Abstract- This paper presents a three-phase, five-level and seven level cascaded multilevel voltage source inverter based active filter to improve the power factor and power quality in the distribution network. Cascaded multilevel configuration of the inverter has the advantage of its simplicity and modularity over the configurations of the diode-clamped and flying capacitor multilevel inverters. Shunt compensation for medium voltage distribution systems requires higher rating for voltage source converters (VSCs). Ratings of the semiconductor devices in a VSC are always limited; therefore, for higher rated converters it is desirable to distribute the stress among the number of devices using multilevel topology. The DSTATCOM helps to eliminate the Total Harmonics Distortion (THD) drawn from a Non-Linear Diode Rectifier Load (NLDRL). The compensation process is based on concept of p-q theory. The simulation of the proposed system is carried out in the MATLAB environment using Simulink and power system toolboxes.

Keywords: DSTATCOM, Voltage Regulation, Power Quality, Cascaded H-Bridge, Multilevel Inverters

I. INTRODUCTION

In present day’s power distribution systems is suffering from severe power quality problems. These power quality problems include high reactive power burden, harmonic(s) currents, load unbalance, excessive neutral current etc. The measure of power quality depends upon the needs of the equipment that is being supplied. What is good power quality for an electric motor may not be good enough for a personal computer. Usually the term power quality refers to maintaining a sinusoidal waveform of bus voltages at rated voltage and frequency [1]. Some remedies to these power quality problems are reported in the literature. A group of controllers together called Custom Power Devices (CPD), which include the DSTATCOM (distribution static compensator), The DSTATCOM, is a shunt-connected device [7], which takes care of the power quality problems in the currents. Three phase four-wire distribution systems are used to supply single-phase low voltage loads. The proposed DSTATCOM is modelled and its performance is simulated and verified for power factor correction and voltage regulation along with neutral current compensation, harmonic elimination and load balancing with linear loads and non-linear loads. When the STATCOM is applied in distribution system is called Distribution-STATCOM (DSTATCOM) and its configuration is the same, or with small modifications, oriented to a possible future amplification of its possibilities in the distribution network.

The DSTATCOM exhibits high speed control of reactive power to provide voltage stabilization, flicker suppression. It utilizes a design consisting of a GTO or IGBT-based voltage sourced converter connected to the power system via a multi-stage converter transformer. The DSTATCOM provides leading or lagging reactive power to achieve system stability during transient conditions. The DSTATCOM can also be applied to industrial facilities to compensate for voltage sag and flicker caused by non-linear dynamic loads, enabling such problem loads to co-exist on the same feeder as more sensitive loads. The DSTATCOM instantaneously exchanges reactive power with the distribution system without the use of bulky capacitors or reactors. A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Fig.1, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer.
The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power. The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power.
2. Correction of power factor and
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter.

To understand P and Q flow in a transmission system, consider a simple system that is made up of sending and receiving buses with a transmission cable in between as shown in Fig 2.

![Fig 2: Simple line presentation of generating distribution network](image)

Thus for small line resistances, \( R \ll X \), the active and reactive power components can be approximated to

\[
P_a = \frac{V_s V_r}{X} \sin (\delta_S - \delta_R) \quad (1)
\]

\[
Q_a = \frac{V_s^2 - V_r^2 - V_s V_r \cos (\delta_S - \delta_R)}{X} \quad (2)
\]

It can be seen from the above approximated power components that power flow is dependent on four controlling variables \( V_s, V_r, X \) and \( \delta_S, \delta_R \). Employing shunt compensation at midpoint in the transmission line increases both the active and reactive components of the injected power. For lossless compensator and transmission lines \( V_s = V_r = V \), the injected power at midpoint is now given by

\[
P_{sh} = \frac{V^2}{X} \frac{\sin (\delta_S - \delta_R)}{2} \quad (3)
\]

\[
Q_{sh} = \frac{4V^2}{X} \left(1 - \cos (\delta_S - \delta_R)\right) \quad (4)
\]

Meanwhile, employing series compensation at midpoint with voltage \( V_s \) in quadrature with respect to the line current allows the compensating elements to assist only in the reactive power control. The result in the injected power is given by

\[
P_{ser} = \frac{V^2}{(1-r)X} \sin (\delta_S - \delta_R) \quad (5)
\]

\[
Q_{ser} = \frac{2V^2}{X} \left(1 - \cos (\delta_S - \delta_R)\right) \quad (6)
\]

where \( r \) is the degree of series compensation (0 \( \leq r \leq 1 \)).

**II. OPERATION OF D-STATCOM**

D-STATCOM controllers can be constructed based on both VSI topology and Current Source Inverter (CSI) topology [3,4](Fig 3). Regardless of topology, a controller is a compound of an array of semiconductor devices with turn off capability (i.e., IGBT, GTO, IGCT etc.) connected to the feeder via a relative small reactive filter. The VSI converter is connected to the feeder via reactor LF and has a voltage source (capacitor CD) on the DC side. The CSI converter is connected on the AC side via capacitor CF and has a current source (inductor LD) on the DC side. In practice, CSI topology is not used for DSTATCOM. The reason for this is related to the higher losses on the DC reactor of CSI compared to the DC capacitor of VSI. Moreover, a CSI converter requires reverse blocking semiconductor switches, which have higher losses than reverse conducting switches of VSI. And, finally, the VSI-based topology has the advantage because an inductance of a coupling transformer \( T_r \) can constitute, partially or completely, the inductance of an AC filter. The VSI converters for D-STATCOM are constructed...
based on multi-level topologies [2,5], with or without use of a transformer. These solutions provide support for operation with a high level of terminal voltage. Additionally, DSTATCOM controllers can be a compound of several converters configured to various topologies, to achieve higher rated power or lower PWM-related current ripples. The VSI and CSI topologies are presented in Fig 4. In the parallel configuration (Fig 4a) converters are controlled to share the generated power equally, or at a given ratio, for example proportional to the rated power of the particular converter.

In this solution it is necessary to provide inter converter communication at the control level to distribute information about set controller power or currents. The cascaded multi-level converter topology (Fig 4b) is similar to the parallel configuration, but in this case the constituent converters do not share power equally, but successively, depending on the requirement. In this case, no communication between constituent converters is required, but on the other hand it is also not possible to use common PWM strategy. The converters in this case are exactly the same as for standalone operation. In Fig 4c, d are presented series and parallel master-slave topologies, respectively. The master-slave topologies require a high degree of integration between constituent converters including a control system, and are treated and realised as a single multi converter controller. The master converter (called a "slow converter") has substantially higher rated power and, in consequence, considerably lowers PWM carrier frequency than the slave converter (called a "fast converter"). The task of the master converter is to cover the requirements for power, while the slave has to compensate AC current/voltage ripples using real superposition of voltages (Fig 4c) or parallel superposition of currents (Fig 4d).

The N-level cascaded H-bridge multilevel inverter comprises of (N-1)/2 series connected single phase H-bridges per phase, for which each H-bridge has its own isolated dc source [8,9]. Fig 5 shows one phase of a n-level cascaded H-bridge inverter.

**III CASCADED H-BRIDGE INVERTER TOPOLOGY**

The N-level cascaded H-bridge multilevel inverter
The cascaded H-bridge multilevel inverter is based on multiple two level inverter outputs (each H-bridge), with the output of each phase shifted. Despite four diodes and switches, it achieves the greatest number of output voltage levels for the fewest switches. Its main limitation lies in its need for isolated power sources for each level and for each phase, although for VA compensation, capacitors replace the dc supplies, and the necessary capacitor energy is only to replace losses due to inverter.

IV PROPOSED IRP THEORY

The instantaneous power theory or p-q theory was introduced by Akagi in 1983. This method uses algebra transformation also known as Clarke transform for three phase voltage and current. The three phase voltage and current are converted into α-β using eq. (4) and eq. (5), where iabc are three phase line current and vabc are three phase line voltage.[6]. The proposed instantaneous real-power (p) theory derives from the conventional p-q theory or instantaneous power theory concept and uses simple algebraic calculations [7]. It operates in steady-state or transient as well as for generic voltage and current power systems that allowing to control the active power filters in real-time. The active filter should supply the oscillating portion of the instantaneous active current of the load and hence makes source current sinusoidal.

Fig 6: α-β coordinates transformation

The p-q theory performs a Clarke transformation of a stationary system of coordinates abc to an orthogonal reference system of coordinates α,β. In abc coordinates axes are fixed on the same plane, apart from each other by 120 deg as shown in Fig 6. The instantaneous space vectors voltage and current Va, ia are set on the α-axis, Vb, ib are on the b axis, and Vc, ic are on the c axis. These space vectors are easily transformed into α,β coordinates. The instantaneous source voltages Vsa, Vsb, Vsc are transformed into the α,β coordinate’s voltage by Clarke transformation as follows:

\[
V_{a\beta} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & 1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} v_{abc} \tag{7}
\]

Similarly, the instantaneous source current isa, isb, isc also transformed into the α,β coordinate’s current by Clarke transformation that is given as:

\[
i_{a\beta} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & 1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} i_{abc} \tag{8}
\]

Where α and β axes are the orthogonal coordinates. They Vu, ia are on the α-axis, and Vβ, ib are on the β-axis.

Real-Power (p) calculation:

Let the instantaneous real-power calculated from the α-axis and β-axis of the current and voltage respectively. These are given by the conventional definition of real-power as:

\[
P_{ac} = V_u ia + V_b i_b \tag{9}
\]

This instantaneous real-power Pac is passed to first order Butterworth design based 50 Hz low pass filter (LPF) for eliminating the higher order components; it allows the
fundamental component only. These LPF indicates ac components of the real-power losses and it’s denoted as Pac. The DC power loss is calculated from the comparison of the dc-bus capacitor voltage of the cascaded inverter and desired reference voltage. The proportional and integral gains (PI Controller) are determining the dynamic response and settling time of the dc-bus capacitor voltage. The DC component power losses can be written as

\[ P_{DC(LOSS)} = \left[ V_{DC} \cdot \omega f - V_{DC} \right] \left[ K_p + K_i \right] \quad (10) \]

The instantaneous real-power P is calculated from the AC component of the real-power loss \( \text{pac} \) and the DC power loss \( \text{PDC (Loss)} \); it can be defined as follows:

\[ P = \text{Pac} + \text{PDC (Loss)} \quad (11) \]

The instantaneous current on the \( \alpha, \beta \) coordinates of \( i_{\alpha} \) and \( i_{\beta} \) are divided into two kinds of instantaneous current components; first is real-power losses and second is reactive power losses, but this proposed controller computes only the real-power losses. So the \( \alpha, \beta \) coordinate currents \( i_{\alpha}, i_{\beta} \) are calculated from the \( V_{\alpha}, V_{\beta} \) voltages with instantaneous real power \( p \) only and the reactive power \( q \) is assumed to be zero. This approach reduces the calculations and shows better performance than the conventional methods. The \( \alpha, \beta \) coordinate currents can be calculated as

\[ \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} \begin{bmatrix} V_{\alpha} \\ -V_{\beta} \end{bmatrix} \quad (12) \]

From this equation, we can calculate the orthogonal coordinate’s active-power current. The \( \alpha \)-axis of the instantaneous active current is written as:

\[ i_{\alpha p} = \frac{v_{\alpha p}}{v_{\alpha}^2 + v_{\beta}^2} \quad (13) \]

Similarly, the \( \beta \)-axis of the instantaneous active current is written as:

\[ i_{\beta p} = \frac{v_{\beta p}}{v_{\alpha}^2 + v_{\beta}^2} \quad (14) \]

Let the instantaneous powers \( p(t) \) in the \( \alpha \)-axis and the \( \beta \)-axis is represented as \( p_\alpha \) and \( p_\beta \) respectively. They are given by the definition of real-power as follows

\[ P(t) = V_{\alpha}p(t) + V_{\beta}p(t) \quad (15) \]

The AC and DC component of the instantaneous power \( p(t) \) is related to the harmonics currents. The instantaneous real power generates the reference currents required to compensate the distorted line current harmonics and reactive power.

V. Phase Shifted Carrier PWM Technique

![Phase shifted PWM Technique](image7)

The number of triangular carriers required for a m-level inverter is given by \( m-1 \) and the Carrier phase shift =180/s, where \( s \) is the no. of H-bridges for phase. From the reference currents, the actual source current \( s \) are compared and by using PWM technique the switching signals for voltage source inverter are generated [10].

After getting switching signals from the triangular-sampling current modulator, the DSTATCOM operates in any one of the mode by controlling the firing angles of the switches by using controller which is connected to the converter thereby maintaining system voltage balanced.

VI. MATLAB/SIMULINK RESULTS

The D-STATCOM model is established based on Matlab/Simulink Platform. Here simulation is carried out in different cases such as

1) Implementation of 5-Level D-Statcom using proposed IRP Theory. 2) Implementation of 7-Level D-Statcom using proposed IRP Theory. 3) Implementation of 9-Level D-Statcom using proposed IRP Theory.
Case 1: Implementation of 5-Level D-Statcom using proposed IRP Theory:

Fig. 7 Matlab/Simulink Model of proposed Compensator using IRP Controller

Fig. 7 shows the Matlab/Simulink Model of proposed Compensator using IRP Controller based CHB D-Statcom.

Fig. 8 Source Voltage, Source Current, Load Current with 5-Level DSTATCOM based IRP Controller based Compensator

Fig. 8 shows the Source Voltage, Source Current, Load Current with 5-Level Compensator, due to non-linear diode rectifier pollutes source side current, with IRP Controller based compensator we get source current is sinusoidal.

Fig. 9 Source Side Power Factor with 5-level DSTATCOM with IRP Controller

Fig.9 shows the Source side Power Factor, both voltage & current are maintained sinusoidal and in phase condition.

Fig. 10 FFT Analysis of source current with 5-level compensator using IRP Controller

Fig.10 shows the FFT Analysis of source current with 5-level compensator using IRP Controller, we get THD is 6.22%.

Case 2: Implementation of 7-Level D-Statcom using proposed IRP Theory

Fig. 11 Five Level Output Voltage

Fig.11 Five Level Output Voltage
Fig. 12 Source Voltage, Source Current, Load Current with IRP Controller based 7-level Compensator

Fig.12 shows the Source Voltage, Source Current, Load Current with 7-Level Compensator, due to non-linear diode rectifier pollutes source side current, with IRP Controller based compensator we get source current is sinusoidal.

Fig.13 Source Side Power Factor with 7-Level Compensator

Fig.13 shows the Source side Power Factor, both voltage & current are maintained sinusoidal and in phase condition.

Fig.14 FFT Analysis of source current with 7-level compensator using IRP Controller

Fig.14 shows the FFT Analysis of source current with 7-level compensator using IRP Controller, we get THD is 5.34%.

Case 3: Implementation of 9-Level D-Statcom using proposed IRP Theory

Fig. 16 Source Voltage, Source Current, Load Current with IRP Controller based 9-level Compensator

Fig.16 shows the Source Voltage, Source Current, Load Current with 9-Level Compensator, due to non-linear diode rectifier pollutes source side current, with IRP Controller based compensator we get source current is sinusoidal.

Fig.17 Nine- Level Output Voltage
Fig.18 FFT Analysis of source current with 9-level compensator using IRP Controller

Fig.18 shows the FFT Analysis of source current with 9-level compensator using IRP Controller, we get THD is 4.76%.

TABLE I
POWER FACTOR COMPARISON

<table>
<thead>
<tr>
<th>System</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSTATCOM</td>
<td>0.866</td>
</tr>
<tr>
<td>With DSTATCOM</td>
<td>Unity</td>
</tr>
</tbody>
</table>

TABLE II
COMPARISON BETWEEN THD OF MULTI-LEVEL INVERTERS

<table>
<thead>
<tr>
<th>Level</th>
<th>THD</th>
<th>3rd Harmonic</th>
<th>5th Harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Inverter</td>
<td>28.28</td>
<td>0.00%</td>
<td>21.79%</td>
</tr>
<tr>
<td>5-level</td>
<td>6.22</td>
<td>0.91%</td>
<td>2.06%</td>
</tr>
<tr>
<td>7-level</td>
<td>5.34</td>
<td>0.52%</td>
<td>1.96%</td>
</tr>
<tr>
<td>9-level</td>
<td>4.76</td>
<td>0.31%</td>
<td>1.78%</td>
</tr>
</tbody>
</table>

VII CONCLUSION

The cascaded inverter switching signals are generated using triangular-sampling current controller; it provides a dynamic performance under and steady state conditions, THD analysis also within the IEEE standards. Instantaneous real-power theory based cascaded multilevel inverter based DSTATCOM is connected in the distribution network at the PCC through filter inductances and operates in a closed loop. A five level & seven as well as nine level cascaded multilevel voltage source inverter based DSTATCOM using instantaneous real-power controller is found to be an effective solution using as power line conditioning to compensate harmonics, reactive power and power factor with the IRP controller reduces harmonics and provides reactive power compensation due to non-linear load currents; as a result source current(s) become sinusoidal and unity power factor is also achieved under both transient and steady state conditions. THD analysis also within the IEEE standards. This proposed model is implemented using Matlab Simulink software and the obtained results.

REFERENCES
