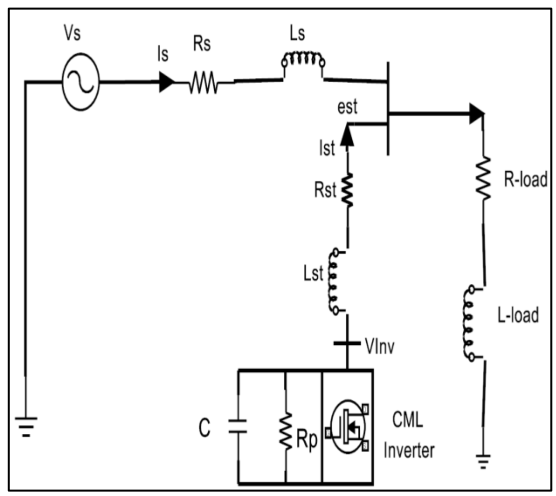

Figure (7): Equivalent circuit of STATCOM.

$$e_{st} - i_{st}R_{st} - L_{st}\frac{di_{st}}{dt} - v_{Inv} = 0$$

$$L_{st}\frac{di_{st}}{dt} = -i_{st}R_{st} + e_{st} - v_{Inv}$$

$$\frac{di_{st}}{dt} = -\frac{i_{st}R_{st}}{L_{st}} + \frac{e_{st} - v_{Inv}}{L_{st}}$$

$$p[i_{st}] = \left[-\frac{R_{st}}{L_{st}}\right][i_{st}] + \frac{1}{L_s}[e_{st} - v_{Inv}]$$

Where,

$$p = \frac{d}{dx}$$

Per-unit representation:

$$R_{st} = R'_{st}Z_{base}$$

Where, $Z_{base} = \frac{V_{base}}{I_{base}}$

$$L_{st} = \frac{L'_{st} Z_{base}}{\omega_{st}}$$

$$i_{st} = i'_{st} i_{base}$$

$$e_{st} = e'_{st} v_{base}$$

$$v_{st} = v'_{st} v_{base}$$

$$p[i_{st}] = \left[-\frac{R'_{st}\,\omega_{st}}{L'_{st}}\right][i'_{st}] + \frac{\omega_{st}}{L'_{st}}[e'_{st} - v'_{Inv}]$$

By performing a DQ transformation results will be:

$$I_{dq} = \begin{bmatrix} I_d \\ I_q \end{bmatrix} = T I_{ri}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} I_r \\ I_i \end{bmatrix}$$

Whereas, Ir and Ii are the real current signal in time t and delayed copy of signal in t-1. The following expression of the imaginary part:

$$p\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -\frac{R'_{st}\,\omega_{st}}{L'_{st}} & \omega \\ \omega & -\frac{R'_{st}\,\omega_{Inv}}{L'_{st}} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \frac{\omega_{st}}{L'_{st}} \begin{bmatrix} e'_d - |v'| \\ e'_q \end{bmatrix}$$

Where, $\omega = \frac{d\theta}{dt}$

$$e'_d = v'_{dc} k \cos(\propto)$$

$$e'_q = v'_{dc} k \sin(\propto)$$

Vector control: By substituting i_d and i_q in the above equations:

$$e'_d = \frac{L'_{st}}{\omega_{st}}(x_1 - i'_q \omega) + |v'|$$

$$e'_q = \frac{L'_{st}}{\omega_{st}}(x_2 - i'_d \omega)$$

Hence, the equation will become:

$$p\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -\frac{R'_{st}\,\omega_{st}}{L'_{st}} & 0 \\ 0 & -\frac{R'_{st}\,\omega_{st}}{L'_{st}} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \frac{\omega_{st}}{L'_{st}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

After compensation of PI controller, the k_p with Proportional controller while k_i as integrator controller.

$$x_1 = (-i'_d + i^*_d)\left(k_p + \frac{k_i}{p}\right)$$

$$x_2 = (-i'_q + i^*_q)\left(k_p + \frac{k_i}{p}\right)$$

VI. PRACTICAL MODEL

A single phase, 220 V, 50 Hz AC source is used. A non-linear load is connected on AC voltage terminals, an inductive load is implemented for first half period of simulation and later capacitive load is connected instead. However, load is drawn 450 watt and 450 VAR that must be delivered by AC generator.

Power factor of 0.7 is detected for the current operation conditions as in figure (6).

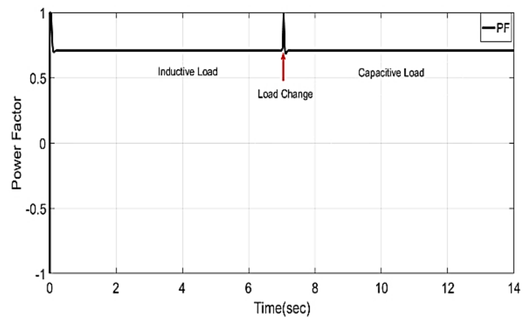

Figure (8): Power factor calculated without STATCOM.

the reactive power is consumable by the load, generator is deemed to produce the required current to the load all the times, in such circumstances, transmission line is subjected of power losses with more demand of reactive power in case of inductive load expansion, this in turn degrades the performance of power system. A single phase STATCOM system is proposed in this paper in order to compensate the reactive power and enhance the system performance.

Table (2) is summarizing the model parameters. For best practice a thirty-one level STATCOM is employed is this system in which reduces the harmonics to the minimum level. A 220/110 V coupling transformer is used to provide the connection between power grid and the STATCOM, that means 110 V RMS (which equal to 115 V (peak to peak)) is required to be generated by STATCOM, each DC capacitor is in turn deemed to produce 10.5 V (reference DC link voltage).

Table (2): The model parameters.

-	**Parameters**	**Values**
Source	Peak Amplitude (Volts)	311.12 V
	Frequency (Hz)	50 Hz
	Phase (Degree)	0 °
Load	Nominal Voltage (Volts)	220Vrms
	Nominal Frequency (Hz)	50 Hz
	Active Power (Watts)	450 W
	Reactive Power Inductive (+Var)	450 Var
	Reactive Power Capacitive	450 Var
	Capacitor Initial Voltage	1 V
Dc Link volt	Reference DC Link Voltage (Volts)	10.5 V
Single	Frequency Input (Hz)	50 Hz

phase PLL	Regulator Gain (Kp)	180
	Regulator Gain (Ki)	32000
	Regulator Gain (Kd)	1
Coupling Transformer	Nominal Power(VA)	1000 VA
	Nominal Frequency(HZ)	50 Hz
Winding 1 Parameters	Voltage (Volts)	220 Vrms
	Resistance (per unit)	0.0005 pu
	Inductance (per unit)	0.0005 pu
Winding 2 Parameters	Voltage (Volts)	110 Vrms
	Resistance (per unit)	0.0005 pu
	Inductance (per unit)	0.0005 pu

STATCOM is inserted closer to the load to reduce the current flowing in transmission line and compensate the required reactive power. Figure (7) depicts the entire simulation of the system.

A proper control scheme is required to control the DC voltage output in capacitors as well as to handle the reactive power of the system. Decoupled Current Control Method and PI controller are used to perform this task.

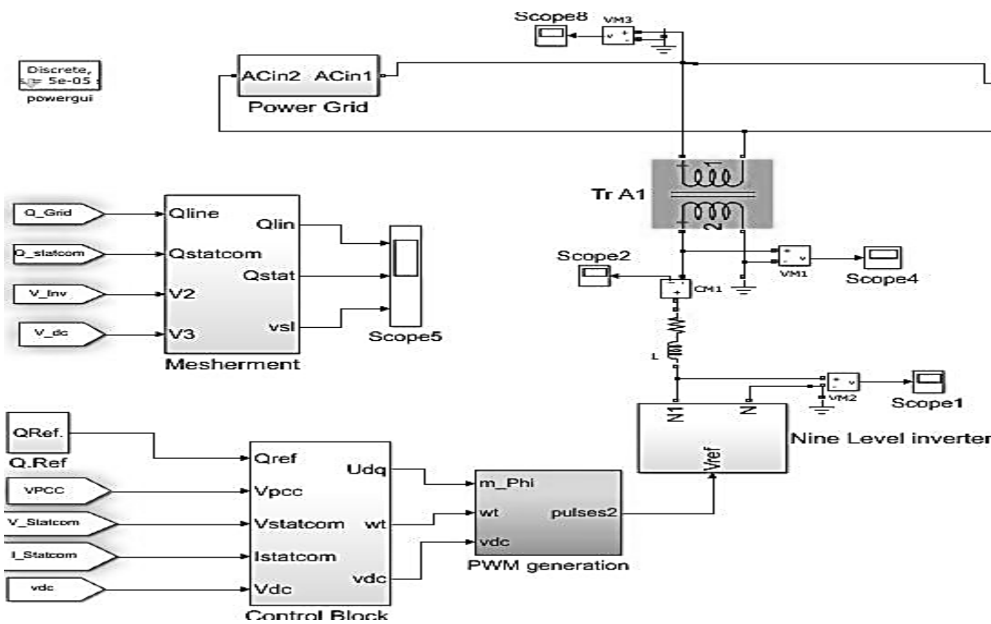

Figure (9): simulation of power system with STATCOM.

VII. CONTROLLING SCHEME

Current decoupling method is used to control the AC current and voltage output from STATCOM. DQ transformation is used to perform the same task as in figure (5), prior to perform DQ, delay is applied to segregate the imaginary part of signal hereafter, phase locked loop (PLL) is applied to synchronous the STATCOM output with grid terminal signal hence output will be in form of sinwt , cosewt. Herein, DQ is performed on the resultant signals. PI controller is used to generate the I_{qref} and I_{dref} for controlling the output voltage in the DC capacitors and for reactive power regulation, this is achieved as in figure (8), two loops are used (OUT loop and IN loop), firstly out-loop is used to generate $I_{d\ ref}$ (direct) which underlying capacitor voltage controller, total of fifteen capacitors are deemed to produce 155 V DC (10.5 V mean value), so the average value of all capacitors is applied into comparator for matching the value with other reference voltage (10.5) hereafter, PI controller is used to generate $I_{d\ ref}$ to control the capacitor voltage. Similarly, $I_{q\ ref.}$ is produced by out-loop to regulate the reactive power. The inner current loop is implemented in the rotational reference framework which is synchronized with the AC terminal voltage. Ed* as shown in figure (8) is obtained by comparing Id with the internal real current reference, while the Eq* is obtained by comparing Iq with the external reactive current reference.

Ed* and Eq* components are transformed back to alpha-beta coordinates and are normalized by capacitor voltage and the resulting values are used further on as modulation indices for the PWM generation. In terms of space vectors in which vdq, idq and vdq-inv are instantaneous space vectors of the transformer secondary side at PCC, STATCOM current and multilevel inverter output voltage in d-q reference frame.

$$V_{dq} = R_f \times i_{dq} + L_f \frac{d}{dt} i_{dq} + j\omega_s L_f \times \ i_{dq} + v_{dq_{inv}}$$

In the steady-state condition the equation will become:

$$V_{dq} = R_f \times i_{dq} + j\omega_s L_f \times \ i_{dq} + v_{dq_{inv}}$$

the voltage vd is constant and vq is zero. Thus, the instantaneous active and reactive powers transferred from the AC system to the STATCOM system are proportional to d-axis and q-axis currents respectively.

$$p(t) = \frac{Vd * Id + Vq * Iq}{2} = \frac{VdId}{2} = -\frac{VdIq}{2} \qquad q(t) = \frac{VqId - VdIq}{2}$$

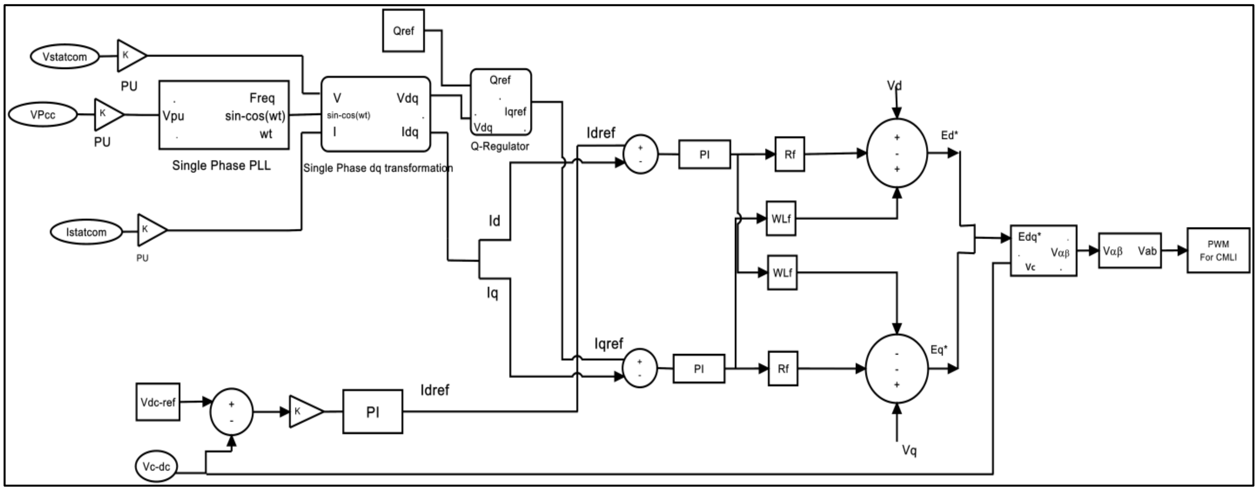

Figure (10): Control strategy.

VIII. RESULTS AND DISCUSSION

At the situation is power system running without STATCOM, the inductive load is drawing 450 VAR of reactive power, source of 220 V, 50 Hz is hereby generating the required power. Power factor is measured in these circumstances close to 0.7 as figure (6) depicts. Now, STATCOM is interfaced near to the load and hence started to compensate the reactive power. At first stage all the capacitors (DC sources) are stabilized by the control scheme to produce an average voltage of 10.5 V as in figure (9).

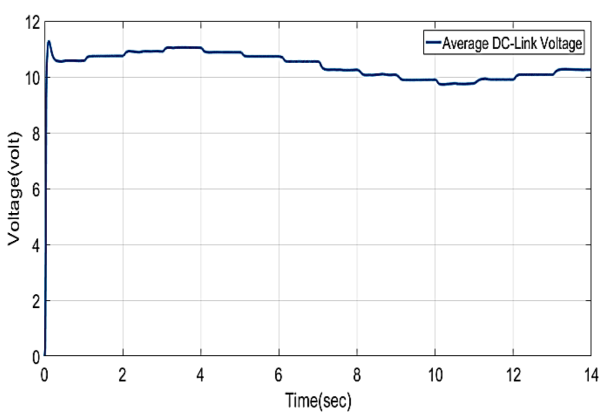

Figure (11): Capacitors average voltage measurement.

So, STATCOM is set to produce voltage of 155 V, figure (10) for all the capacitors which will be rectified to produce a reactive power.

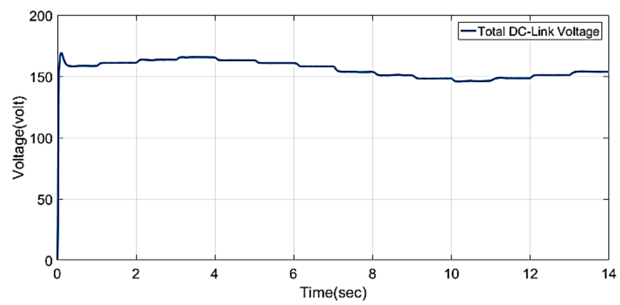

Figure (12): H-bridge inverter output.

Considering the system parameters tabulated in table (2), simulation is set for 14 seconds, during the first half of this period inductive load is inserted (0 second-07 second), load consuming 450 watt and 450 VAR. on the second half of simulation, capacitive load is switched into capacitive as in figure (11).

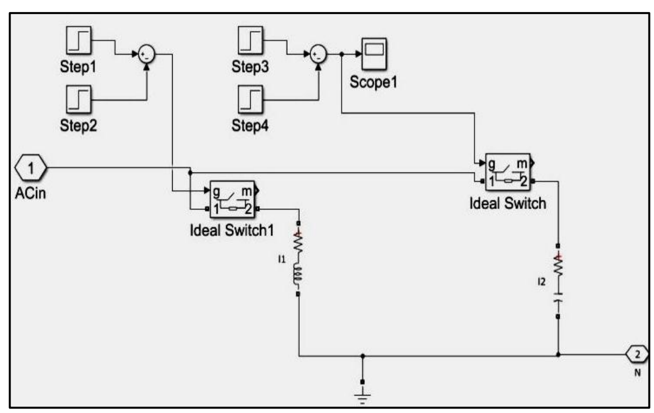

Figure (13): Load switching circuit.

STATCOM is now configured to generate 100, 200, 300 and 400 VAR of reactive power directly to the load during the first half of simulation time, hence the AC generator will reduce reactive into 350 ,250, 150, 50 VAR respectively with each fluctuation in compensator output. Similarly, during the second half of simulation (7-14 second), load nature is switched to capacitive so negative reactive power is inserted by STATCOM as -300, -200, -100 hence the generator is decreases the production of reactive power as the load is provided with same from compensator.

With every step of reactive power injection, the power factor of source is changed; table (3) is describing the entire results.

Table (3): generator PF and Q results.

Time period (s)	STATCOM Q (VAR)	Generator Q (VAR)	Power factor
0-2	100	350	0.78
2-4	200	250	0.87
4-6	300	150	0.94
6-8	400	50	0.99
8-10	-300	-150	0.94
10-12	-200	-250	0.87
12-14	-100	-350	0.78

Harmonics are reduced significantly by using of thirty-one level H-bridge convertor as shown in table (1) so the total harmonics distortion is became 4.4 %.

CONCLUSION

Power systems are subjected to performance distortion due to diversity nature in loads, high demand due to network expansion or even because the distribution issue such as unmanaged subscriptions on power networks. All of these inputs are critical to the performance. In this paper, STATCOM is proposed to handle the reactive power demanded by reactive load, it is compensating Q amount by injecting the same into power grid. This Q enhancement is having great impact on losses reduction in transmission line, voltage regulation at load. Simulation shows the result when STATCOM compensate 100 VAR to a consumer of 450 VAR, the power factor is enhanced by 0.08 (increased). By more and more compensation, load may draw only 50 VAR from the generator and backup the rest form STATCOM, this enhanced the power factor so it reached 0.99 when STATCOM delivering 400 VAR to the load. This is considered as important contribution of power system. Harmonic distortion study has conducted to construct the DC inverters of STATCOM with minimum ripple output; so thirty-one level H-bridge is chosen and hence yielded 4.4% of total harmonic distortion. H-bridge is controlled by phase shifted pulse width modulation which produced a 30 rectangular waveform to trigger the gate in each arm of inverter. Voltage and current in STATCOM are converted into direct and quadrature component I_{d} ref and $I_{q\ ref}$; then two loops of current decoupled control are used to manage the capacitors voltage output and the reactive power of system.

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