A COMPARATIVE STUDY ON COMPENSATING CURRENT GENERATION ALGORITHMS FOR STATIC SYNCHRONOUS COMPENSATOR UNDER NON-LINEAR LOAD CONDITIONS

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Abstract- Cascaded multilevel configuration of the inverter has the advantage of its simplicity over the other Multilevel inverters such as the DCMLI and FCMLI multilevel inverters. This paper presents a three-phase, five level multilevel voltage source inverter based STATCOM to improve power quality and Reactive power compensation in the distribution network. The STATCOM helps to improve the Power factor, Reactive power compensation and eliminate the Harmonics from source current cause by nonlinear load & minimize Total Harmonics Distortion (THD). The compensation current generation process is based on concept of SRF and IRP theory. A phase shifted PWM (PSPWM) techniques is adopted to investigate the performance of CHB Inverter. The results are obtained through Matlab/Simulink software package.

Keywords- 5 level Cascaded H-bridge MLI based STATCOM, Instantaneous power theory, Reactive Power Compensation, Power quality improvement, Synchronous Reference theory, total harmonic distortion (THD).

I. INTRODUCTION

The electric power system is growing day by day in size and complexity with a huge number of interconnections to meet the increase in the electric power demand with high quality power and with high reliability. Now a day the requirement for power quality becomes more and more important due power sensitive load such as Inverter, Computer, Microcontroller-Microprocessor based devices etc & so to keep safety of the electrical equipment and consumer satisfaction [1].

Electric Power quality is a term which has drawn tremendous attention in power engineering in the recent years. A group of controllers together also called Custom Power Devices (CPD) or FACTs devices, which includes the DSTATCOM, DSVR, SSSC, UPFC and UPQC etc. Among these the Static synchronous compensator is a shunt-connected device[2], which takes care of Reactive power Compensation and hence the power quality problems in the currents. It consists of a dc capacitor, three-phase inverter (IGBT, MOSFET/Thyristor) module, ac filter, coupling transformer/coupling inductor and a control strategy.

The basic block diagram of the DSTATCOM is shown in fig.1, it consists of voltage-sourced inverter which converts an input dc voltage into a three-phase output voltage at fundamental frequency. Current sensor and Voltage sensor are required to sense distorted current and voltage for reference current generation also PI controller for maintaining capacitor dc voltage. The DSTATCOM employs a Proportional Integral (PI) controller to maintain the output voltage at a fixed voltage level. The DSTATCOM can also be seen as a current-controlled source also current source converter. The generalized IRP(Instantaneous reactive power) theory and SRF(Synchronous reference frame ) theory which are valid for sinusoidal or non-sinusoidal waveforms and balanced or unbalanced three-phase power systems are proposed. The inverter from DSTATCOM acts as a Voltage Source Converter(VSC) that VSC is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the DSTATCOM generates or absorbs the desired VAR at the point of connection to overcome the power quality problems and provide the reactive power compensation.

THD is the measure of power quality. The total harmonic distortion (THD) is the ratio of the RMS value of the sum of all harmonic components and the RMS value of the fundamental component, for both current and voltage.
Where \( h \) is the order of harmonics. To overcome these problems STATCOM is used which satisfies the need of adjustable solution requirement to the power quality problems such as voltage sag, voltage swell, interruption [1]. In order to compensate the distorted currents and power quality problems STATCOM injects currents equal but in phase opposition with the harmonic components so that only the fundamental components flows in the point of common coupling (PCC). The STATCOM is connected in shunt to the disturbing loads, unbalanced and nonlinear, as seen in Fig. 1, causes the supply currents to be near sinusoidal and balanced. STATCOM compensate current harmonics, supply reactive power to the load and perform power factor correction.

In this paper simulated results of Five level cascade H bridge type multilevel inverter based STATCOM is presented. This paper presents a comprehensive analysis of STATCOM using two (SRF and IRP theory) algorithms for derivation of reference current signals. These reference current signals are then compared with actual supply current for generation of actual reference current. Then these generated reference currents compared with phase shifted triangular waves for generation of switching signals, this is called phase shifted pulse width modulation technique (PSPWM). In section II the topology of 5 level cascade Multilevel Inverter is discussed. In section III Procedural steps to control STATCOM are discussed. In section IV & V basics of IRP theory and SRF theory and their respective control algorithms are presented. In section VI DC side control is discussed. In section VII Phase shifted PWM discussed. A comparative analysis of simulation results is presented in section VIII. Finally in section IX concludes the results.

**II. TOPOLOGIES OF MULTILEVEL INVERTER**

Now a days Cascade multilevel inverters are increasingly used in high power applications due to its direct high voltage output with no need of filter characteristic. An \( m \)-level cascade multilevel inverter consists of \( (m-1)/2 \) single-phase full bridges in which each bridge has its own separate dc source. Cascade MLI has various advantages over other MLI such as Diode Clamped MLI and Fixed capacitor MLI. For reactive power compensation Cascade H-Bridge Multilevel inverter is prefer.

In Fig. 2 cascade multilevel inverter is shown. It consists of single phase full bridges connected in series. In this configuration if \( S=8 \) no of full bridge cells then the number of output levels is \((2^S-1)\). With \( S=2 \) there will befive levels in phase voltage and peak magnitude is \( SV_{dc} \) [5].

\[
\text{THD}(\%) = \sqrt{\frac{1}{S}} \sum_{k=2}^{\infty} \left( \frac{I_k}{I_1} \right)^2 \times 100
\]

Where \( I_k \) is the order of harmonics

In operation of STATCOM, the harmonic component of load current is derived from harmonic detection circuit and reverses it as the reference compensated current. Then switching signal for multilevel inverter is generated such that AC side output current correctly trace reference current so that source current will be free from distortion and approaches towards sinusoidal waveform.

**III. PROCEDURAL STEPS TO CONTROL STATCOM**

The control strategy of STATCOM is complex process which can be understood by following procedural steps:

A. Signal monitoring
B. Getting compensating signals
C. Generating gating signals.

**A. Signal monitoring**

For the extraction of compensating signals, instantaneous voltage and current signals are required which are also useful to observe total harmonic distortion (THD), power factor, active and reactive power. These signals are sensed by using voltage sensor (potential transformer PT) and current sensor (current transformer CT) respectively are then compared with generated reference signals to generate gating signals.

**B. Derivation of compensating signals**

The important part of STATCOM control is the generation of compensating signals in terms of voltages or currents. The control methods used to generate compensating signals are based on frequency domain or time domain techniques. The compensation in frequency domain is based on Fourier analysis technique but it results in large response time. The compensation in time domain are based on instantaneous derivation of compensating signals.
commands in terms of voltage or current signals from distorted voltage or current signals. This uses simple algebraic calculations and transformations. There are many control methods in time domain, but which I have studied are:

- Instantaneous power (p-q) theory
- Synchronous reference (d-q) method

C. Generation of gating signals
The gating signals to control solid state devices of VSC i.e. 5-level Cascaded H-bridge MLI are generated by using phase shifted pulse width modulation (PWM)

IV. THE P-Q THEORY
The P-Q/IRP theory proposed in 1983 by Akagi et al to control active filter (AF) is based on the time domain. It is valid for both steady-state and transient operation as well as for generic voltage and current waveforms, allowing the control of the active filters in real-time. Since only algebraic calculations are required the additional advantage of simplicity is achieved by using this method. It consists of an algebraic transformation (Clarke transformation) of three phase voltages and currents in the a-b-c coordinate to α-β-0 coordinate. The main advantage of using Clarke transformation is separation of zero sequence components [3]-[4].

The p-q theory calculations are carried out as shown in Figure 3. From the received values of phase voltages (va, vb, vc), load currents (ia, ib, ic) and DC voltage, the controller calculates the reference currents given by (8) based on control algorithm shown in Figure 2. These currents then compared with supply current and the inverter uses these reference currents to produce the compensation currents which are injected in power system by the inverter.

V. SYNCHRONOUS REFERENCE FRAME THEORY
The synchronous reference frame theory or d-q theory [5] is based on time domain reference signal estimation techniques. It performs the operation in steady state or transient state as well as for generic voltage and current waveforms. It allows controlling the active power filters in real time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation.
In this strategy, the reference frame d-q-0 is determined by the transformation angle θ with respect to the α-β-0 frame applied in the p-q theory [6]. It is based on the transformation of the stationary reference frame three phase variables (a,b,c) to synchronous reference frame variables (d,q,0) whose direct (d) and quadrature (q) axes rotate in space at the synchronous speed Ws, which is the angular electrical speed of the rotating magnetic field of the three phase supply given by Ws=2*Pi*f where f is the frequency of the supply. If θ is the transformation angle, then the current transformation from a-b-c to d-q-0 frame is calculated as

\[
\begin{bmatrix}
 d \\
 q \\
 0
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
 \cos \theta & \cos \left( \frac{\pi}{3} \right) & \cos \left( \frac{\pi}{2} \right) \\
 -\sin \theta & -\sin \left( \frac{\pi}{3} \right) & -\sin \left( \frac{\pi}{2} \right) \\
 \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
 a \\
 b \\
 c
\end{bmatrix}
\]

Where

\[
\theta(t) = \int_0^t Wc(t) dt + \theta_0
\]

The sine and cosine functions are required to maintain the synchronization with supply voltage and current. The d-q transformation output signals are dependent on the load current which consists of fundamental and harmonic components and the performance of the Phase Locked Loop (PLL). The PLL circuit provides the rotation speed (rad/sec) of the rotating reference frame, where W is set as fundamental frequency component and 30 degree phase angle followed by sin and cos for synchronization.

The (id - iq) currents are sent through low pass filter (LPF) for filtering the harmonic components of the load current, which allows only the fundamental frequency component and 30 degree phase angle followed by sin and cos for synchronization.

The DC voltage of each converter unit should be balanced to work system at normal state and to make sure that losses of STATCOM are provided by source[11]. The Dc side voltage control diagram is shown in Fig.6 Average of each leg voltage is taken and then compared with reference voltage and error is given to PI controller which generates loss component of APF. This loss component is added to fundamental load component as shown in Fig.3 and Fig.4

VII. CARRIER PHASE SHIFTED PWM

In the phase shifted pulse width modulation technique all triangular carriers have same frequency and the same peak to peak amplitude but there is a phase shift between any two adjacent carrier waves of magnitude given by

\[
\phi = 360^\circ \left(\frac{m-1}{m}\right)
\]

Where m is the voltage levels of multilevel inverter

Gate signals are generated by comparing the modulating signals with the carrier signals[11]. The carriers TW1 and TW2 are used to generate gating for the upper switches in left legs of power cells H1 and H2 in Fig.1 respectively. Fig.7 gives the block diagram to generate the gating signals, where Tw1 and Tw2 are two triangular carrier waves shifted by 90 degree from each other.

VIII. SIMULATION RESULTS

The purpose of the simulation is to show the effectiveness of IRP and SRF methods for reactive power compensation and maintaining sinusoidal source currents when the source supplying a non-linear load. The MATLAB/Simulink simulation tool is used to develop a model that allowed the simulation of the IRP and SRF theory calculations [6]-[11], which are implemented in the controller of the STATCOM (Figure 3 and 4). The load is simulated to include harmonic distortion from a three phase uncontrolled rectifier. Because of non-linear load the source current become distorted and it contains harmonic components as
shown in Figure 8.1. In Figure 8.2 Active and Reactive power is shown without statcom.

Fig.9 shows the Matlab/Simulink power circuit model of STATCOM. It consists mainly source block, non-linear load block, control block, STATCOM block and measurements block. The system parameters for simulation study are source voltage of 380V, 50 Hz AC supply, DC bus capacitance 3000e-6 F, Inverter series inductance 10 mH, Source resistance of 0.1 ohm and inductance of 0.9 mH, Load resistance and inductance are chosen as 10mH and 100 ohms respectively.

To make the source current distortion free, STATCOM operate to compensate the current harmonics by injecting the compensating current. The Figure 9.1 indicates that after compensation the main currents are sinusoidal even when the load is non linear.

From Figure 9.2 and 9.3 it is observed that STATCOM system is providing reactive power compensation by both SRF and IRP theory respectively. Fig 9.3 shows the 5 Level Cascade H-Bridge MLI voltage waveform.

Figure 10 shows the harmonic spectrum of Phase –A Source current with DSTATCOM. The THD of source current without DSTATCOM is 66% and with DSTATCOM and with SRF algorithm is 4.86%
Figure-11 shows the harmonic spectrum of Phase –A Source current with DSTATCOM. The THD of source current without DSTATCOM is 66% and with DSTATCOM and with IRP algorithm is 4.76%

Figure.11 Harmonic spectrum of Phase-A Source current with DSTATCOM

TABLE : Harmonic compensation by SRF & IRP theory

<table>
<thead>
<tr>
<th>Source Current THD with</th>
<th>THD without compensation</th>
<th>THD with compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRF theory</td>
<td>66%</td>
<td>4.86</td>
</tr>
<tr>
<td>IRP theory</td>
<td>66%</td>
<td>4.76</td>
</tr>
</tbody>
</table>

From above Table it is seen that without compensation, the THD level of the source current is very high which do not comply with the IEEE 519 harmonic standards. After compensation by IRP and SRF theory, the THD level of the source current is reduced considerably for all three phases which comply with the IEEE 519 standards. Comparing these tables it is confirmed that SRF theory gives better performance than the IRP theory method.

CONCLUSION

In this paper the performance analysis of IRP and SRF methods of compensation current generation for STATCOM under distorted supply and non-linear load conditions based on simulation studies is discussed. Both SRF and IRP theory gives satisfactory result for reactive power compensation. Comparative study brings that, the IRP theory gives a better approach than SRF theory for compensation of harmonic currents and takes appropriate corrective measure for the THD in improvement of the power under distorted supply and non-linear load conditions.

REFERENCES