CASCADED MULTILEVEL INVERTER BASED ON STATCOM

Manoj yadav[1], Harish kumar[2], Perminder Balyan[3]

[1,2,3] Department of Electronics and Communication, Gurgaon Institute of Technology and Management, Bilaspur- Gurgaon, MD University, Rohtak,(India)

ABSTRACT

This dissertation is dedicated to a comprehensive study of static synchronous compensator (STATCOM) systems utilizing cascaded-multilevel inverters. Among flexible AC transmission system (FACTS) controllers, the STATCOM have shown feasibility in terms of cost effectiveness in a wide range of problem-solving abilities from transmission to distribution levels. A cascade multilevel inverter is a power electronic device built to synthesize a desired AC voltage from several levels of DC voltages. A method is presented showing that a cascade multilevel inverter can be implemented using only a single DC power source and capacitors. To operate a cascade multilevel using a single DC source, it is proposed to use capacitors as the DC sources for all but the first source. A standard cascade multilevel inverter requires's' DC sources for 2s+1 level. To be able to operate in a high-voltage application, a large number of DC capacitors are utilized in a cascaded multilevel inverter-based STATCOM.

To obtain a low distortion output voltage or a nearly sinusoidal output waveform, a triggering signal should be generated to control the switching frequency of each power semiconductor switch. To control the reactive power instantaneously, this system is modeled using the ABC transform which calculates the instantaneous reactive power. This model is used to calculate the instantaneous reactive power and design a control scheme. The simulation result of MATLAB/Simulink software indicates the superior performance of the proposed control system, as well as the precision of the proposed models.

Keywords -- ***ABC Coordinates, Cascaded Multilevel Inverter (H-Bridge), Static Synchronous Compensator***

I. INTRODUCTION

Numerous industrial applications have begun to require high power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result a multilevel power inverter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel inverter not only achieves high power ratings but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind and fuel cells can be easily interfaced to a multilevel converter system for a high power application.

The concept of multilevel inverters has been introduced since 1975[1]. The term multilevel began with the three level inverters [2]. Subsequently, several multilevel inverter topologies have been developed. However, the elementary concept of a multilevel inverter to achieve higher power is to use a series of power semiconductor switches with several lower voltages dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries and renewable energy voltage sources can be used as the multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected.

Inverters are often used to provide power to electronics in the case of a power outage or for activities such as camping, where no power is available. An inverter converts a direct current (DC) or battery power into an alternating current (AC) or household power. A multilevel inverter is a more powerful inverter, meaning it does the same thing as an inverter except provides energy in higher power situations [3].

Inverters convert DC power into AC power through waves called either sine waves or modified sine waves. Sine waves are the waves that are typically found in power from a power plant. Modified sine waves are made to simulate sine waves. Inverters with modified sine waves work well for backup power in houses and are much less expensive. Although there are several types of inverters, all standard inverters use only one switch, or in other words, one power circuit.

Unlike standard inverters, multilevel inverters make use of renewable energy sources. Wind, fuel cells and even photovoltaic energy can be added to a multilevel inverter as DC sources. These environmentally-friendly energy sources can then be converted into AC currents. However, while multilevel inverters are capable of producing large amounts of energy, the amount of energy produced is dependent upon how much DC power is being used. Higher sources of DC power will provide more powerful AC power. A Multilevel power converter system is a simpler solution than running direct power lines for different voltages.

There are three structures for multilevel inverters:

1.1 Cascaded H-Bridges

In Fig. 1, each DC power source is connected to an H-bridge inverter. The single inverter has four switches. By using different combinations of switches, the single inverter can produce three different AC voltage outputs.

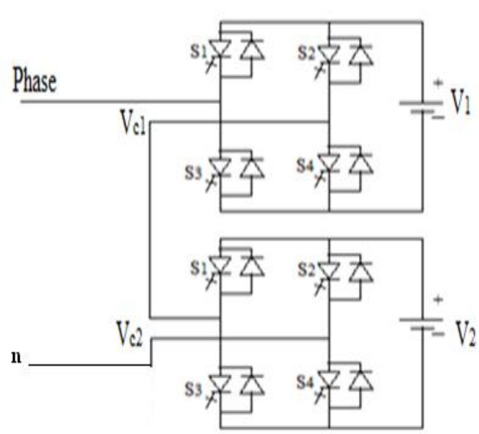


Figure 1: Three level Cascaded inverter

1.2 Diode-Clamped Multilevel Inverter

This inverter is suitable for transmission of DC current on an AC transmission line or variable speed motors. Precise monitoring and control are required to prevent overcharging or discharging.

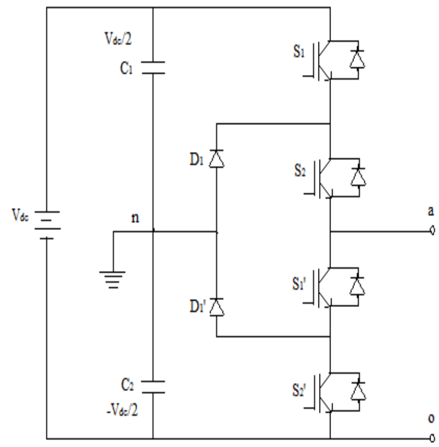


Figure: 2 Three level diode-clamped inverter

In Fig. 2, the dc bus voltage is split into three levels by two series-connected bulk capacitors C_1 and C_2. The middle point of the two capacitors 'n' can be defined as the neutral point. The output voltage V_{an} has three states: $V_{dc}/2$, 0, -$V_{dc}/2$. For voltage level $V_{dc}/2$, switches S_1 and S_2 need to be turned on; for $–V_{dc}/2$, switches S_1' and S_2' need to be turned on; and for the 0 level, S_2 and S_1' need to be turned on.

The key components that distinguish this circuit from a conventional two-level inverter are D_1 and D_1'. These two diodes clamp the switch voltage to half the level of the dc-bus voltage. When both S_1 and S_2 turn on, the voltage across *a* and 0 is V_{dc}, i.e., $V_{ao} = V_{dc}$. In this case, D_1' balances out the voltage sharing between S_1' and S_2' with S_1' blocking the voltage across and blocking the voltage across C_1 and S_2' blocking the voltage across C_2. Notice that output voltage V_{an} is ac, and V_{ao} is dc. The difference between V_{an} and V_{ao} is the voltage across C_2, which is $V_{dc}/2$. If the output is removed out between *a* and 0, then the circuit becomes a dc/dc converter, which has three output voltage levels: V_{dc}, $V_{dc}/2$, and 0.

1.3 Capacitor-Clamped Multilevel Inverter

This inverter has a similar design to a diode-clamped inverter. However, the clamping diodes have been replaced with capacitors. The design requires only two switch combinations to create a voltage output. Tracking the output of all the capacitors is complicated, as is pre-charging all of the capacitors [2].

Fig. 3 illustrates the fundamental building block of a phase-leg capacitor-clamped inverter. The circuit has been called the flying capacitor inverter with independent capacitors clamping the device voltage to one capacitor voltage level. The inverter in Fig. 3 provides a three-level output across *a* and *n*, i.e., V_{an}= $V_{dc}/2$, 0, or $–V_{dc}/2$. For voltage level $V_{dc}/2$, switches S_1 and S_2 need to be turned on; for $–V_{dc}/2$, switches S_1' and S_2' need to be turned on; and for the 0 level, either pair (S_1,S_1') or (S_2,S_2') needs to be turned on.

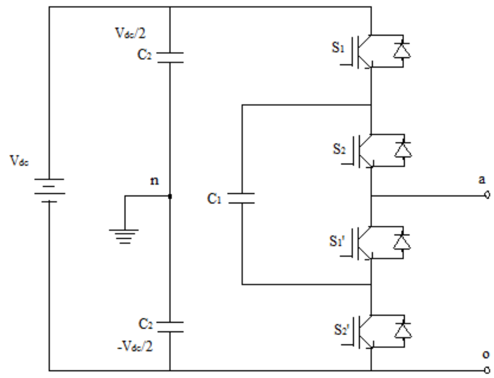


Figure: 3 Three level Capacitor – clamped inverter

Clamping capacitor C_1 is charged when S_1 and S_1' are turned on, and is discharged when S_2 and S_2' are turned on. The charge of C_1 can be balanced by proper selection of the 0-level switch combination.

II. MULTILEVEL INVERTERS

Multilevel inverter technology has emerged recently as a very important alternative in the area of high-power medium-voltage energy control. In recent years, industry has begun to demand higher power equipment, which now reaches the megawatt level. Controlled ac drives in the megawatt range are usually connected to the medium-voltage network. Today, it is hard to connect a single power semiconductor switch directly to medium voltage grids (2.3, 3.3, 4.16, 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 include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductors must withstand only reduced voltages [4].

2.1 Flexible alternating current transmission system

It is a technology which provides a methodology for the utilities to effectively utilize their assets, enhance transmission capability by loading lines to their full transmission capability, and therefore, minimize the gap between the stability and the thermal limits, and improve grid reliability.

The FACTS (Flexible alternating current transmission systems) technology is based on the use of reliable high-speed power electronics, advanced control technology, advanced microcomputers, and powerful analytical tools. The key feature is the availability of power electronics switching devices at high kV and kA levels.

2.2 Flexibility of Electric Power Transmission

“The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady-state and transient margins.”

"A power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability."

With the advancement of power semiconductor devices , particularly the devices with turn-off capability, the cost of FACTS technology continues to decrease, and this will make the FACTS technology all the more reliable. The development of FACTS controller has followed two distinctly different technical approaches both resulting in a comprehensive group of controllers that solve some of the transmission problems.

The first group is based on thyristor devices with only gate turn-on control, and its turn-off depends on the current reaching zero value as per circuit and system conditions. FACTS controllers in this group employ reactive elements or a tap-changing transformer with thyristor switches as controlled elements. The second group uses devices such as gate turn-off thyristor (GTO), MOS turn–off thyristors (MTO), and integrated gate-commutated thyristors (IGCT), and similar devices that have turn –on and turn-off capability.

The second group uses self-commutating static converters operating as controlled voltages sources for FACTS applications. Since direct current in a voltage-sourced converter flows in either direction, the converter valve have to be bi-directional, and also, since the dc voltage does not reverse, the turn-off devices need not have reverse voltage capability; such turn-off devices are known as asymmetric turn-off devices.

Thus, a voltage-sourced converter is made up of an asymmetric turn-off device such as GTO with a parallel diode connected in reverse as shown in Fig. 4.

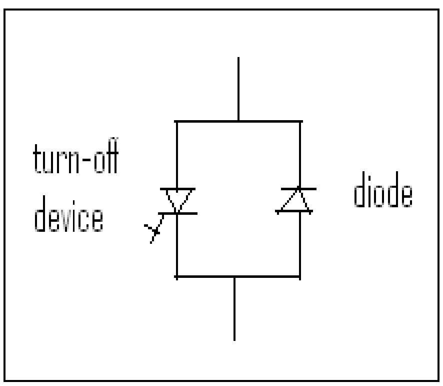


Figure: 4 Valve for a voltage-sourced converter

2.3 Static Synchronous Compensator (STATCOM)

The STATCOM is the first power-converter-based shunt-connected controller. Instead of directly deriving reactive power from the energy-storage components, the STATCOM basically circulates power with the connected network. The reactive components used in the STATCOM, therefore, can be much smaller than those in the SVC.

A typical solution for the continuous control of reactive power is static VAR compensator (SVC), a combination of thyristor-controlled reactor (TCR) and thyristor-switched capacitors (TSC). The reactive power output of SVC is adjustable in the order milliseconds but dependent on the system voltage which limits the ability to mitigate the network voltage instabilities. The new breed of VAR compensators is based on self-commutated AC/DC power converters. Their performance is superior to SVCs, being capable of operating at rated power nearly independent of the system voltage and controlling the reactive power output in the order of microseconds.

A representative of converter based VAR compensators is STATCOM, Static synchronous compensator. STATCOM is a self-commutated AC/DC power converter connected in parallel with the power system through coupling reactors. The power electronic switches of the converter are controlled to produce approximately sinusoidal output AC voltages, being in phase with the mains voltages, from the DC-source. Depending on the magnitude of the AC-voltages produced the VARs are either generated or absorbed.

STATCOM provides a superior solution for VAR control, voltage regulation, flicker compensation, and fault-ride through improvement. Also grid current harmonic filtering is possible if sufficiently high switching frequency can be used. Typical applications include flicker compensation of large industrial loads such as arc furnaces and VAR control of wind farms. Benefits of STATCOM are improved power quality and network stability, increased transmission capacity, and improved fault-ride through capability and grid code compliance of renewable generation.

The Fig. 5 shows the basic circuit for a Static Synchronous Compensator (STATCOM) and Fig. 5.1 shows its voltage current characteristics.

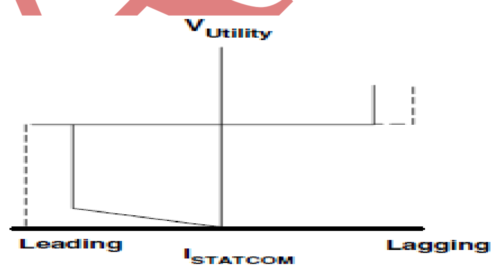


Figure: 5 characteristics of a STATCOM

Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are however, other uses, the most common use is for voltage stability. A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source.

For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; on the other hand, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power. The response time of a STATCOM is shorter than that of an SVC, mainly due to the fast switching times provided by the IGBTs of the voltage source converter. The STATCOM also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage (as the current can be maintained at the rated value even down to low AC voltage).

2.4 Power Circuit and Operation Principle

An eleven level, three-phase STATCOM based on the cascading configuration is illustrated in Fig. 5.1.

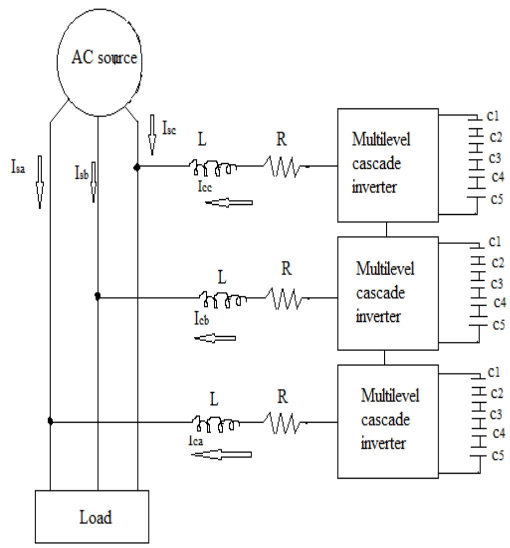


Figure: 5.1 Structure of the STATCOM with cascade multilevel inverter

Fig. 5.1 illustrates the connection diagram for a wye connection 11-level inverter using the cascade voltage source H-bridge inverters.

Fig. 6 shows the structure of one unit of H-bridge inverter. Each HBI can generate three level output, $+V_{dc}$, o and $-V_{dc}$.

Fig. 6 shows the simulated output voltage of the single phase H-bridge inverter circuit.

When the inverter output voltage is higher than the ac system voltage, leading reactive current is drawn from the system (vars are generated). When the inverter output voltage is lower than the ac system voltage, the lagging reactive current is drawn from the system (vars are absorbed). When the inverter output voltage is equal to the AC system voltage reactive power exchange is zero.

Fig. 7 shows a single phase equivalent circuit of the STATCOM, where V_s is the source voltage phasor, V_c is ac output of STATCOM, and L and R represent respectively a set of linked AC reactor and equivalent resistance including STATCOM losses.

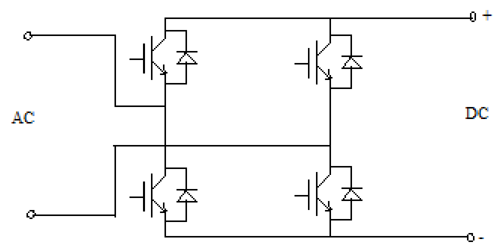


Figure 6: Simulated 1-phase inverter output voltage

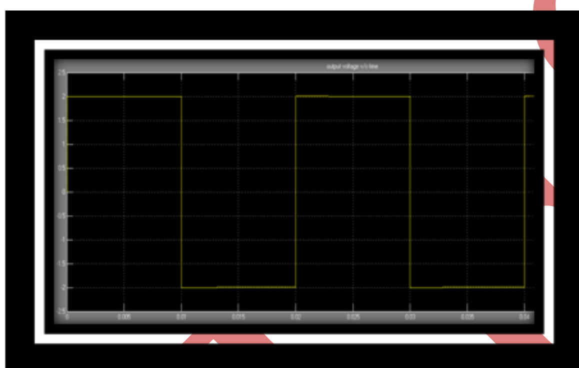


Figure: 6.1 H-Bridge inverter with IGBT/diode

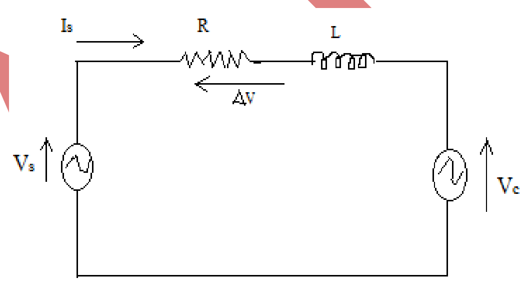
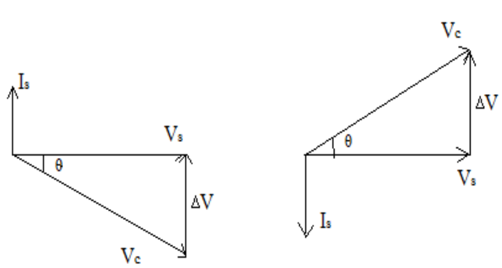


Figure: 7 Single phase equivalent circuit

The AC voltage controlled STATCOM can control the amplitude of AC voltage by causing a small amount of active power to power flow into or out of the STATCOM.

Fig. 7.1 shows a phasor diagram in the case that V_c lags V_s.



(a) Leading current (b) Lagging current

Figure: 7.1 Phasor diagram of the STATCOM

In Fig. 7.1, it is in phase with V_s, so that a small amount of active power flows into SVC, thus the dc capacitor is charged. In the case where V_c leads V_s, as shown in Fig. 7.1, a small amount of active power flows out, thus the dc capacitor is discharged. Accordingly, a large amount of reactive power drawn by the STATCOM can be controlled by adjusting the phase angle by the small amount.

III. CONTROL OF REACTIVE POWER

It is well known that the amount and type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage.

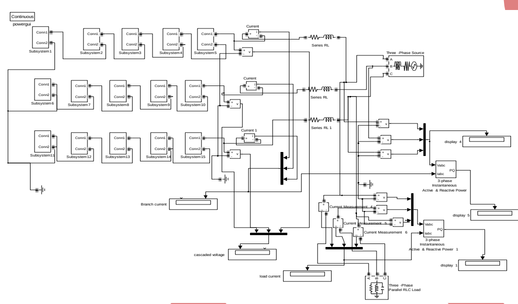


Figure: 8 simulated circuit of the STATCOM with 11-level cascaded multilevel inverter

The reactive power supplied by the STATCOM is given by equation (5.8),

$$Q = V_{statcom} - V_s \text{ .... } \mathbf{(5.8)}$$

Where, $V_{statcom}$ and V_s are the magnitudes of STATCOM output voltage and system voltage respectively and X is the equivalent reactance between STATCOM and the system. When Q is positive, the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system.

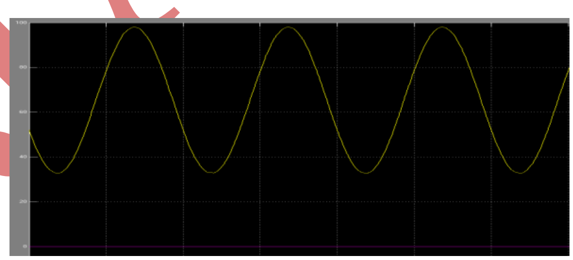


Figure: 8.1 Reactive power in 3-phase cascaded eleven level inverter based STATCOM

Since the modulating signals are the same for the inverters in the system, the fundamental component of the STATCOM output voltage is N time of that of each inverter, provided that the voltage across the DC capacitor of each inverter is the same. As a result, the STATCOM output voltage can be controlled by the Modulation index to its ability to control the output voltage by the modulation index; the proposed STATCOM has extreme fast dynamic response to system reactive power demand [5].

IV. CONTROL OF DC CAPACITOR VOLTAGE

If all the components were ideal and the STATCOM output voltage were exactly in phase with the system voltage, there would have been no real power exchange between STATCOM and system therefore the voltages across the DC capacitors would have been able to sustain.

However, a slight phase difference between the system voltage and the STATCOM output voltage is always needed to supply a small amount of real power to the STATCOM to compensate the component loss so that the DC capacitor voltages can be maintained. This slight phase difference is achieved by adjusting the phase angle of the sinusoidal modulating signal. If the real power delivered to the STATCOM is more than its total component loss, the DC capacitor voltage will rise, and vice-versa.

This real power exchange between STATCOM and the system is described by Equation (5.9) below,

$$P = \frac{V_s V_{statcom}}{X} \sin(\delta) \quad \text{.................. (5.9)}$$

Where, δ is the phase angle difference between STATCOM voltage and the system voltage [5]

V. SIMULATION RESULT

Fig. 9.1 shows the load current waveform of a single phase H-bridge inverter when the load is RL. For this type of load, current will not be in phase with output voltage and diodes connected in antiparallel with IGBTs will allow the current to flow when the main IGBTs are turned off.

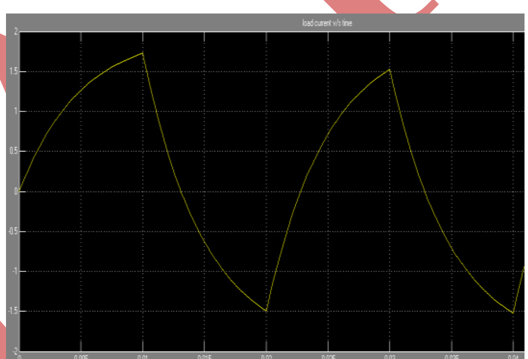


Figure: 9 Load current v/s time

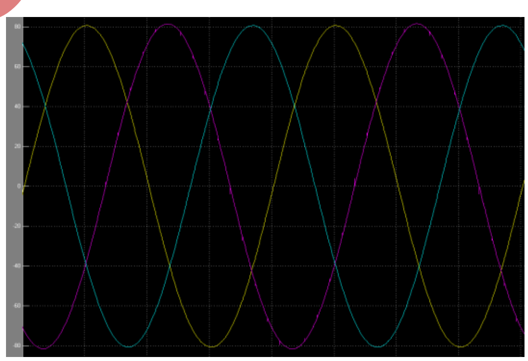


Figure 9.1: Three-phase ac supply voltage in STATCOM with cascaded multilevel inverter

VI. CONCLUSION

In conclusion, among the mature multilevel inverter topologies, the cascaded-multilevel VSC is the most promising alternative for the STATCOM application. It requires the least number of components to achieve the same number of output voltage levels. With its modularized structure, the Cascaded Multilevel Inverter can flexibly expand the output power capability and is favorable to manufacturing. Control complexity of the Cascaded Multilevel Inverter is, however, directly proportional to the number of H-bridge inverters. In the STATCOM application, the AC voltage of each H-bridge converter is derived from its DC capacitor voltage or supply voltage, which needs to be individually regulated. As the number of voltage levels increases, the voltage-imbalance problem becomes more of a concern.

To achieve as stable a system as possible, a well-defined model and an effective DC-link-balancing method are necessary. The cascaded seven-level, nine-level, eleven-level and thirteen-level and fifteen inverters have been used as the studied system. And, the cascaded fifteen level inverter based STATCOM is designed according to the simplified model in abc coordinates. The simulation results show superior performances of the designed abc coordinates inverter based STATCOM. The STATCOM has the great advantage of a fewer number of devices. The VSI is extremely fast in response to reactive power change. The simulation of the STATCOM is performed in the Simulink environment and the results are presented.

REFERENCES

[1] R.H. Baker and L.H. Bannister, *Electric power converters U.S. Patent 3* 867 643, Feb. 1975.

[2] Jose Rodriguez, Jih-Sheng Lai and Fang Zheng Peng, Multilevel Inverters: A Survey of Topologies, Controls, and Applications, *IEEE Transactions on Industrial Electronics*, 49(4), 2002, 724-738

[3] P.S. Bimbhra, *power electronics (*Khanna publishers, New Delhi, ISBN-81-7409-056-8.

[4] Leon M. Tolbert, Fang Zheng Peng and Thomas G. Habetler, Multilevel Converters for Large Electric Drives, *IEEE Transactions on Industry Applications*, 35(1), 1999, 36-42

[5] T. Manokaran, B. Sakthivel and S. Mohamed Yousuf, Cascaded Multilevel Inverter based Harmonic Reduction in STATCOM, *International Journal of Engineering Science and Technology*, 2(10), 2010, 5424-5431