Implementation of Novel Vector based Current Control Method for DC Capacitor Voltage Regulation in DStatcom

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Abstract—**This paper introduces a novel current control method to regulate the capacitor voltage of DStatcom and thereby improve the quality of electrical power in the distribution system continuously. Proportional Integral controller seems to be appropriate in regulation of voltage and that is limited to some extent. The proposed control strategy regulates the capacitor voltage of DStatcom along with elimination of power quality problems. A vector based Hysteresis current controller is used with hysteresis comparators in multilevel integrated with a switching table which shows fast transient response for load parameter variations. An evaluation is carried out with MATLAB/Simulink and it shows excellent performance. The performance of the method is found good for DStatcom with both balanced linear and nonlinear loads.**

Keywords—component; Shunt Active Filter; PI Controller; Multilevel Hysteresis Controller; PWM; VSI; Harmonics

I. INTRODUCTION

Nonlinear loads are increasing day by day as year passes by. As these loads introduces harmonics that increases the reactive power consumption in the distribution system that needs to be considered in current scenario, power quality has gained its importance in recent years in research field[5]. The effects of the non-linear loads can be reduced by means of adding filters to the system. Passive filters and active filters are the types used to do the same.

Different controllers can be used to generate reference compensation current for the distribution system. Whenever we connect a system to a non-linear load, the load needs both active component and harmonic and the reactive component too. In a compensated system the active fundamental component should be supplied by the source but the filter has to supply both harmonic component and also reactive component consumed by the load component. The compensation is done by the capacitor voltage in DStatcom. The capacitor voltage should be maintained nearer to its calculated value given as reference for the balance of reactive power between load and the custom power device. P, PI, PID controllers can be used to regulate DC capacitor voltage which in turn will compensate the system. A very good mathematical model is needed for efficient control of DC Voltage regulation

by the controllers which may or may not give good results under variable load conditions.

The DStatcom is a custom power device. It consists of Voltage Source Converter (VSC) and a storage element which can be made to act as active power filter which can act as a source of reactive power in distribution systems[6]. D-Statcom is used to regulate the voltage magnitude of all the AC buses it is connected by means of injecting or enthralling reactive power from the distribution system.

Literature says that most of the works is carried out in this field related to power quality which tries to enhance the quality of power reduced due to variable loads connected to the system. Voltage sags and swells are some example of power quality reduction[12]. DStatcom is also capable of improving power factor and reduction of harmonics of the feeder to which it is connected and thereby enhance the steady state performances [14].

Different literatures explain this work with different controllers. A paper in literature explains the Damping of power system oscillations by STATCOM[4]. The device is controlled by Fuzzy Logic Controller by which the DC Voltage of it is regulated. Bang-Bang controller also gets associated with that controller in regulation process. Various variables of the system is measured in local mode and given to the controllers to get the process done. In another paper multilevel inverter used in cascaded fashion operated by a different switching technique added with swapped gating signals is used in Statcom[3]. Swapped Thyristor gate signals is used to drag out the fundamental component of output voltage and take that as output and eliminating the need to care about harmonics[17]. Various controllers are employed to improve the performance of the designed system along with the conventional controllers. Transient stability enhancement is dealt using Fuzzy logic control. Voltage sag and Voltage Swell is mitigated using D-STATCOM which are results of connecting variable loads. Compensation of voltage done by genetic algorithm applied to a custom power device(Statcom) shows better results in regulating the voltage for varying loads and it almost reaches the nearest value to the nominal value[6]. With no reactive power measurements the voltage

regulation can be done only with the values of voltage measurements then and there. PWM control method is applied to DStatcom and DVR. The reliability and quality of power flowing through the distribution system depends on modelling and analysis of conventional controllers applied to shunt and series devices in power systems. These systems along with the PWM controllers are implemented in parallel transmission lines to exchange reactive powers between the lines.

PI controller is presented along with many controllers like fuzzy logic, hysteresis controller because of its good performance. All these proposed work uses PI for scheduling and the other controller as a new design and to compare the performance along with PI. A fast voltage controller is the final aim of all the papers and is presented in general with different modelling strategy[13].

A shunt active filter connected to a distribution system as a custom power device has also been discussed. The capability of active power filter is seen to be more while applying in line voltage regulation of the distribution system. A power factor control loop is included separately if its needs to be concentrated. The control method in this paper flows with constant power but the current is varied which acts as compensation parameter which is dragged towards its sinusoidal nature. These all are clubbed into a separate block which acts as a control block for the device. First and second peak values along with increased settling time are the lacking factors in all these papers.

II. SYSTEM CONFIGURATION

A Voltage Source Converter(VSC) connected to a storage element namely DC Capacitor is connected to a particular bus or to the point of common coupling which is named as DSTATCOM when the custom power device is connected to a distribution system[7]. Three phase AC distribution system connected to non-linear loads made non-linear by power electronic devices and to varying balanced loads. The three phase feeders are connected to the voltage source inverter via coupling transformer. The coupling transformer will act as a potential transformer and it does isolation too. This setup will be act in such a manner that the magnitude of the bus voltage of the distribution system is maintained constant. The deviation of bus voltage caused by consumption of more reactive power by the inductive loads will be compensated by DStatcom by means of firing the power electronics devices at the right moment. DStatcom also cancels out the harmonics and its accuracy falls on extracting the right fundamental component. VSC used to absorb some real power from the system to compensate the reactive power which in turn helps in maintaining the voltage profile of the connected distribution system. Frequency variation is dealt at Point of Common Coupling(PCC) by connecting a passive filter. The real power is stored in the storage element which is later used to compensate the reactive power need and so the DC Capacitor voltage needs to be maintained constant[16]. PI(Proportional Integral) controller is employed for this purpose.

The diagrammatic representation of the distribution system and the connected loads is shown in Fig. 2. The system is

contaminated by the nonlinear loads. SAPF injects compensating currents and cleans the contaminated system by injecting currents in opposite phase to the harmonic currents. This is calculated by comparing the voltage of the line (V_{PCC}) and the device voltage(V_{PWM}) and thereby injecting controlled currents at PCC. Matching the harmonic current value(i_h*) to the SAPF current(i_{AF}) generated by VSC is the main thing done by the system. The performance of the filter depends upon finding the harmonic current value accurately and framing a good control system to match the compensating current to be with same amplitude and in just anti-phase to the harmonic current[1]. For a perfect compensation of harmonics not only the injecting inverse magnitude is important but also that should be done without any delay or the delay should be minimum. Generally, Frequency domain and Time domain techniques are available to derive harmonic reference current. The proposed system has reduced the delay and the controllers are tuned for making the system reliable to different loading conditions.
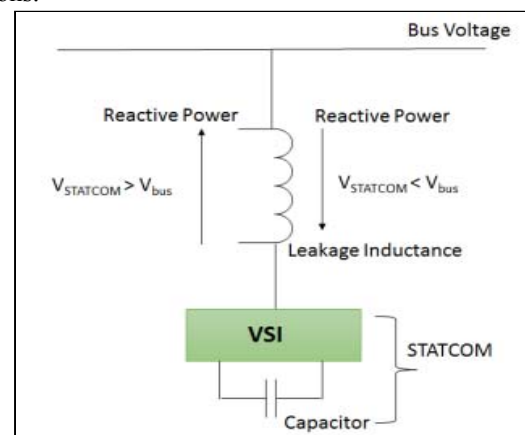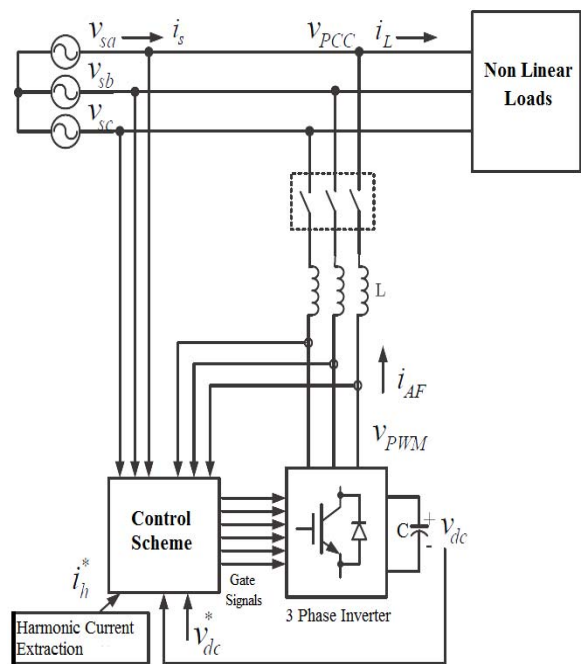

Fig. 1. Simple DStatcom

Fig. 2. System configuration for shunt active filter

III. CONTROLLER ACTIONS

A. Elimination of Harmonics

The instantaneous values of all the three phase lines i.e from grid are measured. Three phase values i_{sa}, i_{sb}, i_{sc} is not easy to process and so they are transformed into $\alpha\beta$ coordinates by Clarks transformation[8]. Then the stationary $\alpha\beta$ coordinates is transformed to rotating dq coordinates in order to find the phase angle of the harmonic currents injected by the non-linear loads. Upon finding the negative sequence currents i_d', i_q' and filtering the current through low pass filter we can get the pure current[11]. Now the original signal which is added with harmonics, the actual value of harmonics(i_h*) to be eliminated can be calculated. Now the dp values are transformed back to the actual instantaneous value by inverse transformation method. Now we would have obtained the harmonic currents for the three phases i_{ha}, i_{hb}, i_{hc} which is to be eliminated.

The block diagram of the control method is depicted in fig. 3. Active filtering and passive filtering are the two types of filtering to filter out the harmonics generated by non-linear loads.

1. Passive filtering

Depending upon the system frequency a passive filter will form impedance by its combination of inductor, capacitors and resistors. Passive filter by its principle will insert a leading or lagging current tuned by the varying load current on the fundamental frequency.
The drawbacks of the above filter are
The resonance created by equalising the value of inductor and capacitor[15]. The size of the filter circuit is bulk. The weight is also increased depending upon the loads added to the system.

2. Active filtering

In order to make the source current pure sinusoidal we should either generate harmonic current or harmonic voltages depending upon the harmonics generated by the loads connected to the system[9]. Series and parallel active filters can be very well connected and coordinated with passive filters and the compensation can be done to voltage or current.
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Some of the advantages of active filters are
- Flexibility and adaptablity
- Elimination of harmonics
- Less size

Disadvantages of active filters include its high cost and bulky size which makes its less usable in real time.

A shunt active power filter consists of a VSC combined with or without a energy storage circuit and the filters which are discussed above. Energy storage circuit maybe inductive or capacitive mostly it will be capacitive. Filters can be either passive or a shunt active power filter.

Control section consists of blocks starting form measurements of actual line current, Clark's transformation, PLL, Multilevel hysteresis comparators, firing angle control and the VSC.
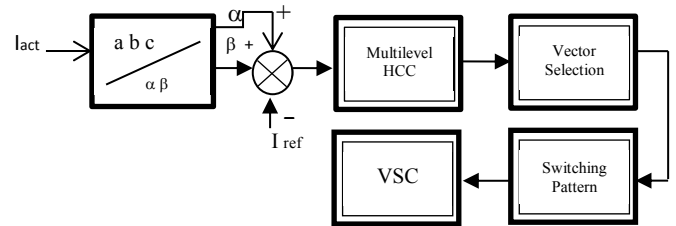

Fig. 3. Control Diagram for Depollution of Harmonics

Upon calculating the harmonic currents in all the three phases and filtering the current components it is processed through multilevel hysteresis current controller(HCC) which is purely a vector based scheme. This method shows very good steady state and transient performance in reducing the switching frequency of the inverter to a greater extent[2]. The error is basically kept under some tolerance region which is calculated before in hand. The voltage vectors measured in space vector form will be classified automatically as zero and non-zero values and it will be made to follow some commands which lead to reduction of switching frequency.

Multilevel HCC always deals with current vector as $\alpha - \beta$ coordinates and they are processed through vector selection panel which selects the vector according to the amplitude and phase value of the harmonics. The selected vector will be processed to maintain the value of actual current within the square tolerance region. The firing angle control to VSC is then generated by the pattern generated from the vector selected. The oscillation in the current due to non-linear loads will be reduced along with reducing the switching frequency of the overall system. The selection of opposite phase vectors is the uniqueness in this method.

a)Pulse Width Modulated VSI

The three phase voltage (V_{abc}) of the inverter is defined by

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} xa \\ xb \\ xc \end{bmatrix} \quad (1)$$
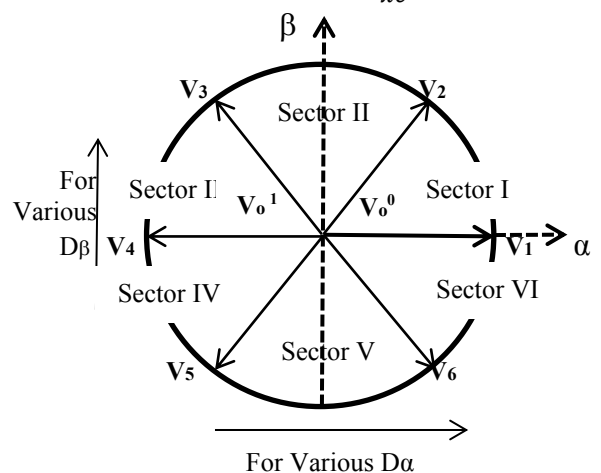

Fig. 4 Voltage vector selection

The output voltage of the inverter will have different states of conduction and it depends on the conduction of each leg conduction in the inverter. The states will be either zero or one and the corresponding opposite vector state will be just opposite to that.

Different conducting states gives different voltage outputs as described by the following equations.

$$\left[\begin{array}{c} V_n = \frac{2}{3}\text{Vdc}\exp\left(\frac{2\pi j(m-1)}{3}\right), m = 1,2,3\ldots \\ V_0^1 = V_0^0 = 0 \end{array} \right. \qquad (2)$$

The current error can be calculated by the following equation

$$L\frac{di_e}{dt} + Ri_e = Ldi_{ref} + Ri_{ref} - (V_n - e_o) \qquad (3)$$

Since resistance is negligible, inverter output voltage can be defined as

$$V_n^* = e_o + Ldi_{ref}/dt \qquad (4)$$

So the current error vector becomes

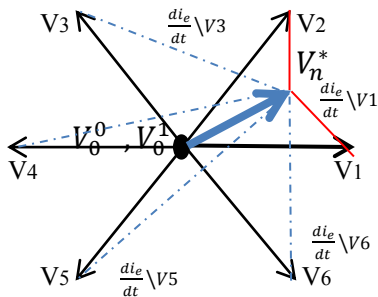$$L\frac{di_e}{dt} = V_n^* - V_n \qquad (5)$$

Fig. 5. Current error derivative vector corresponding to V_n^* in Sector 1

Based on the above equations are used to nullify inverter current error. Least Ldi_e/dt is required to obtain minimum switching frequency.

The proposed HCC will generate the switching pattern according to the Vo vector and corresponding nearby non zero vectors to reduce the tracking vector.

b) New vector based HCC

The simple logic behind the new method is subtraction by applying opposite phase value of same amplitude to the error vector[10]. Hysteresis controller compares and processes the current value accordingly to reduce the error and maintain it below the tolerance region.
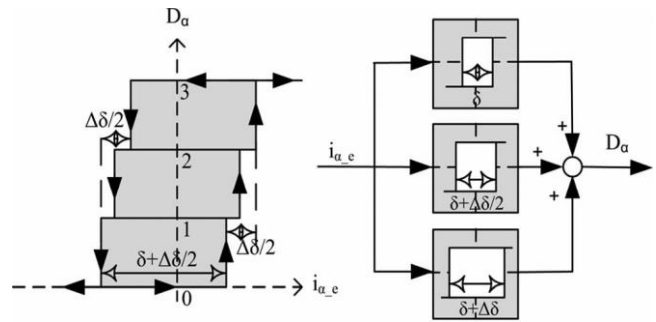

Fig. 6. Block diagram of multilevel hysteresis controller

Based on the control strategy overall switching pattern is generated. The switching table of the proposed method and VSI switching pattern is given below.

The inverter switching pattern is given below.

$$\left.\begin{array}{l} \text{V1: } 1\ 0\ 0 \\ \text{V2: } 1\ 1\ 0 \\ \text{V3: } 0\ 1\ 0 \\ \text{V4: } 0\ 1\ 1 \\ \text{V5: } 0\ 0\ 1 \\ \text{V6: } 1\ 0\ 1 \\ V_0^1 : 1\ 1\ 1 \\ V_0^0 : 0\ 0\ 0 \end{array}\right\} \text{Sector I to VI}$$

The accuracy of the current controller determines the selection of tolerance level of the comparators[18]. The output voltage of the inverter purely depends upon the values of multilevel hysteresis comparators which in turn will reduce the current error and thereby reduces the harmonics of the system.
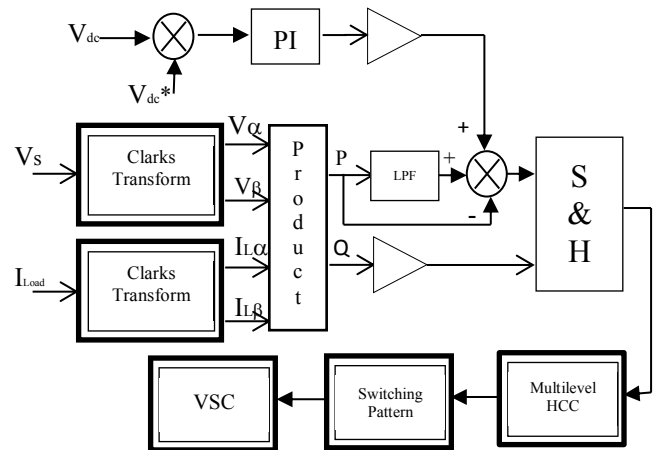
B. DC Bus Voltage Control

Fig. 7. PI controller for DC Capacitor voltage regulation

DC Capacitor voltage is maintained at some constant voltage. Neglecting the resistance of the conductor, applying joules law to capacitor, switching losses too the value of capacitor will be maintained. As these factors will come into account there will be remarkable loss in the capacitor voltage

which will regularly affect the actual process of compensating the losses in the system which in turn will affect the stability of the overall system. Conventional PI controller can be employed to maintain its value and used to try to maintain its own stability. The controller will get both the actual value of capacitor voltage *(Vdc)* and the reference voltage(Vdc*) and that value will be compared to the supply voltage and the load current that results in a command which lead to constant capacitor voltage.

IV. SIMULATION RESULTS

DStatcom is designed in MATLAB Simulink and its output is analyzed under various loading conditions. To test the system various parameters are used that are displayed in the Table 1.

Table 1 SIMULATION PARAMETERS

Simulation parameters	Value
Supply Voltage	400V RMS, 50HZ
Balanced Load	R=8Ω
Non Linear Load	50A Full wave rectifier
Capacitor voltage – DStatcom	2200 μf
Reference DC Voltage	1.2kV
Interface Inductor	R - 0.1Ω, L - 10μH

Capacitor reference voltage is selected as per the formula given below.

$$V_{dc} = 3\sqrt{3}\ V_s cos\alpha/\pi \qquad (6)$$

α - Delay Angle

If delay angle equals zero, equation becomes

$$V_{dc} = 3\sqrt{3}\ V_s/\pi \qquad (7)$$

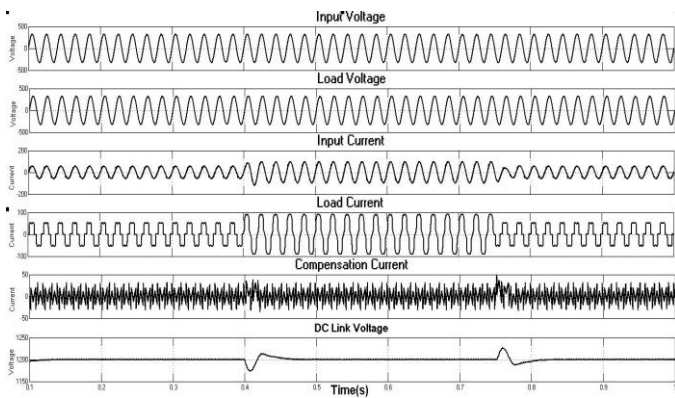So the preset limit of the energy storage element C will be three times of 1.6 times of per phase supply voltage.

Fig. 8. Simulated response of the SAPF with vector based

Hysteresis controller: Source Voltage (V$_{sa}$); Load Voltage(V$_L$); Input Current(i$_{sa}$); Load Current(i$_{La}$); APF current(i$_{fa}$); Dc link capacitor voltage(V$_{dc}$)

Simulation is conducted and the results are presented above.

Both the controllers (PI and Vector based Hysteresis) are responsible for the quality power to be delivered by the system. For the system whose parameters are defined in Table 2 the linear load is applied at 0.4th sec 0.75 secs to test the performance of the system for variation of balanced load added to the already existing full wave rectifier which is a non- linear load. The shown in the figure 8 clearly explains the compensation made by the controller. The best results are obtained (i.e THD < 5%) by the vector based hysteresis controller.

PI controller controls the voltage level of the DC capacitor nearest to the reference value selected as per the formula given by equation (7). The capacitor voltage drops at sec after application of balanced load but the PI controller recovers it back within1-2 cycles. It also rises up to some value once load is disconnected at 0.7 sec and that's also recovered within 2 cycles.
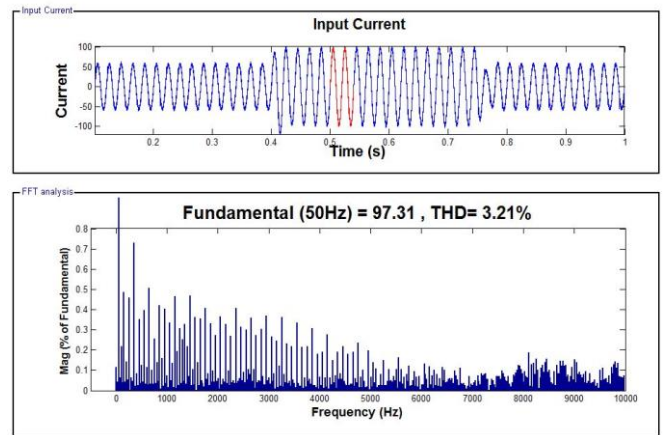

Fig. 9. Source Current Spectrum After Compensation

Whenever we connect a non-linear load to the distribution system, the supply voltages and the input current get distorted. Non-linear current is drawn from the good distribution system when it is connected to a three phase full wave rectifier made of diode bridge which draws around 50A non sinusoidal current from the system. The harmonics present in system are only due to the non-linear loads connected to the system. The objective of the vector based Hysteresis controller is to reduce the harmonics by compensating the harmonic currents.

The waveforms of the supply voltage and the source currents are similar in phase after compensation. Fig. 9. reveals the truth about the compensation current supplied which also shows the harmonics generated. Fig. 8. explains compensation of harmonics and the reduction of distortion in the supply current. Finally the THD of source current has been reduced below 5%. Thus the harmonics in the supply current is eliminated by compensating with other anti-phase current.
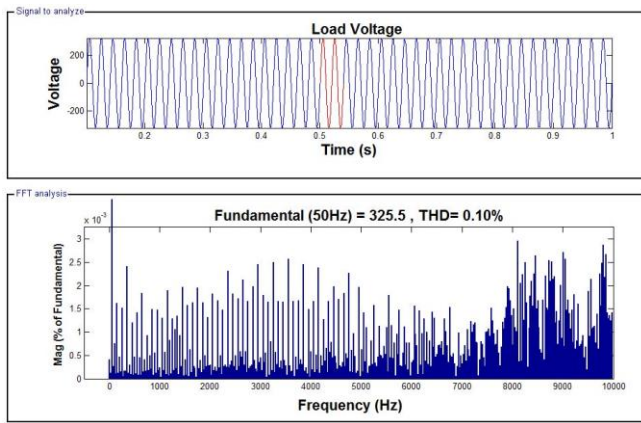
Fig. 10. Load Voltage Spectrum after compensation

Fig. 10. explains the harmonics and the waveform shape of load voltage of the distribution system. The result shows that the harmonics of the system is compensated by the shunt active power filter and thus the harmonics has been reduced to 0.10% before and after application of load to the system.

V. CONCLUSION

A Quality distribution system has been designed by connecting DStatcom in shunt and made to act as active filter. Pulse Width Modulated techniques is applied to Voltage Source Converter in DStatcom connected to non-linear load along with a balanced resistive load. The performance of the system has been discussed in terms of power quality improvement. Harmonic elimination and voltage profile maintenance of the distribution is done by Multilevel Hysteresis current controller. Further PI controller is found good in maintaining DC Capacitor voltage at the desired level with less overshoots and undershoots caused by the variation in load. Controller coordination and the overall performance of the system found good with these controllers for these loads.

Different new controls methods can be employed to test the system under these conditions and various other loading conditions. The same system with the same performance can be implemented in real time in the near future.

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