ABSTRACT

The voltage source converters are to be designed with higher capacity for the purpose of maintaining the voltage profile constant by means of shunt compensators especially in distribution systems of medium voltages. Yet, designing converters of large rating imposes restrictions with respect to the stress and uniform distribution of stress in various devices is quite challenging in multi-level topology. The structure of cascaded arrangement of such inverters is very simple and expandable compared to other existing designs. This investigation aims to provide active filtering by the use of cascaded VSC particularly for 5-level and 7-level in distribution circuits for enhancing the quality of power. For experimental analysis a nonlinear rectification load using diodes (NLDRL) is considered and to abolish the Total Harmonic Distortion (THD) as well as to get a fairly reasonable power factor, the DSTATCOM (Distribution Static Compensator) is being used. The principal theory associated in the compensating process is the p-q philosophy. For validating the entire design by means of simulation MATLAB package is chosen.

Keywords-- DSTATCOM, Instantaneous power theory, Power quality, Cascaded H-Bridge Multilevel Inverter, Proportional-Integral (PI) control, D-Q reference frame theory, Proportional-Integral (PI) control.

INTRODUCTION

The multi-level inverters are gaining reputation among industrialists and scholars because of its growth in terms of high power capability and controlling capacities. In literature a variety of such inverters with high-level topology had been discussed including the H-bridge type, diode-clamping arrangements and even the flying capacitors [1]. Adding many levels in the inverter will unnecessarily augment the power rating and hence there exists an optimum level pertaining to a specific requirement. Nevertheless, the higher level inverters will provide a loftier voltage at the output, lessen the THD and relieve the stress due to higher voltages and it would also diminish the EMI problems.

The raising power demand necessitates the expansion of electrical power network by means of many interconnecting feeders and makes the system huge and intricate. Moreover, the role of long distance and large power transmission lines become more important. On one hand the power network has to safely operate the electrical apparatuses but on the other hand it has to serve its clients with quality of power to gratify the customers. From late 90’s the word “Power quality” has become an integral part of power transactions. The quality of power ultimately relies on the supply machines. The standard or typical power quality implies to sustain the sinusoidal wave produced at the bus bar with rated voltage and frequencies. The main glitches in maintaining the quality of power are the unbalanced current and voltages, repeated fluctuations, dip in voltage, sudden surging of voltage and disruptions in power [2]. These problems affect the normal operation of the system and sometimes they lead to tripping of protective devices. In this viewpoint maintaining the quality of power or enhancing it to the preferred level is paramount nowadays.
The DSTATCOM is nothing but a regular STATCOM applied to distribution circuits with slight alterations or adjustments. The changing of magnitude and phase angle of the voltage of the converter with regard to the terminal voltage of the line, it is possible to adjust the real power as well as the reactive power. This device utilizes the inverter for the purpose of changing the DC voltage at the link (at the capacitor) to a modifiable voltage (both the magnitude and phase angle). Hence the Distributed-STATCOM may be regarded as voltage controlled source though current-controlled option is also possible in few cases [3].

Out of various available standard inverter topologies, the H-Bridge model is extensively used because it is very simple by construction. Also, it is possible to adapt several modulation methodologies with this model. The number of bridges can be added to augment the voltage levels [4]. This paper investigates the use of Distributed-STATCOM by using proportional plus integral two-term controller for designing 5-level and 7-level CHB to lessen the reactive power and so the harmonics for nonlinear loading conditions. This design is broadly utilized for power quality enhancements for its lesser losses during switching, culminating the harmonica of higher orders as well as for its low electromagnetic interference [5].

DESIGN OF MULTILEVEL BASED DSTATCOM

Principle of DSTATCOM

The general structure of 2-level Distributed-STATCOM is displayed in Fig.1. This possess a VSC and an energy storing device, which is DC in nature. Also, a transformer is coupled to the distributing network in parallel. The inverter primarily changes the DC voltage across the storing device into 3-phase AC voltage at the output. The in-phase voltages are coupled to the system at its output via the coupling transformer’s reactance. Whenever the phase and the amplitude of the output voltage of Distributed-STATCOM is adjusted there happens an effective and required real and VAR power transfer amongst the Distributed-STATCOM and the AC system. This sort of arrangement permits this effective power transfer possible either by consuming or producing the real and VAR power [6].

Figure 1: Schematic Diagram of a DSTATCOM
The inverter connected parallel to the AC system would offer several functions. This kind of structure may serve 3 various purposes viz. regulating the voltage and VAR compensation, power factor adjustment and culmination of harmonic currents.

**Control for Reactive Power Compensation**

It is always mandatory to provide a voltage of having stable magnitude to the sensitive loads. Such loads cannot withstand frequent variations while the system is exposed to severe disturbance. Therefore, a controlling system is needed to sustain the voltage at constant amplitude. No VAR meter is needed as the controlling system measures only the root mean square value of load-point voltage. A standard method in which the width of the sinusoidal pulse is modulated has been applied for the switching operation of inverter as the response is better and the configuration is simple. This is being applied for low-power usage and hence this PWM practice provides a higher flexible choices than the conventional fundamental frequency methods employed in FACTS controllers. In addition, switching of higher frequencies may be employed to enhance the outcome of the converter with substantial reduction in losses during switching [3].

![Figure 2: PI Control for Reactive Power Compensation](Image)

The error signal of controlling system is generated by comparing the reference signal, which is the voltage to the output terminal voltage. The deviation of these values is producing an error signal, which is then processed through a 2-term proportional plus integral controlling action. The output of this controller (the phase angle $\delta$) is ultimately given as an input to the signal generator to develop requisite PWM output. It is noteworthy to mention at this point of time that the indirect controlling action make it possible to transfer the real and VAR in the network at the same time. It the proportional plus integral controller that develops the necessary angle through the error signals and through its action it makes the value of error to zero. Therefore, the output RMS voltage becomes constant and equal to the input reference voltage.

**Control for Harmonics Compensation**

The instantaneous current component technique, which is an improved version of synchronous frame procedure is illustrated in literature [7]. This is simply known as “id-iq” principle. In the frame theory, the speed keeps on changing at the frame because of imbalance and harmonic voltages. The variation is dependent on the voltage waveform of 3-phase network. In the improved version, the compensating currents are derived through the instantaneous quantities of real and VAR elements of current with regard to the non-linear sensitive load. Likewise, the principal voltages $V$ of all the three phases a, b, and c and the corresponding instantaneous currents in $\alpha-\beta$ components are computed using the formula given by equation (1). The “C” in this expression denotes Clarke Transformation Matrix. The components of load currents are calculated from reference frame procedure using equation (2).

$$\begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix} = \begin{bmatrix} C \end{bmatrix} \begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix}$$

$$\begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix}, \theta = \tan^{-1}\frac{I_{l\beta}}{I_{l\alpha}}$$
The cascaded structure of multi-level Distributed-STATCOM using inverter based on instantaneous active-power principle is coupled to the distributing circuit exactly at the point of common coupling via inductive filter and the entire arrangement serves as a closed loop. The configuration is depicted in Fig.4. The source, which is 3-phase AC is connected to the load. The non-linearity of the load develops fundamental as well as harmonic components of power. The whole reactive power from the active power filter will not have harmonics and there is no phase difference with respect to the load voltage. The waveform will also be sinusoidal. In the meantime, the filter should offer the compensating current for estimating the fundamental components and the harmonic components of current as well the VAR.

**Cascaded H-Bridge Inverter Topologies**

The Cascaded H-bridge configuration for ‘n’ level will have 0.5 (n-1) single phase bridges for each phase and are connected in tandem. Every single bridge will have individual isolated DC source. The configuration for single phase is displayed in Fig.5.
This series arrangement is built on 2-level inverter outputs; the output of both will have a phase shift with respect to each other. Though it contains 4 switches and diodes, it is capable of producing maximum possible voltage at the output with minimum number of switches. The restricting factor is that it should possess isolating power source in each level and for every single phase. The DC supply is being substituted by capacitors and the energy of the capacitor compensates the loss of the inverter [9-12].

The Fig.6 demonstrates the arrangement of Half H-bridge and with the help of this arrangement it is possible to have dual voltage levels. The voltage level for respective switching is tabularized in Table 1.

**Table 1: Switching table for Half Bridge**

<table>
<thead>
<tr>
<th>Switch Turn ON</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>Vdc/2</td>
</tr>
<tr>
<td>S1</td>
<td>-Vdc/2</td>
</tr>
</tbody>
</table>

**Half H-Bridge**

**Full H-Bridge- Two level inverter**
The full bridge model is illustrated through Fig. 7. Here, at a time two switches are made to operate to produce the required voltage level as listed in Table 2. The number of levels for this configuration is computed as $2n+1$; $n$ representing the number of bridges cascaded. The voltage level at every step can be found as $(V_{dc}/n)$ [13].

### Full H-Bridge - Three level inverter

The switching table for 3-level is displayed via Table 3.

#### Table 3: Switching table for Full Bridge Three Level

<table>
<thead>
<tr>
<th>Switch Turn ON</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, S2</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>S3, S4</td>
<td>$-V_{dc}/2$</td>
</tr>
</tbody>
</table>

### Full H-Bridge - Five level Inverter

The higher level (5 level) bridge structure is shown in Fig. 8 and the state of switches for requires voltage for this case is provided in Table IV. Even if the structure possess 8 switches, just 2 switches are functioning to produce 50% of $V_{dc}$. Because the number of switches operated is less, the losses during switching are also lesser. The rate of change of voltage $(dv/dt)$ in 5-level inverter is only half of that of 3-level. Ultimately, the stress imposed to the switches are minimized and so the EMI [14].

#### Table 4: Switching table for Full H-Bridge of five level Inverter

<table>
<thead>
<tr>
<th>Switch Turn ON</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, S2, S6, S4</td>
<td>$V_{dc}/2$</td>
</tr>
<tr>
<td>S1, S2, S5, S6</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>S2, S4, S6, S8</td>
<td>0</td>
</tr>
<tr>
<td>S3, S4, S6, S8</td>
<td>$-V_{dc}/2$</td>
</tr>
<tr>
<td>S3, S4, S7, S8</td>
<td>$-V_{dc}$</td>
</tr>
</tbody>
</table>
The next higher level inverter of interest is the 7-level for which, the diagram is displayed in Fig.9 and related Table V contains the switching status versus the level of voltage [15].

**Table 5: Switching table for Full H-Bridge of seven level inverter**

<table>
<thead>
<tr>
<th>Switch Turn ON</th>
<th>Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, S2, S6, S8, S10, S12</td>
<td>Vdc/3</td>
</tr>
<tr>
<td>S1, S2, S5, S6, S10, S12</td>
<td>2Vdc/3</td>
</tr>
<tr>
<td>S1, S2, S5, S6, S9, S10</td>
<td>Vdc</td>
</tr>
<tr>
<td>S2, S4, S6, S8, S10, S12</td>
<td>0</td>
</tr>
<tr>
<td>S3, S4, S6, S8, S10, S12</td>
<td>-Vdc/3</td>
</tr>
<tr>
<td>S3, S4, S7, S8, S10, S12</td>
<td>-2Vdc/3</td>
</tr>
<tr>
<td>S3, S4, S7, S8, S11, S12</td>
<td>-Vdc</td>
</tr>
</tbody>
</table>

**Figure 9: Seven level CHB inverter**

**Figure 10: Reference current generator using instantaneous real-power theory**
PROPOSED INSTANTANEOUS POWER THEORY

The 3-phase currents and voltages in instantaneous p-q theory applies algebra transformation which was familiarized by Clarke. These parameters are transformed into α-β as given by equations (4) and (5). Here, \(i_{abc}\) denotes the line current and \(v_{abc}\) represents the line voltage [6]. The mentioned theory utilizes easier algebraic computations. This is well applied both for transient and steady state situations for current and voltages in the power systems and thus enable to have control over active-power filters in reality. The filter should offer an active component of instantaneous current to the load so as to suppress the oscillations or disturbance and thus make a possibly a sinusoidal current [16].

![Diagram of α-β coordinates transformation](image)

The abc coordinates of a stationary system are transformed into orthogonal coordinates α,β in a reference frame by means of p-q principle. The axes of the former is fixed to the same plane and displaced through 120 as given in Fig.11. \((V_a,i_a), (V_b,i_b), (V_c,i_c)\) are the instantaneous values of voltages and currents of respective axis and represent the space vectors, which are then converted to the other coordinate using the following expressions:

\[

\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}

\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
V_{\alpha} \\
V_{\beta}
\end{bmatrix}

\tag{4}

Likewise, the source currents in abc coordinates \(i_{asa}, i_{isb}, i_{isc}\) respectively are shifted to α-β coordinates using the following transformation as proposed by Clarke:

\[

\begin{bmatrix}
i_{a0} \\
i_{b0} \\
i_{c0}
\end{bmatrix} = \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}

\begin{bmatrix}
i_{a} \\
i_{b} \\
i_{c}
\end{bmatrix}

\tag{5}

The “α” and “β” axes as mentioned earlier belong to orthogonal coordinates. \(V\) and \(I\) are on both the axes.

Real-Power (p) calculation:

The corresponding voltages and currents in the orthogonal coordinate are projected in β-axis [17]. The value of active real power at any instant may be computed from the current and voltage values respectively in the axes of α-β axes. They may be provided as per regular description of active real power as:

\[
P_{ac} = V_{\alpha} i_{\alpha} + V_{\beta} i_{\beta}
\tag{6}
This power is sent to the low pass filter, which is constructed as per Butterworth design for first order with 50 cycles per second frequency for removing the higher order elements. This permits only the base frequency to pass through it. The LPF actually designates the loss due to real power components and is represented as Pac. The loss due to DC-power is computed by comparing the capacitor voltage at DC bus in the inverter to the reference value. The proportional plus integral controller helps to find the dynamic output as well the time of settling of voltage across the DC-capacitor. The loss due to DC-power may be inscribed as:

\[ P_{DC\ (loss)} = [V_{DC\, \text{ref}} - V_{DC}] [K_p + \frac{K_i}{s}] \]  

The power at any instant comprising of both the losses due to AC-real power and DC power may be denoted as “P” and mathematically computed as per the expression given below:

\[ P = P_{ac} + P_{DC\ (Loss)} \]  

The current at any instant available at \( \alpha-\beta \) coordinates are separated into 2 types of instantaneous values viz. the loss due to real power and VAR loss and the presented controller calculates only the component due to active-real power loss [18]. Thus the currents in the \( \alpha-\beta \) coordinates are derived from the values of voltages in those coordinates that are relating only the active-real power elements; the VAR is supposed to be void. This method simplifies the calculation procedure and offers improved performance in comparison to the commonly available methods. The currents belonging to \( \alpha-\beta \) coordinates are computed using,

\[
\begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix}
    V_\alpha & V_\beta \\
    V_\beta & -V_\alpha
\end{bmatrix}
\]  

Using the above expression, the real power current of orthogonal coordinate may be calculated. The real-current component of \( \alpha \)-axis can be given as:

\[ i_{\alpha} = \frac{V_\alpha p}{V_\alpha^2 + V_\beta^2} \]  

Likewise, the value of the same in the other axis is given by,

\[ i_{\beta} = \frac{V_\beta p}{V_\alpha^2 + V_\beta^2} \]  

Now, \( p_\alpha \) and \( p_\beta \) may be denoted as the power at any instant at the respective axis. They may be defined mathematically as,

\[ P(t) = v_\alpha p(t)i_\alpha p(t) + v_\beta p(t)i_\beta p(t) \]  

The introduction of DC component by the presence of capacitor voltage provided by the link bus over the AC values will create harmonic current. The active-real power at any instant will produce the sufficient and necessary current for compensating the distorted current in the line because of the influence of harmonics and also for the VAR power.

MATLAB MODELING & SIMULATION RESULTS

The design of Distributed-STATCOM is simulated using MATLAB-Simulink. The several cases included in the design are (i) Distributed-STATCOM 5-level model using Standard and Intelligent Controller (ii) Distributed-STATCOM 7-level model by means of Standard and Intelligent Controller [19].
Case 1: Execution of 5-Level Distributed-STATCOM using Standard & Intelligent Controller

Figure 12: Matlab/Simulink Model of proposed Compensator using Conventional & Intelligence Controller
The suggested compensator model CHB Distributed-STATCOM using MATLAB-Simulink by using Standard and Intelligent Controller has been shown in Fig.12.

**Figure 13:** Source Voltage, Source Current, Load Current with 5-Level Conventional Controller based Compensator

The source voltage and current from source and that to load has been depicted for the compensator with 5-level model in Fig.13. The ripple in the “source current” is mainly due to the rectifier, which is not linear. The source current waveform becomes more sinusoidal by means of Standard Controller [20].

**Figure 14:** Source Side Power Factor with Standard Controller based

The supply power-factor is represented through Fig.14. It is evident that the waveforms of both the voltage and currents are sinusoidal and the phase difference amongst them is zero.
Figure 15: FFT Analysis of source current with compensator using Conventional Controller

The Fast-Fourier Transform study with regard to the supply current while having Standard Compensator is displayed in Fig.15. The Total Harmonic Distortion in this case is found nearly to be 4.83%.

Figure 16: Source Voltage, Source Current, Load Current with Intelligence Controller based Compensator
The source voltage and current from source and that to load has been depicted for the compensator with 5-level model in Fig.16. The ripple in the “source current” is mainly due to the rectifier, which is not linear. The source current waveform becomes more sinusoidal by means of suggested Intelligent Controller. The output can be viewed in Fig.17.

![Figure 17: Five Level Output Voltage](image17)

The supply power-factor is represented via Fig.18. It is obvious that the waveforms of both the voltage and currents are sinusoidal and the phase difference amongst them is zero.

![Figure 18: Source Side Power Factor with Intelligent Controller](image18)

![Figure 19: FFT Analysis of source current with compensator using Intelligent Controller](image19)
Fig. 19 shows the FFT Analysis of source current with compensator using Intelligence Controller, we get THD is 0.78%, which is noticeably reduced than the Standard Controller.

**Case 2: Implementation of 7-Level D-Statcom using Conventional & Intelligence Controller.**

![Figure 20: Source Voltage, Source Current, Load Current with Conventional Controller based Compensator](image1)

The source voltage and current from source and that to load has been depicted for the compensator with 7-level model in Fig. 20. The ripple in the “source current” is mainly due to the rectifier, which is not linear. The source current waveform becomes more sinusoidal by means of Standard Controller.

![Figure 21: Source Side Power Factor Conventional Controller](image2)

The supply power-factor is represented through Fig. 21. It is evident that the waveforms of both the voltage and currents are sinusoidal and the phase difference amongst them is zero.
Fig. 22 shows the FFT Analysis of source current with compensator using Standard Controller; we get THD is 4.08%. The output voltage for this case can be viewed through Fig. 23. It may also be perceived that the THD is lesser for 7-level with Standard Controller.

**Figure 22: FFT Analysis of source current with compensator using Conventional Controller**

**Figure 23: 7-Level Output Voltage**
Figure 24: Source Voltage, Source Current, Load Current with Intelligence Controller based Compensator

The source voltage and current from source and that to load has been depicted for the compensator with 7-level model in Fig.24. The ripple in the “source current” is mainly due to the rectifier, which is not linear. The source current waveform becomes more sinusoidal by means of suggested Intelligent Controller.

Figure 25: Source Side Power Factor

The supply power-factor is epitomized through Fig.25. It is apparent that the waveforms of both the voltage and currents are sinusoidal and the phase difference amongst them is zero.

Figure 26: FFT Analysis of source current with compensator using Intelligence Controller
CONCLUSION

A five level & seven level cascaded multilevel voltage source inverter based Distributed-STATCOM 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 with controller. They diminish the effect of harmonics and make power compensation with respect to VAR especially for the cases of load currents that are not linear. The non-linearity is being culminated by the use of controlled compensators and it enables to accomplish a sinusoidal current and makes the power-factor high,i.e. unity. This is not only true for the transient conditions but also applies to steady-state situations. The outcomes obtained through Intelligent Controller are superior to Standard Controller for both 5- and 7-level inverters. The implemented model utilized simplest computations for calculating the reference currents. For analysis, the triangular-sampling current controllers have been utilized for the purpose of generating the switching signals of cascaded-inverter. This is made to have a dynamic performance under the situations of steady-state and even during transient conditions. From the experimental results, it is found that the percentage THDs calculated are as per the standards provided by IEEE.

REFERENCES


19. Dinesh, M., & Bhaskar, K. B. Manipulation of Cascaded H-Bridge Multilevel Inverter with Minimum Number of Switching Devices, DOI: https://doi.org/10.1109/TEC.2008.2001455