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Power Quality Improvement using DSTATCOM for Microgrid Applications

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Abstract: *Power quality (PQ) has become a major concern with the wide application of power electronic loads in distribution system. These loads result in power quality problems like harmonic distortion in utility source currents, excessive neutral current, poor utility power factor, voltage harmonics, voltage unbalance and interference with communication systems. To avoid these problems passive filters were used but, due to their inability of solving all the power quality issues, customs power devices (CPDs) have emerged as reliable technology. Distribution Static Compensator (DSTATCOM) is used for mitigate current and voltage related power quality issues.*

DSTATCOM is a shunt connected active power filter, which is used to overcome current related PQ problems. It is connected at point of common coupling (PCC) to supply harmonic, reactive components of load currents and also provide neutral current compensation. This makes the source currents balanced and sinusoidal with Unity Power Factor (UPF) operation. The work presented in the thesis deals with topologies of voltage source inverter (VSI), theories for generation of reference signals and current/voltage controllers for generation of switching pulses.Instantaneous reactive power theory and instantaneous symmetrical component theory used for reference currents generation for DSTATCOM are analysed. Simulation studies are performed in MATLAB/Simulink environment to validate different reference signal algorithms

Keywords**:** *Distribution system,Power Quality,Distribution Static Compensator(DSTATCOM),Voltage Source Inverter(VSI).*

1. INTRODUCTION

From day to day, the utilization of electrical energy is increasing. Most of the loads used in domestic, commercial and industries are inductive (non-linear) in nature [1-2]. Some of the examples of nonlinear loads are uncontrolled & controlled rectifiers; variable speed drives both AC & DC, uninterrupted power supplies, arc furnaces, electronic ballast, programmable logic controllers etc. All these devices are economical, flexible and energy efficient, they may deteriorate power quality by injecting harmonic current into the power system and consuming excessive reactive power, as they are drawing non-sinusoidal current from utilities, this can cause many problems such as resonance, excessive neutral currents, low power factor etc.

Harmonics produces harmonic current, poor power factor, unbalance, voltage sag & swell, reactive power burden. High harmonic neutral currents result in voltage distortion, common mode noise, and overloaded power feeders and transformers. Harmonic distortion in power system will cause additional power losses and malfunctioning of protective relay & switch gears. It also increase the risk of electromagnetic interference with neighbouring communication lines.power quality problems can be divided into three categories; namely:(i) power quality related to voltage, (ii) power quality related to current, (iii) power related to frequency. Custom Power Devices (CPDs) used to reduce power quality such as Dynamic Voltage Restorer (DVR), Unified Power Quality conditioner (UPQC), Active Power Filters (APFs) and Distributed Static Compensator (DSTATCOM) are used to mitigate the power quality problems in a distributed power system.

DSTATCOM is one of the best custom power devices in a low medium voltage power distribution system A Distribution Static Compensator (DSTATCOM) can be used for compensation of reactive power and unbalance loading in the distribution system. To make the DSTATCOM efficient, an energy storage device gets coupled with it. The performance of DSTATCOM depends on the control algorithm used for extraction of reference current components.

The DSTATCOM is a shunt connected compensator, which performs rapid reactive power exchange with an ac power system, to improve transient voltage stability and dynamic voltage control, prevent voltage collapse and damp power oscillations. For reactive power compensation, a DSTATCOM provides reactive power as needed by the load, and therefore, the source current remains at unity power factor (UPF). Since only real power is being supplied by source, load balancing is achieved by making the source reference current balanced. Reference source current used to decide the switching of the DSTATCOM has real fundamental frequency component of the load current, which is being extracted by these techniques.

1.1 Design and function of DSTATCOM

A DSTATCOM consists of a 3-phase inverter using SCRs, MOSFETs or IGBTs. The design of the DSTATCOM includes a Voltage source inverter, interfacing inductor and ripple filter. The main function of DSTATCOM is to provide reactive power as demanded by the load. Therefore, with the help of DSTATCOM source currents are maintained at unity power factor and reactive power burden on the system gets reduced. Rating of the DSTATCOM depends on the required reactive power compensation and degree of unbalance will be present into the load because the harmonics power is generally very less. So, these are the two dominating powers that will actually ensure that power rating of the devices hence, this current rating of the DSTATCOM is affected by the load power rating and the voltage rating depending on the DC bus voltage. The ripple filter is used to filter the switching ripples of the voltage and current at point of common coupling (PCC).

The design of the DC bus capacitor depends on the energy storing capability needed during the transient condition.The required compensation to be provided by the DSTATCOM decides the rating of the VSC components, inductor to block circulating current and moreover we require to actually boost up the DC bus voltage. high-pass filter tuned at half of the switching frequency is used to the filter out the noise or the switching ripples from the point of common coupling.

1.2. Modelling of the Distribution System with DSTATCOM

From the below fig the DSTATCOM is connected to the point of common coupling(PCC) through an interfacing ripple filter. The corresponding input power distribution system capacitor voltage and current are denoted as $v_{d様}$ and $id_{様}$respectively. The output voltage and current of the DSTATCOM are denoted as $v_{様}$ and $i_{様}$ respectively. The source voltage and current are denoted as vs and i_s respectively. The source impedance is modelled as the connection of R_s and L_s . An uncontrolled diode rectifier with a resistive R_l and inductive L_l load serves as a nonlinear load connected to the PCC and the corresponding current is denoted 1as i_l. The detail algorithm for switching signal generation of VSC is shown in the fig. 2

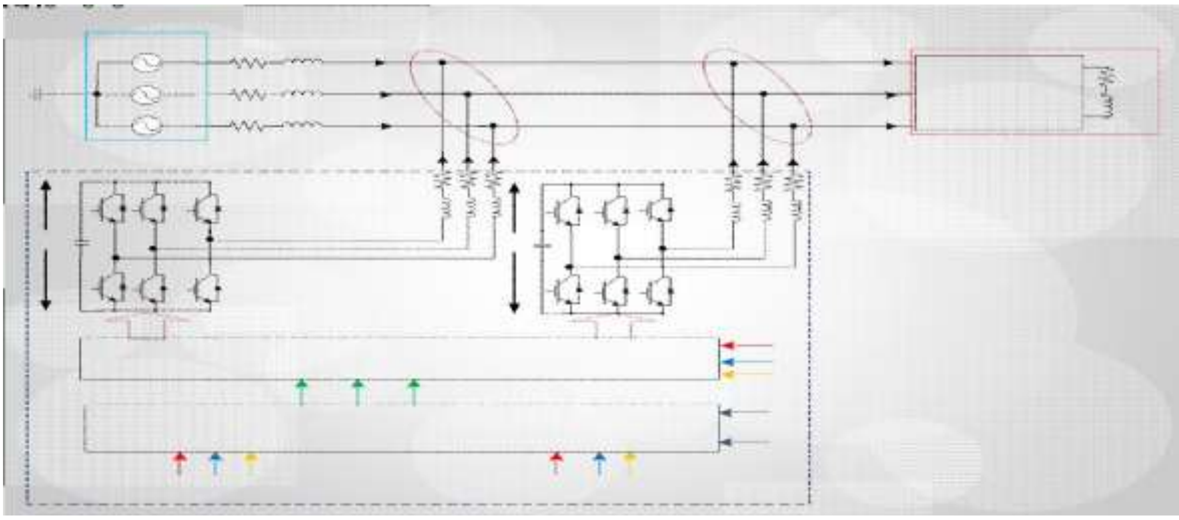

Fig.1: Design of distribution system with different topology based DSTATCOM

2. Instantaneous Reactive Power Theory

Instantaneous reactive power theory was proposed by Akagi et.al. in 1983-84 [24] and it is also called as *pq* theory. To understand *pq* theory one should know $\alpha\beta0$ transformation (also known as the Clarke transformation). One main application of transforming in this theory is to generate reference currents used for control of three phase inverters. The instantaneous supply voltages and load currents in natural *abc* coordinates are transformed into mutually orthogonal $\alpha\beta0$ coordinates and are given as follows, along with definitions of active and reactive powers after transformation.

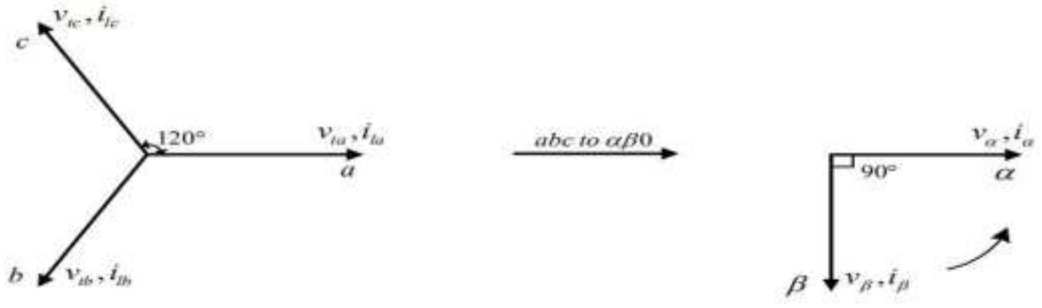

Fig.2: *abc* to $\alpha\beta0$ transformation

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{ta} \\ v_{tb} \\ v_{tc} \end{bmatrix}$$

…………(2.1)

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix}$$

…………..(2.2)

Let the instantaneous real, reactive and zero sequence powers be denoted by *p*, *q* and *p*0 respectively. Then the three phase instantaneous power is given by

p and *q* can be rearranged as following

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad \text{.....} \ (2.3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \quad \text{......} (2.4)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \quad \text{......} \ (2.5)$$

$$p_{3\phi} = v_{ta} i_{ta} + v_{tb} i_{tb} + v_{tc} i_{tc} \quad \text{……….(2.6)}$$

After clark transformation, the instantaneous real power, defined as product of instantaneous voltage on one axis and instantaneous current on the same axis, is given as

$$p_{3\phi} = v_\alpha i_\alpha + v_\beta i_\beta + v_o i_o$$

$$p_{3\phi} = p + p_o \quad \ldots\ldots\ldots\ldots(2.7)$$

The instantaneous reactive power (q) is defined by using cross product of the instantaneous voltage in one axis and the instantaneous current in the other axis. Therefore q is given as

$$q = v_\alpha i_\beta + v_\beta i_\alpha$$
$$= v_\alpha i_\beta - v_\beta i_\alpha \quad \ldots\ldots\ldots\ldots(2.8)$$

Using (2.1) and (2.2), instantaneous reactive power in *abc* coordinates is given as

$$q = -\frac{1}{\sqrt{3}}[(v_a - v_b)i_c + (v_b - v_c)i_a + (v_c - v_a)i_b]$$
$$= -\frac{1}{\sqrt{3}}[v_{ab}i_c + v_{bc}i_a + v_{ca}i_b]$$

$$\ldots\ldots(2.9)$$

The reactive power in 2.9 is proportional to the quantity of energy that is being exchanged between the phases of the system. This implies that q does not contribute to the energy transfer between the source and the load at any time.

From (2.7) and (2.8),The instantaneous power in the α - axis and β - axis are defined as follows.

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha \\ v_\beta i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_{\alpha p} \\ v_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} v_\alpha i_{\alpha q} \\ v_\beta i_{\beta q} \end{bmatrix}$$

$$p = \frac{v_\alpha^2}{v_\alpha^2 + v_\beta^2} p + \frac{v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q + \frac{v_\beta^2}{v_\alpha^2 + v_\beta^2} p + \frac{-v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q \quad \ldots\ldots\ldots\ldots(2.10)$$

$$p = p_{\alpha p} + p_{\alpha q} + p_{\beta p} + p_{\beta q} = p_\alpha + p_\beta$$

Similarly, the reactive power q can be divided into two components corresponding to the products of voltage along α axis and current along β axis and vice versa.

$$q = v_\beta i_\alpha - v_\alpha i_\beta \quad \ldots\ldots\ldots\ldots\ (2.11)$$

From eqns. 2.7and 2.10, the instantaneous three phase active power is given by

$$p_{3\phi} = p_\alpha + p_\beta + p_o \quad \ldots\ldots\ldots(2.12)$$

The instantaneous active and reactive powers consists of two parts, a DC or average value part indicated by overbar (-) and an oscillating component indicated by overtilde. These can be written as follows

$$p = \bar{p} + \tilde{p}$$

$$q = \bar{q} + \tilde{q}$$

$$p0 = \bar{p}0 + \tilde{p}0 \ldots\ldots\ldots\ldots\ldots\ (2.13)$$

Now, the load powers that can be compensated in terms of $\alpha\beta0$ coordinates are $\tilde{p}l$, $\bar{q}l$, $\tilde{q}l$ and $p0 = \bar{p}0 + \tilde{p}0$. Let us assume that the compensator supplies complete reactive power required by the load. Thus compensator reactive power is given as

$$q_f = q_1 \quad \ldots\ldots\ldots..(2.14)$$

Similarly, instantaneous active power supplied by the compensator to the load is

$$pf = \tilde{p}l + \bar{p}0 \ldots\ldots\ldots(2.15)$$

The reference currents for the compensator using (2.5), can be written as

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_f \\ q_f \end{bmatrix} \ldots\ldots\ldots(2.16)$$

Using (3.1), (3.2) and (3.3), the reference filter currents in $\alpha\beta0$ frame is given as

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}_l + \bar{p}_o \\ q_l \end{bmatrix} \quad (2.17)$$

The reference filter currents in *abc* phase system can be obtained using inverse Clark transformation and is given as

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fo} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \sqrt{3}/2 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\sqrt{3}/2 & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fo} \end{bmatrix} \quad (2.18)$$

For a practical compensator, switching and ohmic losses are considered. These losses should be met from the source in order to maintain the dc link voltage constant. Let these losses are denoted by P_{loss}, then the following formulation is used to include this term.

$\Delta\bar{p} = \bar{p}_{l0} + P_{loss}$ ………(2.19)

Compensator supplied power equations after including power loss component

$p_{f0} = p_{l0}$

$p_{f\alpha\beta} = \tilde{p}_{l\alpha\beta} - \Delta\bar{p}$

$q_{f\alpha\beta} = q_{l\alpha\beta}$

………..(2.20)

Once these compensator powers are obtained, compensator currents are computed. Inverse clark transformation to these currents results in abc frame using equations 2.18 and 2.19. Once reference currents are generated they have to be synthesized by voltage source inverter (VSI). To synthesize, switching pulses are required. Required pulses are generated using control scheme explained above.

3. Theory of Instantaneous Symmetrical Components

The theory of instantaneous symmetrical components can be used for the purpose of load balancing, harmonic suppression, and power factor correction [2], [4]. The control algorithms based on instantaneous symmetrical component theory can practically compensate any kind of unbalance and harmonics in the load, provided we have a high bandwidth current source to track the filter reference currents. Any three phase quantity can be divided into positive, negative and zero sequence component.

$$i_{fa}^{*} = i_{la} - i_{sa}^{*} = i_{la} - \frac{(v_{sa} - v_0) + \gamma(v_{sb} - v_{sc})}{\Delta_1}(P_{lavg} + P_{loss})$$

$$i_{fb}^{*} = i_{lb} - i_{sb}^{*} = i_{lb} - \frac{(v_{sb} - v_0) + \gamma(v_{sc} - v_{sa})}{\Delta_1}(P_{lavg} + P_{loss})$$

$$i_{fc}^{*} = i_{lc} - i_{sc}^{*} = i_{la} - \frac{(v_{sc} - v_0) + \gamma(v_{sa} - v_{sb})}{\Delta_1}(P_{lavg} + P_{loss}).$$

The term P_{lavg} is obtained using simple moving average filter and P_{loss} is obtained from the PI controller. The error between DC voltage reference and actual DC voltage are processed through PI controller to obtain P_{loss}. This will control the DC link voltage by adjusting the small amount of real power absorbed by the inverter of DSTATCOM. This small amount of real power is adjusted by changing the amplitude of the fundamental component of the reference current. The AC source provides some active current to recharge the DC capacitor. Thus, in addition to reactive and harmonic components, the reference current of the DSTATCOM has to contain some amount of active current as compensating current. This active compensating current flowing through the shunt active filter, regulates the DC capacitor voltage. When the source voltages are balanced$v_0 = 0$ in the above equations.

4. MATLAB RESULTS AND DISCUSSION

This section includes simulation results of Compensating power quality issues using reference quantities generation theories. Tabulated values have been considered for all the simulations. All the simulations are done in MATLAB/Simulink environment and schematic is shown in 2.5

Fig. 3.2 illustrates currents drawn by load and supplied by source without any compensating devices. It is observed that source currents are not balanced and sinusoidal as load consists of both linear and non-linear loads. The total harmonic distortion (THD) of source waveforms are in the range of 11.3% - 14.8%. But, allowable THD in power system is 5% according to IEEE std 1547 [27]. Therefore, compensation is required, which is achieved in simulations by using above mentioned theories.

Fig 3.2 represents compensation achieved using *pq* theory. It is observed that source currents supplied by the source are sinusoidal and THD is 0.79% in all the three phases. It is also observed that waveforms of load currents are as desired and harmonics are supplied by compensator which is shown in fig 3.1. Although *pq* theory is able to compensate the power quality issues but it has some setbacks. If the nature of load is linear and harmonics are absent, still resolutions of active and reactive components of the current based on *pq* theory gives harmonics. Source currents majorly consists of third harmonic which is not possible for linear loads. Also, instantaneous reactive power $q(t)$ as defined by *pq* theory does not really identify the power properties of load instantaneously.

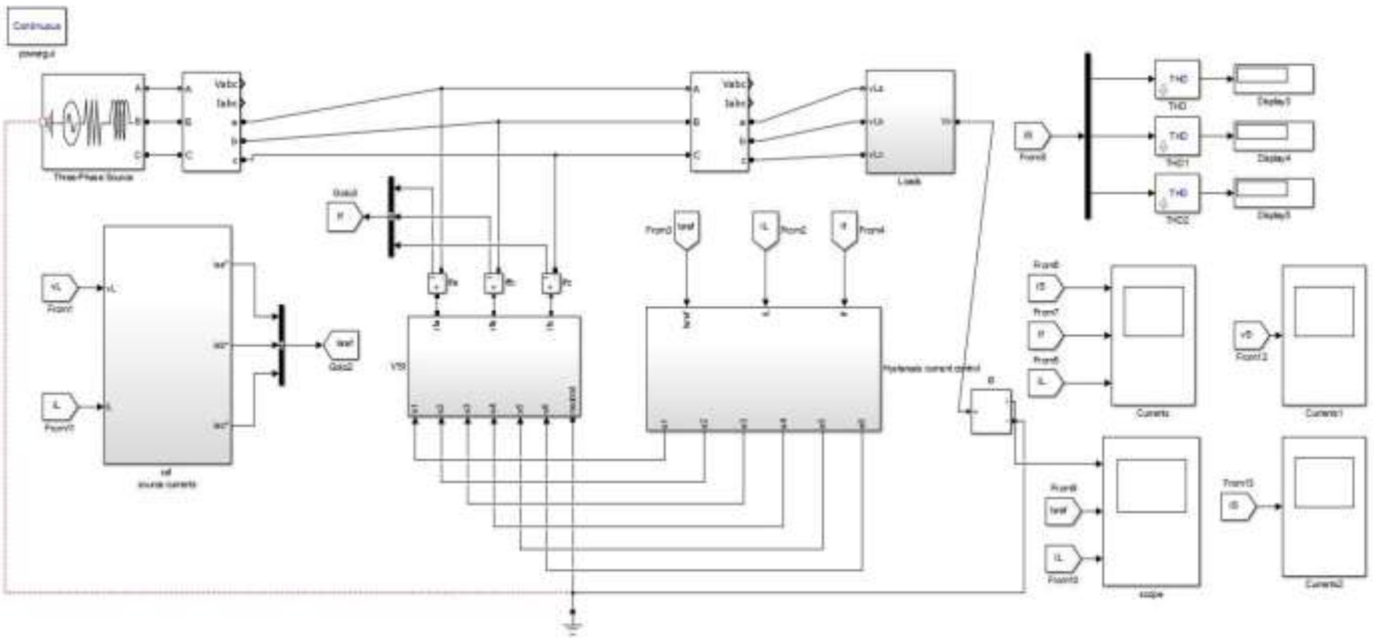

Fig3: Simulation diagram

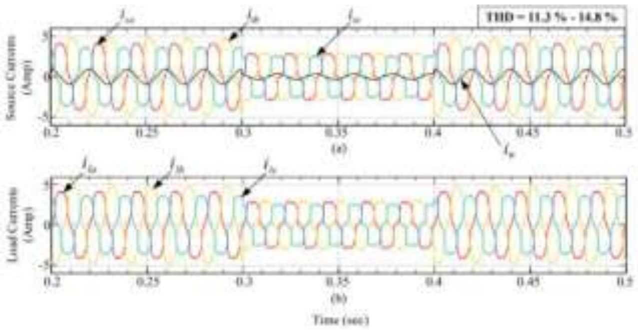

Fig.3.1 Simulation results before compensation (a) Source currents before compensation, (b) Load currents before compensation

Both powers $p(t)$ and $q(t)$ are time varying quantities, so that apair of their values at any single point of time does not identify the power properties of load . Thus it is observed that *pq* theory is unable to achieve complete compensation. Hence symmetrical component theory is considered and used widely. Compensation achieved by using symmetrical component theory is shown in fig 3.1. It is observed that waveforms are balanced, sinusoidal and harmonic free. Neutral current is very close to zero as balanced currents are supplied by source. The THD value of source waveforms are 0.27%.

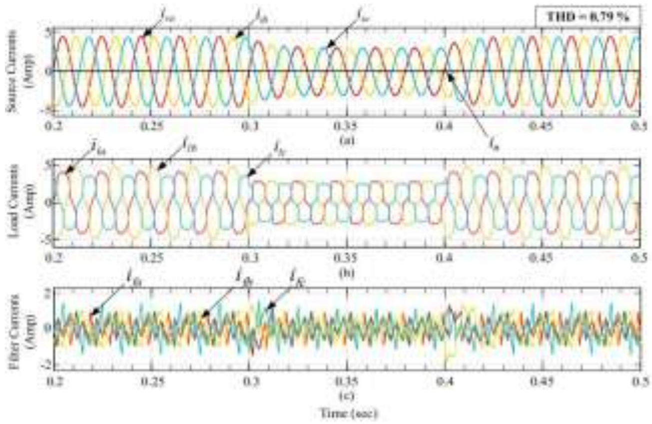

Fig.3.2 Simulation results of compensation using *pq* theory (a) source currents after compensation, (b) load currents after compensation, (c) injected filter currents

Thus compensation using symmetrical component theory is achieved with almost unity power factor. The above simulation studies represents current compensation which is achieved by DSTATCOM is shown.

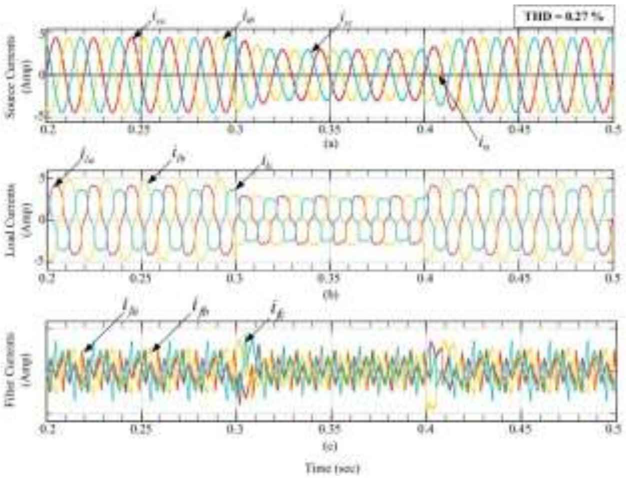

Fig3.3 Simulation results of compensation using symmetrical component theory (a) Source currents after compensation, (b) Load currents after compensation, (c) Injected filter currents

5. CONCLUSION

The extensive use of power electronic loads and unbalanced loads in power system has deteriorated power quality. Some of the power quality issues are voltage/current unbalance, distortion, voltage sag/swell, fluctuations and frequency variation. To overcome this effects passive filters were used but due to their inability to compensate harmonics, custom power devices have emerged. Among the custom power devices, DSTATCOM for current related problems and DVR for voltage related problems are used popularly. Compensation of current related power quality issues, simulations are done in MATLAB/Simulink environment. Compensation achieved by custom power devices in simulations is explained by dividing into three major blocks such as topology and design of VSI, reference signal generation and synthesization of switching pulses. A Neutral clamp inverter topology has been chosen for VSI because of its independent control, less number of switches and path for zero sequence. Hysteresis controller has been used for synthesizing switching pulses which are given as input to VSI switches. This controller was preferred in this work because of fast dynamic response, zero magnitude/phase error, independent of system parameters and ease of implementation. For reference signal generation in-phase compensation was used in DVR while in case of DSTATCOM *pq* theory and instantaneous symmetrical component theory have been used.

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