Performance of DSTATCOM Control with Instantaneous Reactive Power Theory under Ideal and Polluted Grid

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***Abstract*-This paper discusses the modeling and design of Instantaneous Reactive Power Theory for control of DSTATCOM. Conventional IRPT and modified version in the form of Complete Harmonic Elimination is discussed and modeled. Results with sinusoidal grid as well as non-sinusoidal voltages are presented in this paper. The compensator has the ability to improve power factor, regulate voltage, reduce harmonics in supply current and provide load balancing. Several aspects of control are compared in three phase, three wire system.**

***Index Terms*—compensation, power quality, DSTATCOM, voltage regulation**

I. INTRODUCTION

Ever since power electronics was introduced in the late 19th century, the use of non-linear load has increased significantly. Increasingly, problems like voltage deviation during load change and power transfer limitation are observed due to reactive power unbalancing. Most AC loads consume reactive power due to presence of reactance. Heavy consumption of reactive power results in poor voltage quality. Today these problems have caused a substantially higher impact on reliable and secure power distribution system [1]. Maintaining the electric power quality 'PQ' in an electrical distribution system is presently a matter of great concern. The term power quality generally refers to maintaining good quality of power at generation, transmission, distribution and usage of electric power supply [2].

Harmonics are a key factor influencing poor power quality and lead to a lot of disturbances in the distribution system such as electromagnetic interference, overheating if cables and low power factor. Distribution Static Compensator (DSTATCOM) is used to compensate the current based power quality disturbances like reactive power, neutral currents, fluctuations, harmonics and unbalanced currents. An insulated gate bipolar transistor (IGBT) based current controlled 3-phase, 3leg voltage source converter (CC-VSC) with a DC bus capacitor is used as DSTATCOM. In general, a DSTATCOM has a VSC connected to a DC bus and AC side is connected across the consumer end of the power distribution system in shunt. A control algorithm is used to generate reference currents that are compared to the supply currents in indirect current control of the VSC; these are then used to generate gating pulses which are fed directly to the DSTATCOM [3].

Performance of DSTATCOM depends on control scheme used to extract reference current components. Instantaneous Reactive Power (IRP) theory and Synchronous reference Frame (SRF) theory for compensating reactive power and unbalancing in loading are compared with a new adaline based control algorithm in [4] proposed by B. Singh and J. Solanki.

L.S. Czarnecki proposed an approach to generate reference current for Shunt Switching Compensator (SSCs) control using Instantaneous Reactive Power (IRP) p-q theory in [5] in 2009. On the other hand J. Bangarraju, V. Rajagopal and A. Jayalaxmi proposed Instantaneous Reactive Power (IRP) theory control algorithm for three-leg VSC and used it for Dynamic Voltage Regulator (DVR) in [6].

Active filtering generally focuses on compensation techniques where the source voltages are sinusoidal where compensation of harmonic currents with reactive power gives unity power factor (UPF) which results in harmonics free currents [7]. But when the source voltages are non-sinusoidal then some difficulties arise in compensation. Despite the technique used for compensation, perfect compensation of harmonics and reactive power does not take place and unity power factor is not achieved. Salmerón and R. S. Herrera in [8] proposed techniques for load compensation under distorted source voltages.

This paper presents the performance of DSTATCOM controlled by instantaneous reactive power theory (IRPT) or p-q theory under different strategies to extract reference current. These currents are then used to perform load compensation when the distribution system grid voltages are sinusoidal and polluted and feed non-linear load. The performance of DSTATCOM using these strategies are tested and verified in both Power Factor Correction (PFC) mode and Zero Voltage Regulation (ZVR) mode for both ideal (sinusoidal) and practical (non-sinusoidal) voltages in distribution system.

II. SYSTEM CONFIGURATION

A three-phase source with source impedance 'Z_s' feeds a three phase non-linear load. A DSTATCOM is connected at the consumer end in shunt. It is modeled as an IGBT based current controlled VSC that is connected to a DC link capacitor

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'C_{DC}' and its DC side and is connected to three phase AC mains at point of common coupling on its AC side. A detailed block diagram of the system is shown in Fig. 1. All the control strategies are tested and verified in this system in MATLAB/SIMULINK R2015a.

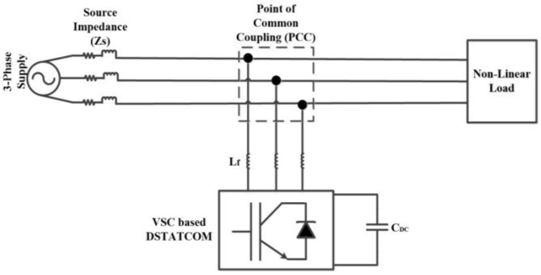

Fig. 1 Block diagram of DSTATCOM connected to grid

III. CONTROL ALGORITHM

This section discusses the conventional algorithm and its modified versions.

A. Conventional Algorithm under Ideal Grid Conditions

The conventional p-q theory uses Clarke transformation or αβ0 transformation, which is used to convert three phase voltages and load currents in αβ0 stationary reference frame.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

The instantaneous active and reactive powers are calculated as:

$$\begin{bmatrix} P_L \\ Q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

As these powers contain both the AC and DC components the AC component needs to be filtered out using a low pass filter.

$$\begin{bmatrix} P_L \\ Q_L \end{bmatrix} = \begin{bmatrix} \overline{P}_L + \widetilde{P}_L \\ \overline{Q}_L + \widetilde{Q}_L \end{bmatrix} \tag{4}$$

Here, $\overline{P}_L$ and $\overline{Q}_L$ are the DC components and $\widetilde{P}_L$ and $\widetilde{Q}_L$ are the AC components of the instantaneous active and reactive powers. Two PI controllers are used to regulate the DC bus voltage 'V_{dc}' and PCC Voltage 'V_t' respectively.

The error in DC bus Voltage at nth sampling instant between the reference DC bus voltage 'V_{dc}^*' and the sensed DC bus voltage 'V_{dc}' is given as:

$$V_{DC}(n) = V_{dc}^*(n) - V_{dc}(n) \tag{5}$$

The output of the DC PI controller is known as the active power component loss 'P_{Loss}'

$$P_{Loss}(n) = P_{Loss}(n-1) + K_{pd}\{V_{DC}(n) - V_{DC}(n-1)\} + K_{pi}V_{DC}(n) \tag{6}$$

Here, K_{pd} and K_{id} are the proportional and integral gain of the PI controller respectively. P_{Loss} is added to the DC component of active power '$\overline{P}_L$' to acquire the fundamental component of active power given by 'P'.

$$P = \overline{P}_L + P_{Loss} \tag{7}$$

The error in PCC voltage at n^{th} sampling instant between the amplitude of the reference PCC voltage 'V_t^*' and the amplitude of sensed PCC voltage'V_t' is given as:

$$V_{te}(n) = V_t^*(n) - V_t(n) \tag{8}$$

$$V_t = \sqrt{\frac{2}{3}(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)} \tag{9}$$

The output of the second PI controller is used to maintain constant PCC voltage at n^{th} sampling instant and is given by 'Q_{Loss}'.

$$Q_{Loss}(n) = Q_{Loss}(n-1) + K_{pd}\{V_{te}(n) - V_{te}(n-1)\} + K_{pi}V_{te}(n) \tag{10}$$

Here, K_{pd} and K_{id} are the proportional and integral gain of the PI controller respectively. Q_{Loss} is added to the DC component of active power '$\overline{Q}_L$' to acquire the fundamental component of active power given by 'Q'.

$$Q = \overline{Q}_L + Q_{Loss} \tag{11}$$

These fundamental components of real and reactive powers are used to obtain the reference currents in α-β frame known as 'i_α^*' and 'i_β^*'.

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{12}$$

The reference three-phase grid/supply currents (i_{refa}, i_{refb} and i_{refc}) are estimated by inverse Clarke Transformation shown as:

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{13}$$

For power factor correction (PFC) mode there are some changes in Equation 11, and the reactive component is taken as zero, shown below as:

$$Q = \overline{Q}_L + Q_{Loss} = 0 \tag{14}$$

B. Modified Versions under Non Ideal Grid Conditions

Under this condition, the grid is considered to be polluted and has 5th and 7th order harmonics in grid voltage along with the fundamental. The conventional p-q algorithm will not work well in such conditions; hence modifications have been suggested in the literature. Three such modifications have been modeled, simulated and tested under these conditions viz. Power Factor Correction (PFC) mode, Zero Voltage Regulation (ZVR) mode and Complete Harmonic Elimination (CHE) strategy using p-q theory.

Both PFC and ZVR mode are incapable of completely eliminating the harmonics currents, so a modification of the PFC mode for harmonic elimination in the distribution system is considered. So in Complete Harmonic Elimination strategy, the three phase voltages and load currents are transformed into αβ0 stationary reference frame by Clarke Transformation as shown in Eq 1.The instantaneous value of load active power is calculated by:

$$P = i_{La}v_{sa} + i_{La}v_{sa} + i_{La}v_{sa} = \overline{P}_L + \widetilde{P}_L \tag{15}$$

The DC component of load active power is filtered out using a low pass filter. The fundamental value of 'v_α' and 'v_β' are $\dot{v}_\alpha$, $\dot{v}_\beta$ obtained by using two band-pass filters tuned to extract the fundamental components of these voltages. The reference currents generated using these components in α-β frame known as 'I_α^*' and 'I_β^*'.

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{\bar{P}_L}{\dot{v}_\alpha^2+\dot{v}_\beta^2}\begin{bmatrix} \dot{V}_\alpha \\ \dot{V}_\beta \end{bmatrix} \tag{16}$$

The reference source currents in a-b-c frame can be calculated using Eq.13.The essence of CHE strategy focuses on filtering the distorted voltages first and using filtered $\bar{P}_L$. Once the reference source currents are generated, these are compared with the sensed source currents (i_{sa}, i_{sb}, i_{sc}) to generate gating pulses of VSC based DSTATCOM.

IV. MODELLING AND SIMULATION

In this section, detailed models have been developed for the conventional and modified version of IRPT. Fig. 2 shows the simulation diagram of conversion of PCC voltages (v_{sa}, v_{sb}, v_{sc}) and the load voltages (i_{La}, i_{Lb}, i_{Lc}) into α-β Frame using Clarke Transformation.

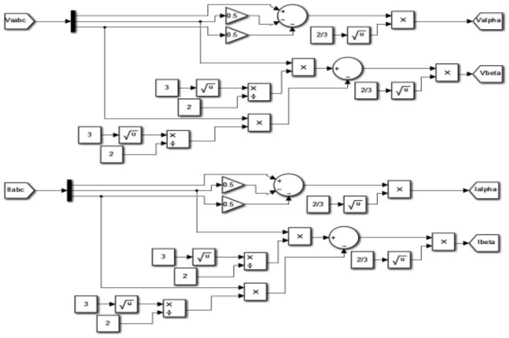

Fig. 2 Conversion from a-b-c to α-β for voltage and currents

Fig. 3 shows the control block diagram for extracting the fundamental component of the real and reactive powers using the phase voltages and load currents in α-β frame and the outputs obtained from the two PI controllers for maintaining the DC bus voltage and AC PCC voltage amplitude respectively.

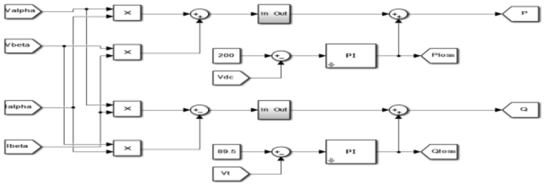

Fig.3 Calculation of fundamental Components of real and reactive powers

Fig. 4 shows how the fundamental supply currents in α-β frame are extracted from the phase voltages and load currents in α-β Frame and the fundamental components of active and reactive powers.

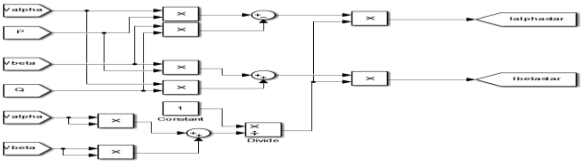

Fig. 4 Computation of fundamental supply currents in α-β Frame

phase reference currents thus generated are compared with the sensed source voltage in distribution system to generate six pulses for the VSC based DSTATCOM.

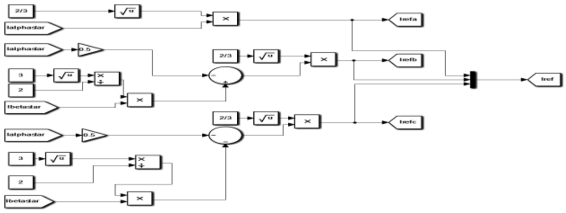

Fig. 5 Computation of reference source currents from α-β to a-b-c frame

Fig. 6 shows the modifications applied to the control algorithm in order to obtain the results in power factor Correction (PFC) mode. The reactive power has been taken as zero in this case.

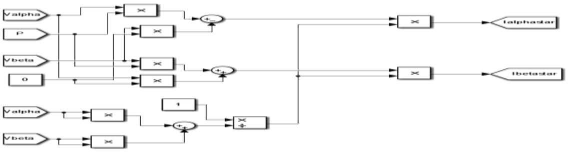

Fig. 6 Fundamental Source Currents in α-β Frame in PFC mode

The modifications that were applied in the control algorithm to implement CHE strategy are shown in Fig. 7.

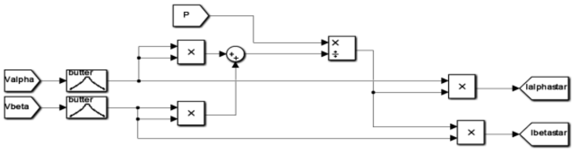

Fig.7: Source Currents extraction in α-β Frame using CHE

V. RESULTS AND DISCUSSION

Three control algorithms have been developed in MATLAB/SIMULINK using Sim power system (SPS) toolbox. The simulations have been executed in Discrete mode using ode 23tb (stiff/TR-BDF2) solver in a sampling time of (5e-6) sec. The FFT analyses of the load and supply currents in PFC/ZVR mode for sinusoidal as well as non-sinusoidal voltage distribution system are shown.

A. FFT Analysis under Sinusoidal Grid Voltages

Fig.8 shows the total harmonic distortion (THD) in load current is 27.17% and in supply current is 3.93% after compensation in phase-a in PFC mode when the voltages in distribution system are sinusoidal. The voltage is sinusoidal and has a low THD of 0.04%.

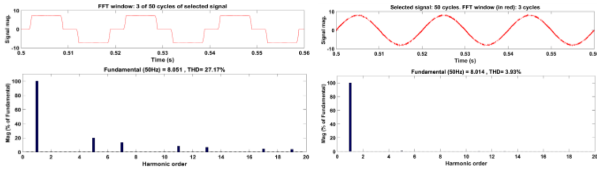

Fig. 8 FFT Analysis of load and source current in PFC mode

The FFT analyses of Load and Source Currents in ZVR mode for sinusoidal voltage distribution system are shown in

Fig. 9 shows the THD in load current is 27.16% and in supply current is 3.86% after compensation in phase-a in ZVR mode when the voltages in distribution system are sinusoidal are shown for three cycles.

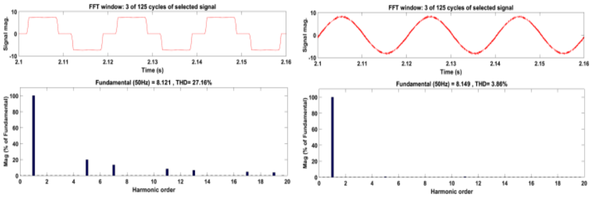

Fig. 9 FFT Analysis of load and source current in ZVR mode

B. *FFT Analysis under Non-Sinusoidal Grid Voltages*

The FFT analysis of PCC voltages, load and source currents in PFC, ZVR and CHE mode for non-sinusoidal voltage distribution system are shown below in Figs.10-12.

The FFT analysis of PCC voltage, load and source currents in PFC mode for non-sinusoidal voltage distribution system are shown in Fig 10. Here the THD values of load current, PCC voltage and in supply current are observed to be 24.75%, 6.4% and 8.52% after compensation in phase-a in PFC mode

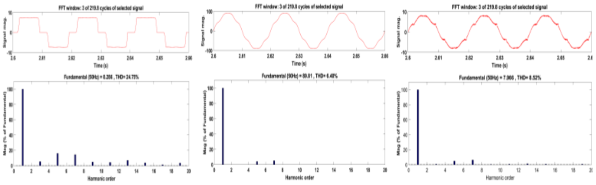

Fig. 10 FFT Analysis of load current, PCC voltage and source current in PFC mode with distorted voltages

The FFT analyses of Load Currents, PCC Voltage and Source Currents in ZVR mode for non-sinusoidal voltage distribution system are shown in Fig. 11, here the THD in load current is 24.74%, PCC voltage is 6.4% and in supply current is 7.60% after compensation ZVR mode using IRPT strategy on DSTATCOM.

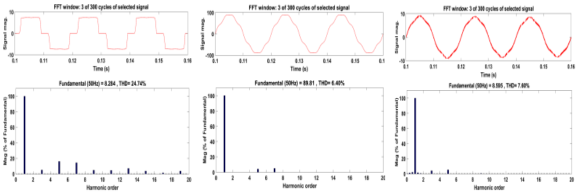

Fig. 11: FFT Analysis of PCC Voltage, load current and source current in ZVR mode with distorted voltages

Currents in CHE Strategy for non-sinusoidal voltage distribution system are shown in Fig. 12, where the THD in load current, PCC voltage and in supply current are found to be 24.75%, 6.4% and 3.64% respectively.

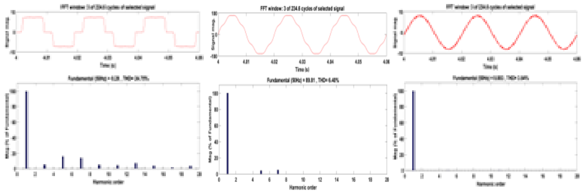

Fig. 12: FFT Analysis of PCC Voltage, Load Current and Source Current

C. *System Performance under Sinusoidal Grid Voltages*

The system performances with DSTATCOM controlled by p-q theory in different modes are now shown below.

When the distribution system has sinusoidal voltages the performance of DSTATCOM using p-q theory in PFC mode is shown in Fig. 13. At time t=0.6 sec phase ‘a’ of the load is disconnected to study the effects of unbalanced load and as we can see that dc link voltage V_{dc} rises momentarily and starts to settle down to 200V due to controller action.

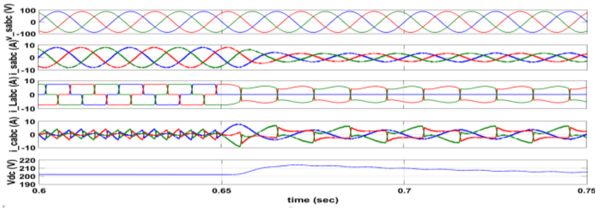

Fig. 13 Performance of DSTATCOM using p-q theory in PFC mode.

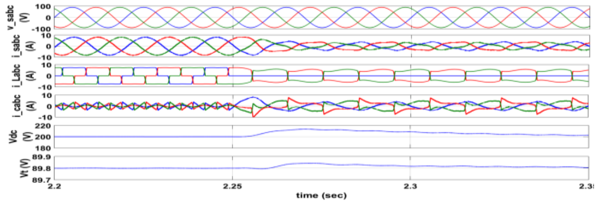

Fig. 14 Performance of DSTATCOM using p-q theory in ZVR mode

In Fig.14 the performance of DSTATCOM using p-q theory in ZVR mode is observed. Two controllers for DC link voltage and PCC voltage have been used here. At time t=2.25 sec, phase ‘a’ of the load is disconnected to study the effects of unbalanced load. It is observed that both the dc link voltage V_{dc} and V_t rise momentarily and then settle down to their reference values of 200V and 89.8V as shown in Fig.14.

5.4 *System Performance under Non-Sinusoidal Grid Voltages*

When the distribution system has non-sinusoidal voltage the performance of DSTATCOM using p-q theory in PFC mode is shown in Fig. 15. At time t=3.2 sec phase ‘a’ of the load is disconnected to study the effects of unbalanced load and as we can see that dc link voltage V_{dc} rises momentarily and starts to settle down to 200V as shown in figure. It is observed that the supply voltages and supply currents are distorted.

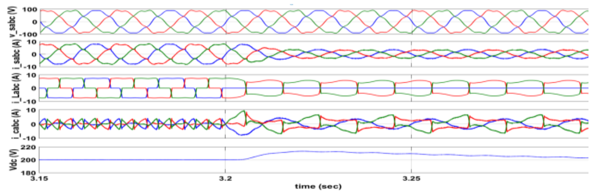

Fig. 15: Performance of DSTATCOM using p-q theory in PFC mode

In Fig.16, the performance of DSTATCOM using p-q theory in ZVR mode is observed. At time t=1.05 sec phase ‘a’ of the load is disconnected to study the effects of unbalanced load and as we can see that dc link voltage V_{dc} rises momentarily and starts to settle down to 200V as shown in figure. Also, the terminal voltage V_t has oscillations of $\pm$2V.

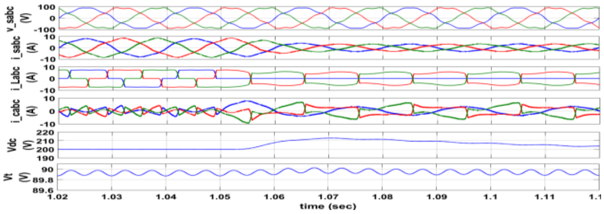

Fig. 16: Performance of DSTATCOM using p-q theory in ZVR mode

In Fig.17 the performance of DSTATCOM using p-q theory using CHE strategy is observed. At time t=4.2 sec, phase ‘a’ of the load is disconnected to study the effects of unbalanced load. It can be observed that dc link voltage V_{dc} rises momentarily and settles down to 200V as shown in figure. The supply currents have become purely sinusoidal.

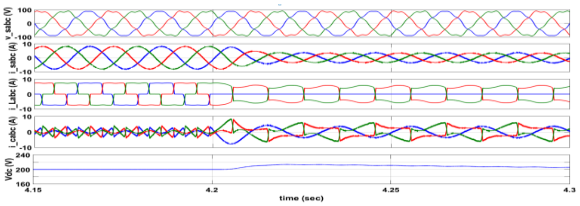

Fig. 17: Performance of DSTATCOM using p-q theory using CHE strategy.

VI. CONCLUSIONS

1. The performance of DSTATCOM controlled by p-q theory in PFC and ZVR mode when distribution system supplies sinusoidal voltage has been studied.
2. The performance of DSTATCOM controlled by p-q theory in PFC, ZVR mode and using complete harmonic elimination strategy when distribution system supplies non-sinusoidal voltage has been studied. Table 1 shows the THD in all the cases studied and verified above.

Table1: THD IN DIFFERENT CASES

VOLTAGE	**MODE**	**THD %**		
		PCC Voltage	***LOAD CURRENT***	***SOURCE CURRENT***
SINUSOIDAL	PFC	0.04	27.17	3.93
	ZVR	0.04	27.16	3.86
NON SINUSOIDAL	PFC	6.40	24.75	8.52
	ZVR	6.40	24.74	7.60
	CHE	6.40	24.75	3.64

As observed in TABLE 1, under non sinusoidal voltage CHE strategy gives the lowest THD of 3.4% in source current after compensation. Conventional IRPT strategy in PFC/ ZVR mode will not be able to reduce THD in source current to less than 5% level as per IEEE 519 standards.

APPENDIX

Supply (grid): 110V, three-phase, 50Hz; Z_s composed of R_s=0.01Ω, L_s=0.1mH; V_{dc}=200V; C_{dc}=1500µF; L_f=2.25mH; PI controller tuned at: k_{pd}=5, k_{id}=20; Nonlinear load: three phase uncontrolled diode rectifier with R=20Ω, L=100mH.

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