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Multi-String Multi Level Inverter Based Statcom For High Power Applications

K.Sudhakar, K.Madhu Babu

Abstract--- **The industrial power sector and domestic power sector requires bulk power transfer from sources, in which, reactive power and power quality (PQ) are the major issues. This paper presents Static VAR compensation scheme and power quality improvement by using Multi-string inverter based static compensator (STATCOM). The scheme consists of multi-string inverter connected through three phase transformer.**

The application of flexible ac transmission system (FACTS) controllers is increased in power system due to their ability to stabilize transmission systems and improve the Power quality in distribution system. Static compensator (STATCOM) is a reliable reactive power controller, and this device also provides active power oscillation damping, voltage regulation etc. In high power applications, var compensation is achieved using multi-level inverters. Among multi-level inverters, Multi-string inverter topology requires less number of switches and DC-sources compared to the cascaded two level inverter.

Multi-string inverters offers improved output waveforms, Reduced total harmonic distortion (THD), less switching losses which in turn reduces cost and complexity of the circuit. Therefore over all control is simple compared to cascaded two-level inverter. The performance of the system is analyzed at balanced and unbalanced supply condition through simulation. Overall Modelling and analysis is developed on MATLAB/ Simulink environment.

Index Terms—**Power quality (PQ), static compensator (STATCOM), flexible ac transmission system (FACTS), total harmonic distortion (THD), multi-string inverter.**

I. INTRODUCTION

Power generation and transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines [1]. Loads like motor loads and other loads, require reactive power for their operation. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and this is known as reactive power compensation [2]-[3]. There are two aspects to the problem of reactive power compensation: load compensation and voltage support. Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads. Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. Two types of compensation can be used: series and shunt compensation. These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed [4]-[5]. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance [6].

It is difficult to provide a stable, secure, controlled, economic quality of power and this is becoming vitally important with the rapid growth in the industrial area. To meet the demanded quality of power in a power system it is essential to increase the transmitted power either by installing new transmission lines or by improving the existing transmission lines by adding new devices. Later they came up with the concept of utilizing the existing transmission line just by adding new devices.It is hard to connect a single power semiconductor switch directly to medium voltage grids (2.3 kV, 3.3 kV, 4.16 kV, or 6.9 kV). For these reasons, a new family of multilevel inverters has emerged as the solution for working with higher voltage levels. Multilevel inverters have received more attention in industrial application, such as motor drives, static VAR compensators and renewable energy systems, etc [7]-[8]. Primarily multilevel inverters are known to have output voltages with more than two levels. As a result, the inverter output voltages have reduced harmonic distortions and high quality of waveforms. Additionally, the devices are confined to fraction of dc-link voltage. These characteristics make multilevel inverter to adopt for high-power and high-voltage applications. Cascade Multilevel Inverter (CMI) is one of the productive topology from multilevel family. It requires large number of power semiconductor switches and THD is high. This paper presents Multi-string inverter topology and requires less number of power semiconductor switches and it has less THD. Thus power quality can be improved effectively.

The Overall paper is organized as : The section I presents introduction about the proposed system. Section II represents control scheme and proposed system description. Section III represents multi-string multi-level inverter topology. Section IV and section V represents

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Simulink model and their results respectively. Overall conclusion is shown in section VI.

II. SYSTEM MODELLING AND DESCRIPTION

The power system model and the STATCOM model is shown in Fig.1. This model represents the connection point of STATCOM in the power system.

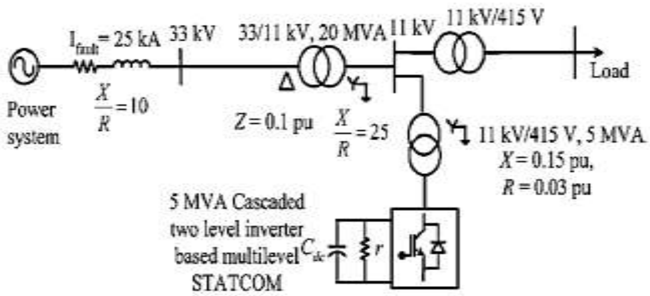

Fig.1 Power system and the STATCOM model

The system consisting of cascaded two-level inverter based STATCOM and topology of the circuit is shown in Fig.2. The low-voltage (LV) side and high voltage (HV) side of a transformer is connected to inverter and grid respectively.

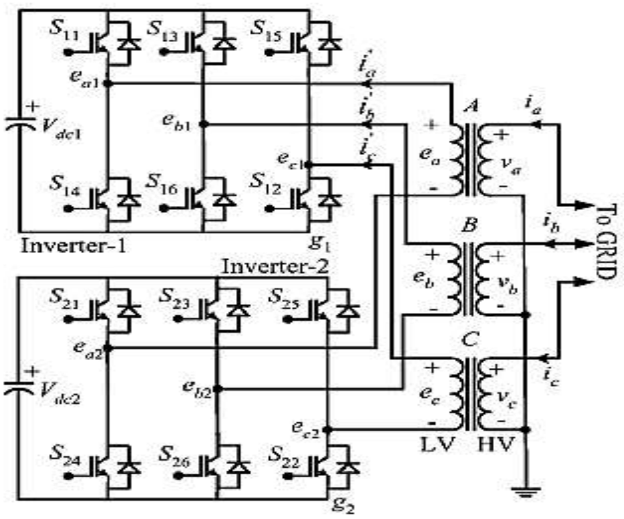

Fig.2. Cascaded two-level inverter based STATCOM

High-voltage (HV) side of transformer three phases are connected to grid and low-voltage (LV) side three phases are connected to three arms of inverters. Multi-level inverter uses the IGBT switches in high power high voltage applications. The two inverters i.e inverter 1 and inverter2 are connected in cascade with sources of dc-link capacitors C_1 and C_2. The actual voltages of two dc-link capacitors are V_{dc1} and V_{dc2}. These voltages are needed to be regulated to maintain constant voltages and to achieve required objective, modulation indices are controlled.

From the Fig.3, the three phase RMS source voltages V_a', V_b' and V_c' referred to the low-voltage side of the transformer. The leakage inductances of low-voltage side windings of the transformer are L_a, L_b and L_c respectively. The transformer losses are represented in terms of resistances, which are r_a, r_b and r_c respectively. The output voltages of inverter1 and inverter2 are e_{a1}, e_{b1}, e_{c1} and e_{a2}, e_{b2}, e_{c2}. Finally leakage resistances of dc-link capacitors C_1 and C_2 are r_1 and r_2 respectively

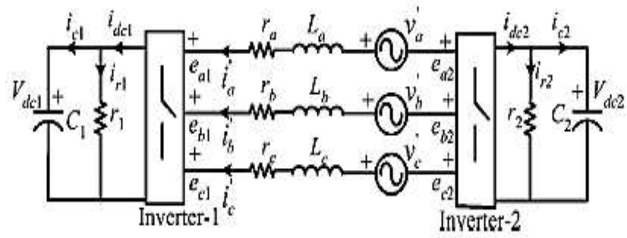

Fig.3 Equivalent circuit of two-level inverter based STATCOM

A. PHASE EQUIVALENT CIRCUIT

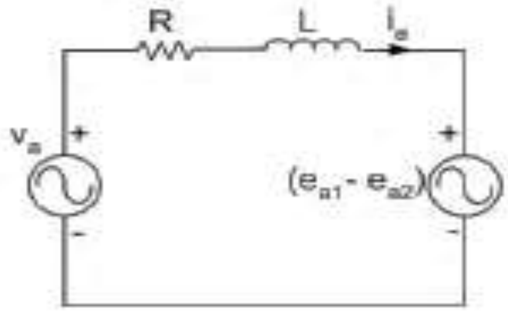

Fig.4. Equivalent circuit of phase a

Equivalent circuit of phase 'a' is shown in Fig.4. In the figure, the RMS source voltage is represented as v_a', total loss in the system is represented as R, the transformer winding leakage inductance is represented as L, the voltage across primary side of the transformer of inverter1 and inverter2 is $(e_{a1}-e_{a2})$.

Applying KVL to the loop

$$-v_a' + R_a I_a' + L_a \frac{di_a'}{dt} + (e_{a1}-e_{a2}) = 0 \qquad (1)$$

Similarly for 'b' and 'c' phases

$$-v_b' + R_b I_b' + L_b \frac{di_b'}{dt} + (e_{b1}-e_{b2}) = 0 \qquad (2)$$

$$-v_c' + R_c I_c' + L_c \frac{di_c'}{dt} + (e_{c1}-e_{c2}) = 0 \qquad (3)$$

By assuming resistances $R_a = R_b = R_c = R$ and inductances $L_a = L_b = L_c = L$, the above can be written in mathematical model form as,

$$\begin{bmatrix} \frac{di'_a}{dt} \\ \frac{di'_b}{dt} \\ \frac{di'_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} V'_a - (e_{a1} - e_{a2}) \\ V'_b - (e_{b1} - e_{b2}) \\ V'_c - (e_{c1} - e_{c2}) \end{bmatrix} \qquad (4)$$

The equation (4) is known as mathematical model in the stationary reference form of cascaded two-level inverter based STATCOM. To control both the active and reactive currents independently, above stationary reference frame equations can be converted into rotating reference frame equations. The source voltage of q-component is set to be zero so that the source voltage of d-component can be align with the synchronously rotating reference frame.

The dynamic model in the synchronously rotating reference frame is give as

$$\begin{bmatrix} \frac{di_d'}{dt} \\ \frac{di_q'}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & \omega \\ -\omega & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_d' - (e_{d1} - e_{d2}) \\ -(e_{q1} - e_{q2}) \end{bmatrix} \qquad (5)$$

Where $v_d{}'$ represents the direct (d)-axis voltage component of ac source and $i_d{}'$, $i_q{}'$ represents d and q axis current components of cascaded two-level inverter.

B. CONTROL STRATEGY

The block diagram of control circuit is shown in Fig. 5. The d-axis and q-axis voltages can be controlled as follows

$$e_d{}^* = -x_1 + \omega L i_q' + v'_d \quad (6)$$
$$e_q{}^* = -x_2 - \omega L i_d' + v'_q \quad (7)$$

Where $e_d{}^*$ and $e_q{}^*$ represents, d axis and q- axis reference voltage components of the inverter. The parameters x_1 and x_2 are known as control parameters and these can controlled as

$$x_1 = (k_{p1} + \frac{k_{i1}}{s})(i_d{}^* - i_d{}') \quad (8)$$
$$x_2 = (k_{p2} + \frac{k_{i2}}{s})(i_q{}^* - i_q{}') \quad (9)$$

Where $i_d{}^*$ is the direct (d)-axis reference current and is given by

$$i_d{}^* = (k_{p3} + \frac{k_{i3}}{s})[(V_{dc1}{}^* + V_{dc2}{}^*) - (V_{dc1} + V_{dc2})] \quad (10)$$

Where $V_{dc1}{}^*$ and $V_{dc2}{}^*$ represents the reference voltages of dc-link capacitors of inverter 1 and inverter2. The reference reactive current component i.e q-axis component $i_q{}^*$ is obtained either from load, when used for load compensation or from voltage regulation loop when used in transmission lines.

Fig.5. Shows that the three phase voltages v_a, v_b, v_c are given to phase-locked loop (PLL) to generate the unit signals $\cos\omega t$ and $\sin\omega t$. Phase lock loop or phase locked loop (PLL) is a type of control system, which is used to generate output signal to match the phase of input signal. These unit signals are used to transform the converter currents $i_a{}'$, $i_b{}'$, $i_c{}'$ into synchronously rotating reference frame currents. So that it is easy to control reactive and active current components. These currents consist of large switching frequency ripples and which are eliminated by using low-pass filters (LPF). The reference voltages to the converter are $e_d{}^*$, $e_q{}^*$ are generated from controller using $(V_{dc1}{}^* + V_{dc2}{}^*)$ and $i_q{}^*$. The inverter supplies desired reactive component of current $i_q{}^*$ and draws active component of current $i_d{}'$ by considering these reference current components. Which can be further used to regulate total dc-link voltage $V_{dc1}{}^* + V_{dc2}{}^*$ of the inverter. Due to these unequal dc-link capacitor voltages, the regulation of this dc-link voltage becomes difficult. For effective control of total dc-link voltage, an additional control method is required. The main dis advantage of this cascaded multi-level inverter based STATCOM is control of individual dc-link voltages is more difficult.

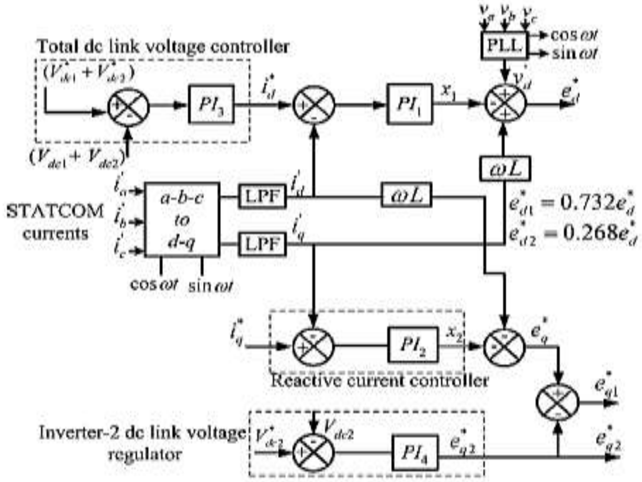

Fig.5. Control circuit diagram

C. DC-LINK BALANCE CONTROLLER

The total dc-link balance controller is used to provide magnitude and phase of resultant voltage supplied by the cascaded inverter. This is given by $e_I < \delta$. In which e_I represents the magnitude of d-axis, q-axis voltage components and δ represents the phase angle of the respective components.

$$e_I = \sqrt{e_d{}^2 + e_q{}^2} \quad \text{and}$$
$$\delta = \tan^{-1}\left((e_q)/(e_d)\right)$$

The active power sharing between the inverter and grid is depends on angle δ. From the figure, the reference voltage components of q-axis of the two inverters $e_{q1}{}^*$, $e_{q2}{}^*$ is obtained as

$$e_{q1}{}^* = e_q{}^* - e_{q2}{}^* \quad (11)$$

$$e_{q2}{}^* = (k_{p4} + \frac{k_{i4}}{s})(V_{dc2}{}^* - V_{dc2}) \quad (12)$$

Where $e_{q1}{}^*$ is used to control the dc-link voltage of inverter1, $e_{q2}{}^*$ is used to control the dc-link voltage of inverter2. The inverter2 dc-link voltage is controlled at 0.366 times that of inverter1 dc-link voltage, so four level operation is obtained and spectrum of harmonics in output voltage is improved.
The dc-link voltage s of inverter1 and inverter2 is expressed in terms of total dc-link voltage V_{dc}.

$$V_{dc1} = 0.732\, V_{dc} \quad (13)$$
$$V_{dc2} = 0.268\, V_{dc} \quad (14)$$

The d-axis voltage component $e_d{}^*$ is shared between inverter1 and inverter2, to regulate the dc-link voltages of inverter1 and inverter2 proportional to their individual dc-link voltages.

$$e_{d1}{}^* = 0.732\, e_d{}^* \quad (15)$$
$$e_{d1}{}^* = 0.732\, e_d{}^* \quad (16)$$

The power transfer to inverter1 is indirectly controlled and for inverter2, power transfer is directly controlled. Therefore inverter2 attain its reference value quickly when compared to inverter1. The control circuit uses the sinusoidal pulse width modulation (SPWM) technique to generate gate signals from the obtained reference voltages. The reference voltages of

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two inverters are in phase opposition so that harmonic spectrum will be appeared at double the switching frequency.

D.UNBALANCED CONDITION

The dc link voltages of inverters consist of double supply frequency components, causes third harmonic components in the ac side of inverter. Whenever load becomes unbalanced or asymmetric fault occurs, the ac side voltage of inverter becomes unbalanced, causes negative sequence voltages appeared in the supply voltage. Therefore large negative sequence currents will flow through inverter and it may leads to trip of STATCOM. Therefore when unbalance occurs STATCOM needs to supply these currents or should eliminate the unbalance in the supply voltages, to prevent inverter trip.
The reference voltage components of inverter is given by

$$e_{dn}^{*} = -x_3 - \omega L i'_d + v'_{dn} \qquad (17)$$

$$e_{qn}^{*} = -x_4 - (-\omega L) i'_{dn} + v'_{qn} \qquad (18)$$

III. MULTI-STRING MULTI-LEVEL INVERTER BASED STATCOM

Multi-string multi-level inverters are the new topology, designed for high power high voltage applications. This paper presents, multi-string multi-level inverter configuration based STATCOM opted for high power applications. The multi-string multi-level inverter topology consisting of number of H- bridge cells, they are connected in series and each H-bridge cell is connected to string. The main advantage of this topology is requirement of switches. In conventional cascaded multi-level inverter, number of switches are 8, where in multi string multi-level inverter, switches are 6. Therefore overall switching losses in multi string multi-level inverter is less. In which two switches will be operate across the main supply at line frequency.
Advantages of multi-string multi-level inverters:

1. Multi-string topology offers better quality in output waveforms.
2. Reduced total harmonic distortion in the output waveform.
3. This topology requires smaller size LC filters.
4. Electromagnetic interference (EMI) is less.
5. Less switching losses across the switches and switches can operate at fundamental frequency.

This paper presents multi-string multi-level inverter, replacing the conventional cascaded two-level inverter. Therefore five-level inverter operation is obtained without using five-level inverter.

IV. SIMULINK MODEL OF THE SYSTEM

The computer simulation using MATLAB/Simulink for multi-string multi-level inverter based STATCOM is shown in Fig 6. Table I shows the different system parameters used in simulations.

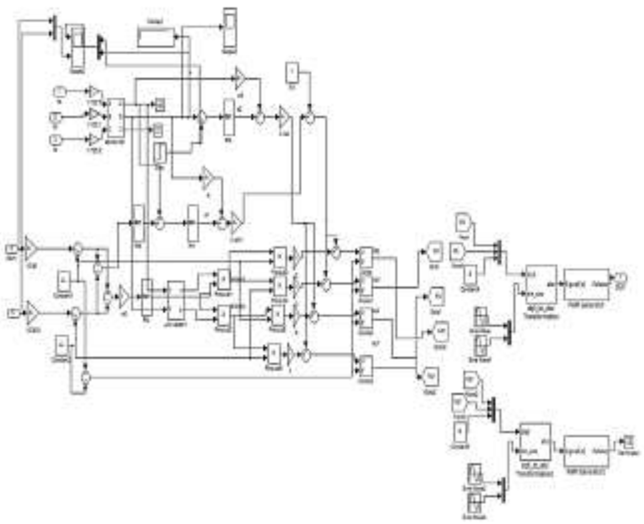

Fig.6. Control circuit

Fig.7. Simulink model of the system

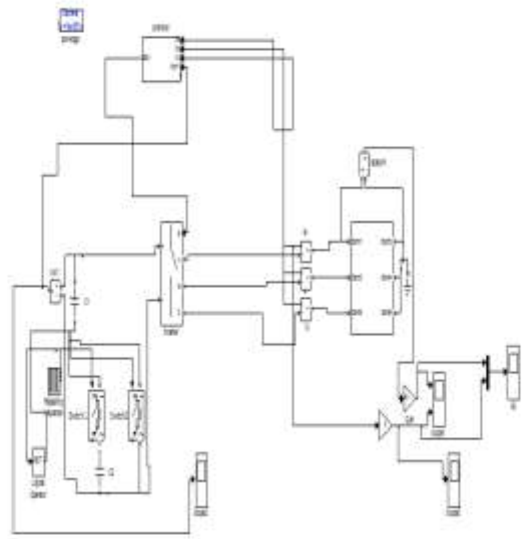

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TABLE 1
SIMULATION PARAMETERS

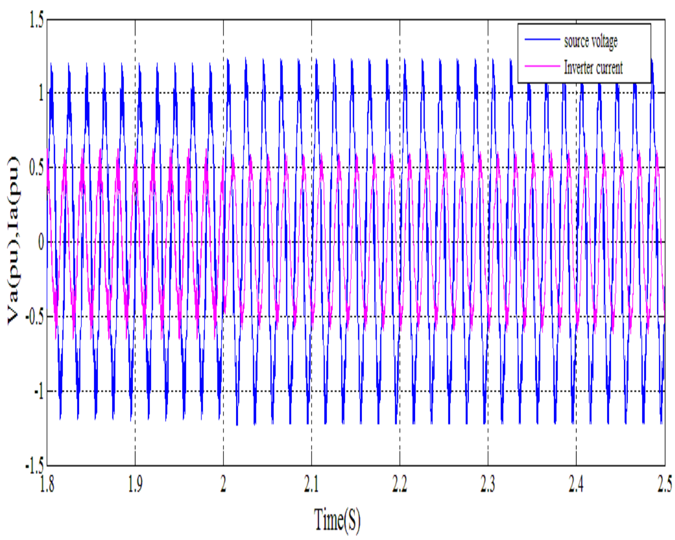
Rated power	5 MVA
Transformer voltage rating	11KV/400
AC supply frequency, f	50 HZ
Inverter-1 dc link voltage, Vdc1	659 V
Inverter-2 dc link voltage, Vdc2	241 V
Transformer leakage reactance, X_l	15%
Transformer resistance, R	3%
DC link capacitances, C_1, C_2	50 mF
Switching frequency	1200HZ

V. SIMULATION RESULTS

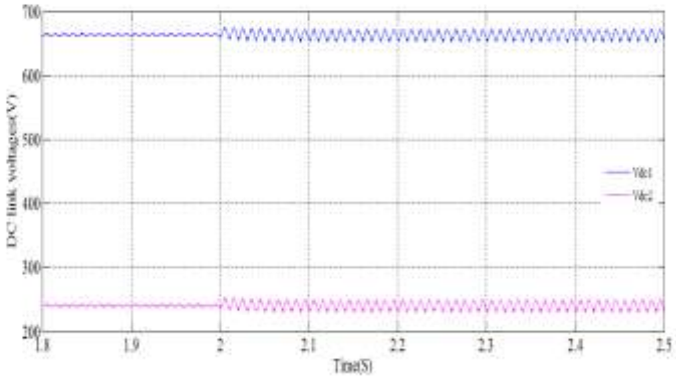
A. Cascaded two level inverter based STATCOM

Fig.8 shows the waveforms of source voltage and inverter current, DC-link voltage of two inverters in the reactive power control case.

In this case reactive power is controlled by setting i_q^* i.e reference reactive current component at a particular reference value. Initially i_q^* is set at 0.5 p.u. At t=2.0 s, i_q^* is changed from 0.5 to -0.5. Dc-link voltage of two inverters are regulated during the STATCOM modes are changed.



(a)



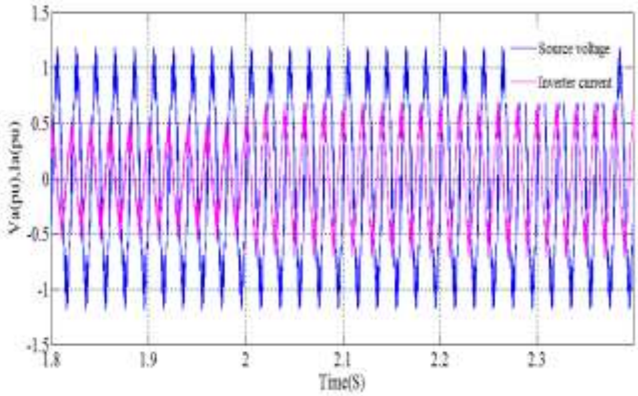
(b)

Fig.8 Reactive power control a) Source voltage and Inverter current. b) DC-link voltages of two inverters

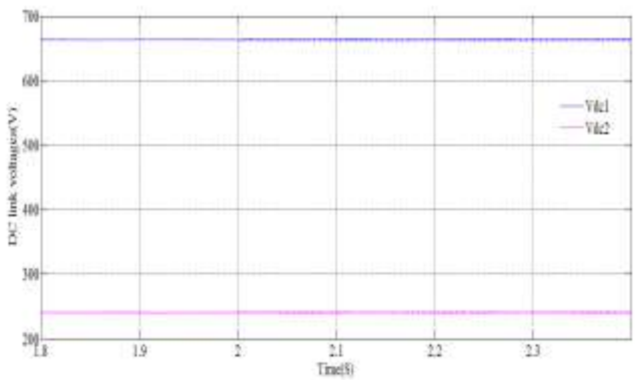
Fig.9 shows the waveforms of source voltage and inverter current, DC-link voltage of two inverters in the load compensation power case.

In this case, reactive power of the load is compensated by the STATCOM. Initially STATCOM supplies the current of +0.5 p.u. When load current increases at t=2.0 s, STATCOM supplies more than +0.5 p.u.

Therefore load compensation is effectively achieved by the STATCOM. The DC-link voltages of two inverters V_{dc1} and V_{dc2} are regulated at their respective values when STATCOM operating modes are changed.



(a)



(b)

Fig.9 Load compensation a) Source voltage and inverter current. b) DC-link voltages of two inverters

Fig.10 shows the waveforms of grid voltages on LV side of the transformer, during the fault condition

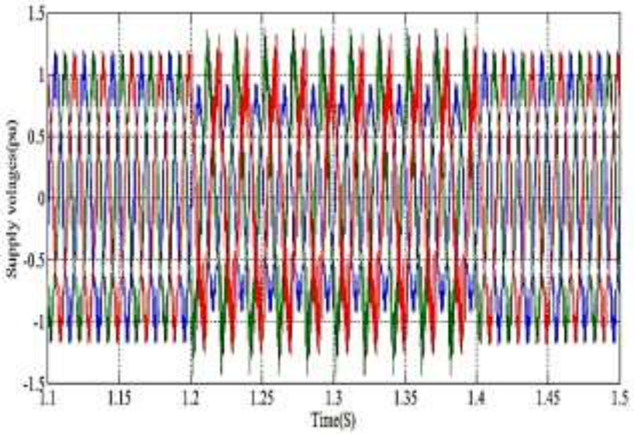


Fig. 10. Operation during fault (a) Grid voltages on the LV side of the transformer.

B. Multi-string inverter based STATCOM

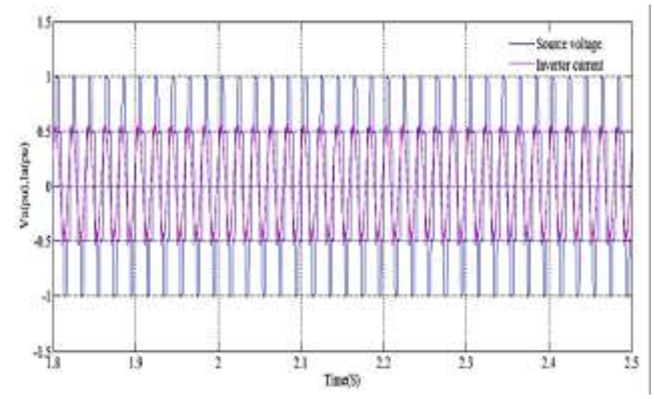
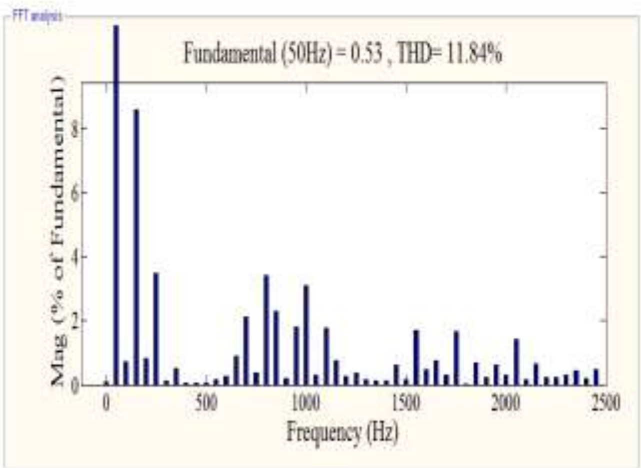


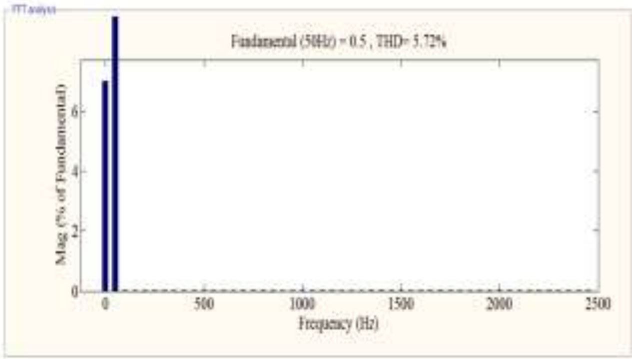
Fig.11. Source voltage and inverter current

FFT ANALYSIS

The frequency spectrum of different signals is obtained by this FFT analysis.



(a)



(b)

Fig.10. FFT Analysis showing THD of load current by using cascaded two-level inverter based STATCOM and multi-string inverter based STATCOM.

Powergui block can be used to obtain the frequency spectrum of any signal directly. The bar graph shows the order of harmonics and its magnitude.

By using Cascaded two level inverter based STATCOM the THD is 11.84% whereas in multi-string multi-level inverter based STATCOM the THD is reduced to 5.72

Type of Inverter	THD in Load current (%)
Cascaded two-level inverter based STATCOM	11.84
Multi-string inverter based STATCOM	5.72

VI. CONCLUSITION

The domestic and industrial power sector requires bulk amount of power. In which reactive power and power quality are major issues. This paper presents, the new topology of multi-string multi-level inverter based STATCOM. The cascaded two –level inverter based STATCOM topology requires large number of switches and consists of high THD. The multi- string inverter based STATCOM requires less number of switches and consists of low THD. This new topology provides reactive compensation and quality of power. Overall system is developed and their results are shown by MATLAB/simulation.

By using Multi-string multi-level inverter based STATCOM the THD is reduced from 11.84% to 5.72%. Thus the power quality is improved. Therefore for effective reactive power compensation and for quality of power supply, multi-string multi-level inverter based STATCOM is best suitable.

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