INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Cascaded Control of a Multilevel STATCOM for Reactive Power Compensation

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Abstract:
This paper deals with the design and implementation of a multilevel voltage source converter asked static synchronous compensator (STATCOM) employing an effective modulation control technique simulated in a MATLAB Simulink environment. The main objective of this paper is to maintain the voltage stability by compensating the reactive power in the power system. Hence, a new efficient control strategy is proposed, in order to reduce the voltage fluctuations like sag and swell conditions and also to isolate current and voltage harmonics in the transmission system. The multilevel STATCOM which can be used at the point of common coupling (PC C), for improving power quality is modeled and simulated using proposed control strategy and the performance is compared by applying it to an llOkv line with and without STATCOM. Relative Harmonic analysis is also discussed in this paper based on the total harmonic distortion (THD) calculations.

Keywords*: Power Quality, Reactive Power Compensation, Voltage Source Converter (VSC), STATCOM, GTO, SHEM, Phase Locked Loop (PLL), Multilevel Inverter, THD*

1. Introduction

Most if not all of the world's electric power supply systems are widely interconnected, involving connection utilities inside own territories which extend to inter-utility interconnections and then to interregional and international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. However, the long switching periods and discrete operation of the devices in the present power grid, cause difficulty in handling the frequently changing loads smoothly and damp out the transient oscillations quickly. Severe black-outs happened recently in power grids worldwide and these have revealed that conventional transmission systems are unable to manage the control requirements of the complicated interconnections and variable power flow. Therefore, improvement is necessary in the security and stability of the power grid, as well as the control schemes of the transmission system. Different approaches such as reactive power compensation and phase shifting have been implemented to meet the requirements. The demands of lower power losses, faster response to system parameter change, and higher stability of system have stimulated the development of the FACTS (flexible AC transmission systems). Based on the success of research in power electronics switching devices and advanced control technology, FACTS has become the technology of choice in voltage control, reactive/active power flow control, transient and steady-state stabilization that improves the operation and functionality of existing power transmission and distribution system. The achievement of these studies enlarge the efficiency of the existing generator units, reduce the overall generation and fuel consumption, and minimize the operation cost. In this paper reactive power compensation is chosen an effective way to improve the performance of the ac system. Hence a multilevel ST ATCOM and a control system should be designed for this purpose. Ben-Sheng Chen and Yuan-Yih Hsu[1] proposed a controller design of STATCOM and gave an analytical approach for harmonics based on Bessel functions. T. Manokaran, B.Sakthivel, and S. Mohamed Yusuf [2] designed a cascaded two level inverter based ST ATCOM for harmonic reduction. R.S. Dhekekar and N.V. Srikanth [3] developed a voltage-source inverter for high-voltage and high-power applications and implemented using Fuzzy control schemes. A hybrid fuzzy-PI (proportional integral) control algorithm of a two-level 12-pulse VSC based ST ATCOM is presented by K. Venkata Srinivasa, Bhim Singh, Ambrish Chandra and Kamal-AI-Haddad [4]. Nitus Voraphonpiput, Teratam Bunyagul, and Somchai Chatratana [5] discussed cascaded multilevel converter circuit with chain link topology. Chunyan Zang, Zhenjiang Pei, Junjia He, Guo Ting, Jing Zhu and Wei Sun [6] sununarized the common modulation strategies of a cascaded 5-level ST A TCOM. The operation of a 48 pulse ST ATCOM in unbalanced systems with negative sequence components have been reported by Carlos A.C. Cavaliere, Edson H. Watanabe, Mauricio Aredes [7]. Naveen Goel, R.N. Patel and Saji T. Chacko [8] discussed about genetically tuned ST A TCOM for Voltage Control and Reactive Power

Compensation. Amir H. Norouzi and A. M. Sharaf [9] developed two control schemes to enhance the dynamic performance of the ST A TCOM and SSSC. Hung-Chi Tsai, Chia-Chi Chu and Sheng-Hui Lee [lO] gave passivitybased nonlinear ST ATCOM controller design for improving transient stability of power systems.

In this paper the proposed control is tested on a power system to which a nine level cascaded multilevel converter is connected. The remaining part of the paper is organized as follows: Section-II gives the working principle of STATCOM; Section-III gives the cascaded multilevel circuit and its implementation in MATLAB simulink; Section-IV gives the ST A TCOM controller and its design; Section-V gives the implementation of STATCOM and its controller to a power system, along with test results and comparison of THD calculations; Section-VI gives the conclusion; references related to this topic.

2. Working Principle of STATCOM

STATCOM is a primary shunt device of the FACTS family, which uses power electronics to control power flow and improve transient stability on power grids. The STATCOM regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. For purely reactive power flow the three phase voltages of the ST A TCOM must be maintained in phase with the system voltages. The variation of reactive power is performed by means of a VSC connected through a coupling transformer. The VSC uses forced commutated power electronics devices (GTO's or IGBT's) to synthesize the voltage from a dc voltage source. The operating principle of STAT ACOM is explained in Fig.4. It can be seen that if V 2> V I then the reactive current Iq flows from the converter tothe ac system through the coupling transformer by injecting reactive power to the ac system. On the other hand, if V 2< V I then current Iq flows from ac system to the converter by absorbing reactive power from the system. Finally, if V2= VI then there is no exchange of reactive power. The amount of reactive power exchange is given by:

$$Q= \frac{V1(V1-V2)}{Xs} \quad (1)$$

Where,
V I: Magnitude of system Voltage.
V2: Magnitude of ST A TCOM output voltage.
Xs: Equivalent impedance between ST ATCOM and the system.

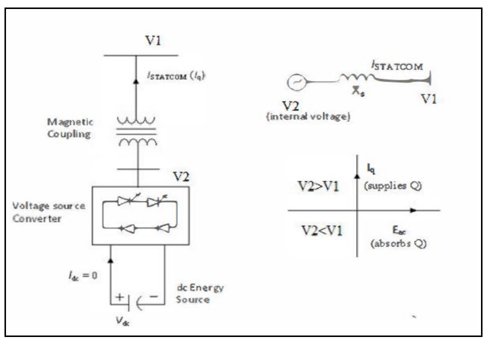


Figure 1: Schematic Configuration of STA COM

3. Cascaded Multilevel Circuit

A cascaded multi-level converter circuit is shown in Fig. 2. It is a three phase VSC which comprises of three single phases and each phase consists of H-bridges connected in series. The three phases in the converter are star connected. Each single phase H-bridge converter has two arms consisting of two pairs of GTO and diode connected in anti-parallel. Each H-bridge has its own capacitor, acting as a voltage source. Individual capacitors of same capacitance are selected to meet the economic and harmonic criteria. The peak output voltage of ST A TCOM is N times to that of the capacitor voltage, where N is the number of H-bridges in each phase. Each H-bridge generates three voltage levels + V de , 0 and - V de and the total output voltage of each phase is the combination of individual H-bridge voltages. A STATCOM with N converters per phase can synthesize 2N+ 1 voltage levels.

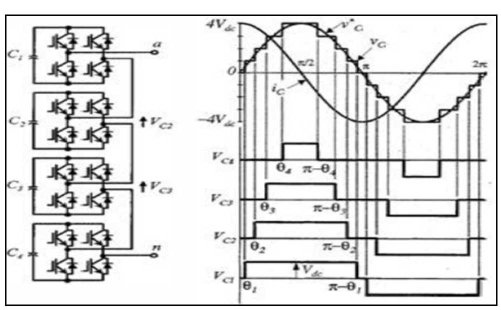


Figure 2: Single phase 9 level H-bridge inverter and switching strategies

The output voltage wave form of the cascaded N-Level STATCOM depends on the switching pattern, which is controlled by the switching angles of the converters. These switching angles can be independently selected, but appropriate switching angles are required to achieve good quality of the output voltage waveform. By employing SHEM, lower order harmonics can be eliminated in the output waveform. The amplitude of the odd hannonic order of the output voltage with 2N+1 level can be represented using Fourier's series method as,

$$V_n = \frac{4V_{dc}}{n\pi} \sum_{k=1}^{n} \cos\left(n\theta_k\right) \quad (2)$$

Where,
Vn is the amplitude of voltage harmonic of nth order
V dc is the DC voltage across the capacitor
N is the number of the bridges in each phase, n is the odd harmonic order
8k is the switching angle of the single phase bridge
In this paper a nine level cascaded multilevel converter is designed and is simulated in MA TLAB simulink environment

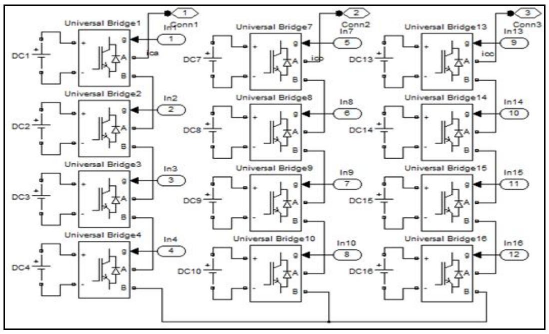


Figure 3: MATLAB implementation of 9 1evel

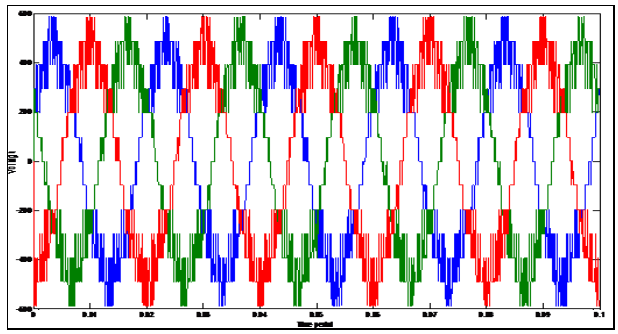


Figure 4: Output voltage of 9 level VSC

The firing angles of the bridges in the converter are so chosen such that 5th, 7th, lith and13th harmonics are eliminated and the THD of phase voltage is minimized. For the optimal values of firing angles the following equations must be solved (considering the modulation index M = 1).

$$Cos(5\,\theta_1) + Cos(5\,\theta_2) + Cos(5\,\theta_3) + Cos(5\,\theta_4) = 0$$
$$Cos(7\,\theta_1) + Cos(7\,\theta_2) + Cos(7\,\theta_3) + Cos(7\,\theta_4) = 0$$
$$Cos(11\,\theta_1) + Cos(11\,\theta_2) + Cos(11\theta_3) + Cos(11\,\theta_4) = 0$$
$$Cos(13\,\theta_1) + Cos(13\,\theta_2) + Cos(13\,\theta_3) + Cos(13\,\theta_4) = 0$$
$$Cos(\theta_1) + Cos(\theta_2) + Cos(\theta_3) + Cos(\theta_4) = (m-1)M \quad (3)$$

This set of nonlinear transcendental equations can be solved by iterative methods such as the Newton-Rap son method. We get,

$$\theta_1 = 6.57°, \qquad \theta_2 = 18.94°,$$
$$\theta_3 = 27.18°, \quad \theta_4 = 45.15$$

Thus, if the H-bridges are symmetrically switched during the positive half-cycle of the fundamental voltage to +V de at 6.57°, +2Vde at 18.94°, +3Vde at 27.18° and +4Vde at 45.l5° and similarly ill the negative half-cycle to -V de at 186.57°, -2V de at 198.94°,-3Vde at 207.18° and -4Vde at 255.15° to eliminate 5th, 7th, 11th and 13th harmonics. The 9 level PWM (pulse width modulation) converter is implemented in MATLAB simulink and respective output voltage waveform is shown in Fig 4.

4. Statcom Controller

The main objective for control of STATCOM is to enhance the power transmission by injecting or absorbing reactive power to or from the grid. The basic control strategy used for the proposed ST A TCOM controller is direct control. In this approach reactive output current can be controlled directly by the internal voltage control mechanism of the converter (e.g.:PWM) in which the internal dc voltage is kept constant. The STATCOM is controlled to deliver either inductive or capacitive currents to the power system by varying its output voltages V2a, V2b and V2e. In the design of the STATCOM controller, the three-phase quantities (voltage and current) are fIrst transformed into direct and quadrature components in a synchronously rotating reference frame. Then, a current regulator is employed for the current control.

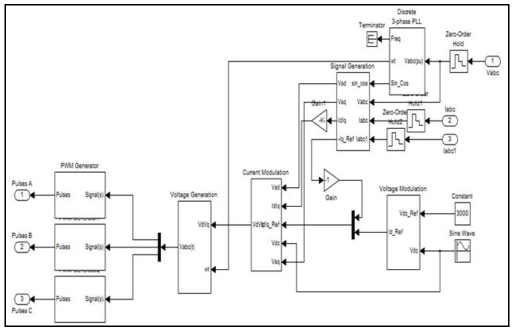


Figure 5: Simulation model of STATCOM Controller

In addition, an ac voltage controller is designed to regulate the PCC bus voltage through a PI controller. The ac voltage controller generates the desired reactive current reference for the current regulator.

In the design of the STATCOM controller, it is essential to have good dynamic response in the transient period and to ensure minimal harmonics at steady state. As shown in Fig. 5, a transient modulation-index controller and a steady-state modulation-index regulator are proposed to achieve the goals of good transient response and minimal steady-state harmonics respectively. Details for the design of transient modulation index controller, steady-state modulation-index regulator, phase locked loop (PLL), abc to dqO transformation, AC voltage controller, Current regulator, PWM generator are described below:

4.1. PLL

The PLL provides the basic synchronizing signal which is the Phase angle of the bus. In the case of a sudden change in the power system, such as load rejection, it takes about half a cycle of voltage (10 ms for 50 Hz) for the PLL to be synchronized with the new voltage phase angle, plus the signal processing delay. During this time the ST ATCOM operates at the previous phase angle, while the bus voltage phase has changed. Depending on the amount of phase angle change and whether it is increased or decreased, an uncontrolled real power, and reactive power exchange would occur between the ST A TCOM and the transmission line during this inherent PLL delay. Therefore depending on the amount of the phase angle change and whether it is increased or decreased, the dc capacitor would be charged or discharged at load switching instants.

4.2. abc to dqO Transformation

This block performs the abc to dqO transformation on a set of three phase signals. It computes the direct axis V d, quadrature axis V q, and zero sequence V 0 quantities in a two axis rotating
reference frame according to the Park's Transformation shown below.

$V_D=\frac{2}{3}\,[V_a \sin(\omega t) + V_b \sin\left(\omega t - \frac{2\pi}{3}\right) + V_c \sin(\omega t + \frac{2\pi}{3})]$

$V_D=\frac{2}{3}\,[V_a \cos(\omega t) + V_b \cos\left(\omega t - \frac{2\pi}{3}\right) + V_c \cos(\omega t + \frac{2\pi}{3})]$

$V_0 = \frac{1}{3}\,[V_a + V_b + V_c]$ (4)

Where (ω = rotating speed (rad/sec) of the rotating frame. C. AC Voltage Controller and Current Regulator: The AC Voltage controller converts V d , V q into reference reactive current 1,,' using appropriate PI Controllers as shown in Fig.5

$i_q^* = G_1(s)[V_{rms} - V_{rms}^*]$ (5)

$G_1(s) = k_1 + \frac{k_2}{s}$ (6)

Similarly Current regulator uses reference reactive current i_q^* and reference direct current i_d^* along with PI Controllers to generate reference direct and quadrature voltages E_d^* , E_q^* respectively.

$E_d^* = -\omega L_f i_q + V_{dc} - x_1$ (7)

$x_1 = G_2(s)[i_d^* - i_d^*]$ (8)

$G_2(s) = k_3 + \frac{k_4}{s}$ (9)

Lf is leakage inductance
V de is capacitor voltage.

4.3. Transient Modulation-Index Controller

The efficient way to modulate the reactive power output Q of the ST A TCOM and to regulate the PCC bus voltage is to control the output voltage of the ST A TCOM in the transient period. ST ATCOM output voltage is proportional to the product of modulation-index (MI) and V de. Since it is impossible to change V de instantaneously, it is desirable to adjust the MI in the transient period such that the PCC bus voltage can be regulated efficiently. Thus, a transient modulation-index controller is proposed to adjust the MI rapidly in the transient period.

$$MI = \frac{\sqrt{E_d^* + E_q^*}}{K\, V_{dc}} \qquad (10)$$

$$\propto = \tan^{-1}\left(\frac{E_q^*}{E_d^*}\right) \qquad (11)$$

4.4. Steady-State Modulation-Index Regulator

It has also been observed that a lower modulation index would give more harmonic contents at steady state. Thus, it is desirable to have the MI fixed at unity in order to ensure minimal harmonics at steady state. To achieve this goal, a steady-state modulation-index regulator is proposed to drive the modulation index to the pre-set value (MI*=1 in this work) at steady state through the action of a PI controller. As shown in Fig.5, the real current reference i_d^* is generated by the proposed steady-state modulation-index regulator as given in equations (12) and (13).

$$i_d^* = G_3\,(s)[MI^* - MI] \qquad (12)$$

$$G_3\,(s) = k_5 + \frac{k_6}{s} \qquad (13)$$

Using the proposed steady-state modulation-index regulator and transient modulation-index controller, the advantage of minimal harmonics can be retained under steady-state situations. When there is a need to adjust the reactive power output during the transient period, the actual MI is no longer equal to the steady-state reference MI which is equal to the pre-set value. As a result, the MI deviates from the steady-state value MI^*. However, this deviation of the modulation index has little effect on steady-state harmonic contents since the transient lasts for only a very short period. With the adjustment of the modulation index by the proposed ST ATCOM controller during the transient period, the ST A TCOM output voltage IV 21 and reactive power Q can be modulated in a very rapid manner.

4.5. PI Controller

PI controller generates a gated command to operate the converters and to compensate the error, which has been calculated by comparing defined values against measured values for both reactive and real powers. This is an integral part of the converters which generates a gated command to operate the converters in order to produce the fundamental voltage waveform which compensates the voltage magnitude by synchronizing with the AC system. The internal control also takes preventive measures to limit the maximum voltage and current from the individual power converter to maintain safe operations under any system contingency. The basic block diagram of power system with the STATCOM and STATCOM controller is shown in fig: 6.6.

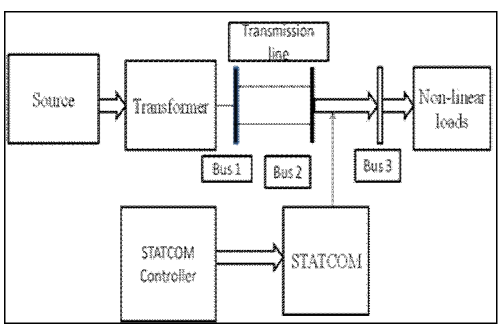


Figure 6: Block diagram of power system with STATCOM.

At the load centre various loads are considered and are connected to system at different instants of time as shown in the Table 1.

No	Time range	Type of load	Load
1	0.1 to 0.2	Non-linear	R=1800n, L=1mH
2	0.3 to 0.4	Inductive	R=0.242n, L=1.537mH
3	0.5 to 0.6	Capacitive	R=400 n, C=50IIF
4	0.0 t0 0.5 and 0.6 to 0.7	Normal load	R=300 n, L= 50mH 0.6 to 0.7

Table 1: Load data of power system.

5. Simulink Model of Transmission System with STATCOM

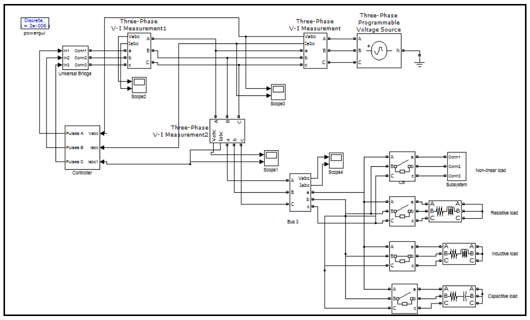


Figure 7: Simulink model of multilevel STATCOM

As shown in table 2, the load will changes according to the time period. In the interval 0.3s to O.4s there is a dip in the voltage level due to inductive load and from 0.5s to 0.6s there is a rise in the voltage level due to capacitive loaded conditions, but such voltage fluctuations are not desirable for a power system. The simulation result for the power system with the SATCOM is shown in fig: 8 and.9.

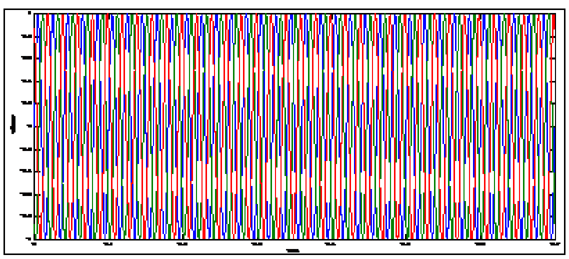


Figure 8: Output voltage of Multilevel STATCOM

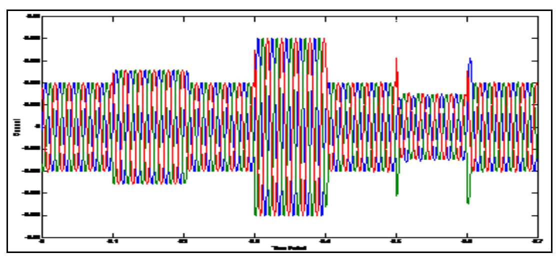


Figure 9: Output current of Multilevel STATCOM

Harmonic content of the current of the power system without STATCOM is shown in fig:10. The THD done through the FFT analysis.

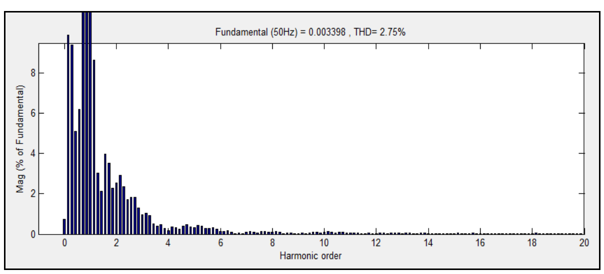


Figure 10: FFT analysis of multilevel STATCOM

We can compensate the voltage limitations at the output side and reduced the harmonic contents in the current by connecting the multilevel STATCOM which can be used at the point of common coupling (PCC).

6. Comparison of Outputs with and without STATCOM

The multilevel STATCOM which can be used at the point of common coupling (PCC), for improving power quality is modeled and simulated using proposed control strategy and the performance is compared by applying it to an ll0kv line with and without STATCOM is shown in fig: 11 and

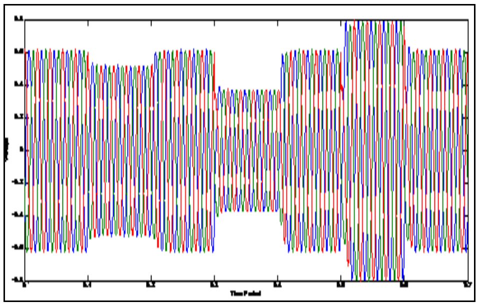
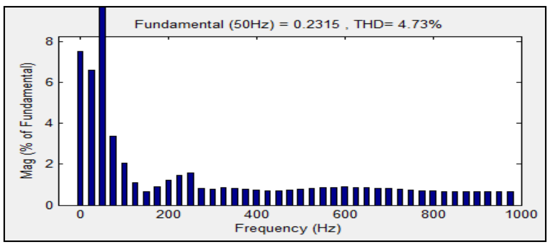


Figure 11: output voltage of the power system without STATCOM
Figure 12: output voltage of the power system STATCOM

6.1. Total Harmonic Distortion (THD)



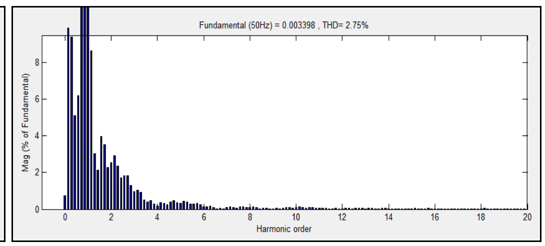


Figure 13: FFT analysis of power system without STATCOM
Figure 14: FFT analysis of multilevel with 9-Level STATCOM

We can compensate the voltage limitations at the output side and reduced the harmonic contents in the current by connecting the multilevel STATCOM which can be used at the point of common coupling (PCC). The power quality is improved by using the 9-level STATCOM. The reduced THD shown in fig: 24. By using the 13-level STATCOM, the THD decreases from up to 1.51. The simulink model of 13-level CHMLI is shown in fig: 6.15.

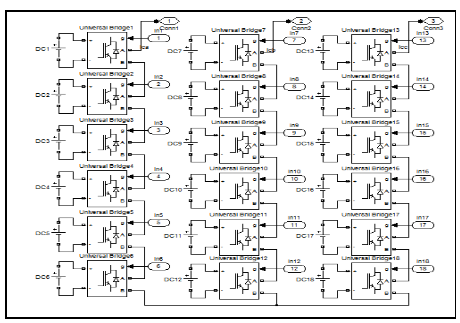


Figure 15: 13-Level Cascade H-Bridge multilevel Inverter

The THD also reduced by using the 13-level compared to the 9-level inverter. This can be done through the FFT analysis and shown in fig:16.

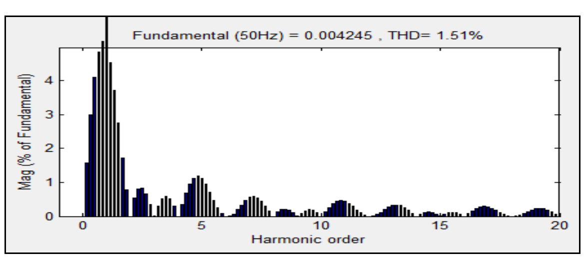


Figure 16: THD of output current (with 13-level STATCOM)

The THD variation with and without STATCOM is shown in table: 2.

S. No	% of THD
Without STATCOM	4.73
With 9-Level STATCOM	2.75
With 13-Level STATCOM	1.51

Figure 2: Results comparison with the THD

7. Conclusion

Cascaded H-Bridge is one of the latest multilevel inverter that has been developed over the last few decades. The decrease in the price of semiconductor devices has allowed the advancement of this technology. The cascaded multilevel inverter with its compact design can easily replaced with diode-clamped and capacitor-clamped multilevel inverter. The output voltage cascaded multilevel inverters is in the form of pulses and also be modulated to achieve the voltage compensation. The modulation techniques available are selective harmonic elimination and pulse width modulation. We can generate the signals to the system through the PWM but by using the selective harmonic elimination technique, we can give the switching periods directly to the CHMLI and also lower order harmonics can be eliminated.

Simulation study is done using CHML with 9-level, selective harmonic elimination method. The THD of the output current for 110KV were found out to be 2.75% from4.73% for a switching frequency of 50Hz with non-linear loads. Experimental results for the method have been provided with non-linear loads. In this, simulation study is done using CHML with 13-level also. The THD of the output current will reduces from 2.75% to 1.51%. The project presents a STATCOM model, developed with 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. On the other hand, the harmonics generated by the STATCOM is kept minimal with the implementation of SHEM. The effectiveness of the proposed control strategy is demonstrated with the help of THD calculations and is found to be minimum when compared with various designs. Hence the proposed STATCOM with it controller employing the direct control strategy is able to maintain the voltage balance under various load conditions.

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