Dynamic performance of DSTATCOM for power quality improvement under nonlinear loads

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***Abstract*:** **This paper presents an implementation of a three phase distribution static compensator (DSTATCOM) using a back propagation (BP) control algorithm for its functions such as harmonic elimination, load balancing and reactive power compensation for power factor correction, and zero voltage regulation under nonlinear loads. A feedforward control algorithm is used for the extraction of the fundamental weighted value of active and reactive power components of load currents which are required for the estimation of reference source currents. A prototype of DSTATCOM is developed using a digital signal processor, and its performance is studied under various operating conditions. The performance of DSTATCOM is found to be satisfactory with the proposed control algorithm for various types of loads. A DSTATCOM is proposed for compensation of reactive power and unbalance caused by various loads in distribution system.**

Keywords: **DSTATCOM, reactive power compensation, voltage unbalance, weights, harmonic elimination, load balancing..**

I. INTRODUCTION

The quality of available power has a direct economic impact on industrial and domestic sectors which affects the growth of any nation. This issue is more serious in electronic based systems. The level of harmonics and reactive power demand are popular parameters that specify the degree of distortion and reactive power demand at a particular bus of the utility. The harmonic resonance is one of the most common problems reported in low- and medium-level distribution systems. It is due to capacitors which are used for power factor correction (PFC) and source impedance.

Power converter-based custom power devices (CPDs) are useful for the reduction of power quality problems such as PFC, harmonic compensation, voltage sag/swell compensation, resonance due to distortion, and voltage flicker reduction within specified international standards. These CPDs include the distribution static compensator (DSTATCOM), dynamic voltage restorer, and unified power quality conditioner in different configurations. Some of their new topologies are also reported in the literature such as the indirect matrix converter-based active compensator where the dc-link capacitor can be removed. Other new configurations are based on stacked multicell converters where the main features are on the increase in the number of output voltage levels, without transformer operation and natural self-balancing of flying capacitor voltage, etc.. The performance of any custom power device depends very much upon the control algorithm used for the reference current estimation and gating pulse generation scheme. Some of the classical control algorithms are the Fryze power theory, Budeanu theory, p-q

theory and SRF theory, Lyapunov-function-based control and nonlinear control technique, etc.

The extraction of harmonic components decides the performance of compensating devices. The algorithm which trained the sample can detect the signal of the power quality problem in real time. Its simulation study for harmonic detection is presented. Many neural network-based algorithms are reported with theoretical analysis in single phase system, but their implementation to DSTATCOM is hardly reported in the available literature.

II. SYSTEM CONFIGURATION AND CONTROL ALGORITHM

The VSC based DSTATCOM is connected through three phase ac mains to three phase non linear loads with internal grid impedence which is as shown in figire 1. The performance of DSTATCOM depends upon the accuracy of harmonic current detection. For reducing ripple in compensating currents, the tuned values of interfacing inductors (L_f) are connected at the ac output of the VSC. A three phase series combination of capacitor (C_f) and a resistor (R_f) represents the shunt passive ripple filter which is connected at a point of common coupling (PCC) for reducing the high frequency switching noise of the VSC. The DSTATCOM currents (i_{Cabc}) are injected as required compensating currents to cancel the reactive power components and harmonics of the load currents so that loading due to reactive power component/ harmonics is reduced on the distribution system. For the considered three phase nonlinear load with approximately 24 kW, the compensator data are given in Appendix A.
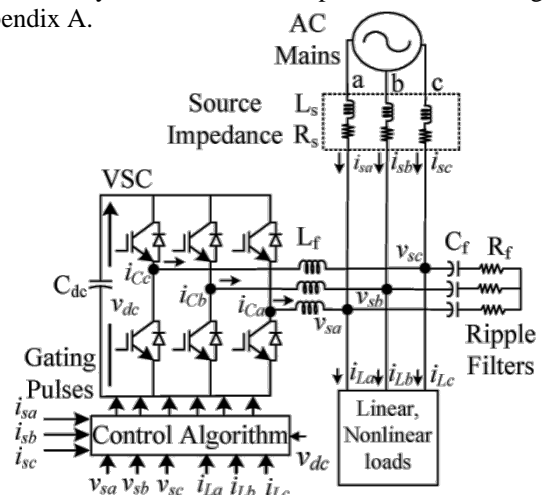

Fig. 1. Schematic diagram of VSC based DSTATCOM

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Fig. 2 shows the block diagram of the training algorithm for the estimation of reference source currents through the weighted value of load active power and reactive power current components. In this algorithm, the phase PCC voltages (v_{sa}, v_{sb}, and v_{sc}), source currents (i_{sa}, i_{sb}, and i_{sc}), load currents (i_{La}, i_{Lb}, and i_{Lc}) and dc bus voltage (v_{dc}) are required for the extraction of reference source currents (i^*_{sa}, i^*_{sb}, and i^*_{sc}). There are two primary modes for the operation of this algorithm: The first one is a feedforward, and the second is the BP of error or supervised learning. The detail application of this algorithm for the estimation of various control parameters is given as follows.

A. Estimation of Weighted Value of Average Fundamental Load Active and Reactive Power Components

A algorithm is used to estimate the three phase weighted value of load active power current components (w_{ap}, w_{bp}, and w_{cp}) and reactive power current components (w_{aq}, w_{bq}, and w_{cq}) from polluted load currents using the feedforward and supervised principle. In this estimation, the input layer for three phases (a, b, and c) is expressed as

$$I_{Lap} = w_o + i_{La}u_{ap} + i_{Lb}u_{bp} + i_{Lc}u_{cp} \tag{1}$$

$$I_{Lbp} = w_o + i_{Lb}u_{bp} + i_{Lc}u_{cp} + i_{La}u_{ap} \tag{2}$$

$$I_{Lcp} = w_o + i_{Lc}u_{cp} + i_{La}u_{ap} + i_{Lb}u_{bp} \tag{3}$$

where w_o is the selected value of the initial weight and u_{ap}, u_{bp}, and u_{cp} are the in-phase unit templates.

In-phase unit templates are estimated using sensed PCC phase voltages (v_{sa}, v_{sb}, and v_{sc}). It is the relation of the phase voltage and the amplitude of the PCC voltage (v_t). The amplitude of sensed PCC voltages is estimated as

$$v_t = \sqrt{\frac{2\left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2\right)}{3}}. \tag{4}$$

The inphase unit templates of PCC voltages u_{ap}, u_{bp} and u_{cp} are estimated as

$$u_{ap} = \frac{v_{sa}}{v_t}, \quad u_{bp} = \frac{v_{sb}}{v_t}, \quad u_{cp} = \frac{v_{sc}}{v_t}. \tag{5}$$

The extracted values of ILap, ILbp and ILcp are passed

through a sigmoid function as an activation function, and the output signals of feedforward section (Zap,Zbp and Zcp) are

expressed as

$$Z_{ap} = f(I_{Lap}) = 1/(1 + e^{-ILap}) \tag{6}$$

$$Z_{bp} = f(I_{Lbp}) = 1/(1 + e^{-ILbp}) \tag{7}$$

$$Z_{cp} = f(I_{Lcp}) = 1/(1 + e^{-ILcp}). \tag{8}$$

Where wo1,wap,wbp and wcp are the selected values of initial weights in the hidden layer and the updated values of three phase weights using the average weighted value(wp) of the active power current component as a feedback signal, respectively.

The updated weight of phase "a" active power current components of load current "wap" at the nth sampling instant is expressed as

$$w_{ap}(n) = w_p(n) + \mu \left\{w_p(n) - w_{ap1}(n)\right\} f'(I_{ap1})z_{ap}(n) \tag{12}$$

Where wp(n) and wap(n) are the average weighted value of active power component of load currents and the updated weighted values of phase "a" at the nth sampling instant, respectively , and wap1(n) and Zap(n) are the phase "a" fundamental weighted amplitude of the active power component of the load current and output of feedforward section of the algorithm at the nth instant, respectively, f'(Iap1) and μ are represented as the derivative of Iap1 component and the learning rate.

Similarly for phase "b" and phase "c", the updated weighted values of the active power current components and the load current are expressed as

$$w_{bp}(n) = w_p(n) + \mu \left\{w_p(n) - w_{bp1}(n)\right\} f'(I_{bp1})z_{bp}(n) \tag{13}$$

$$w_{cp}(n) = w_p(n) + \mu \left\{w_p(n) - w_{cp1}(n)\right\} f'(I_{cp1})z_{cp}(n). \tag{14}$$

The extracted values of Iap1, Ibp1, and Icp1 are passed through a sigmoid function as an activation function to the estimation of the fundamental active components in terms of three phase weights wap1, wbp1 and wcp1 as

$$w_{ap1} = f(I_{ap1}) = 1/(1 + e^{-Iap1}) \tag{15}$$

$$w_{bp1} = f(I_{bp1}) = 1/(1 + e^{-Ibp1}) \tag{16}$$

$$w_{cp1} = f(I_{cp1}) = 1/(1 + e^{-Icp1}). \tag{17}$$

The average weighted amplitude of the fundamental active power components (wp) is estimated using the amplitude sum

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of three phase load active power components (wap1,wbp1 and wcp1) divided by three. It is required to realize load balancing features of DSTATCOM. Mathematically it is expressed as

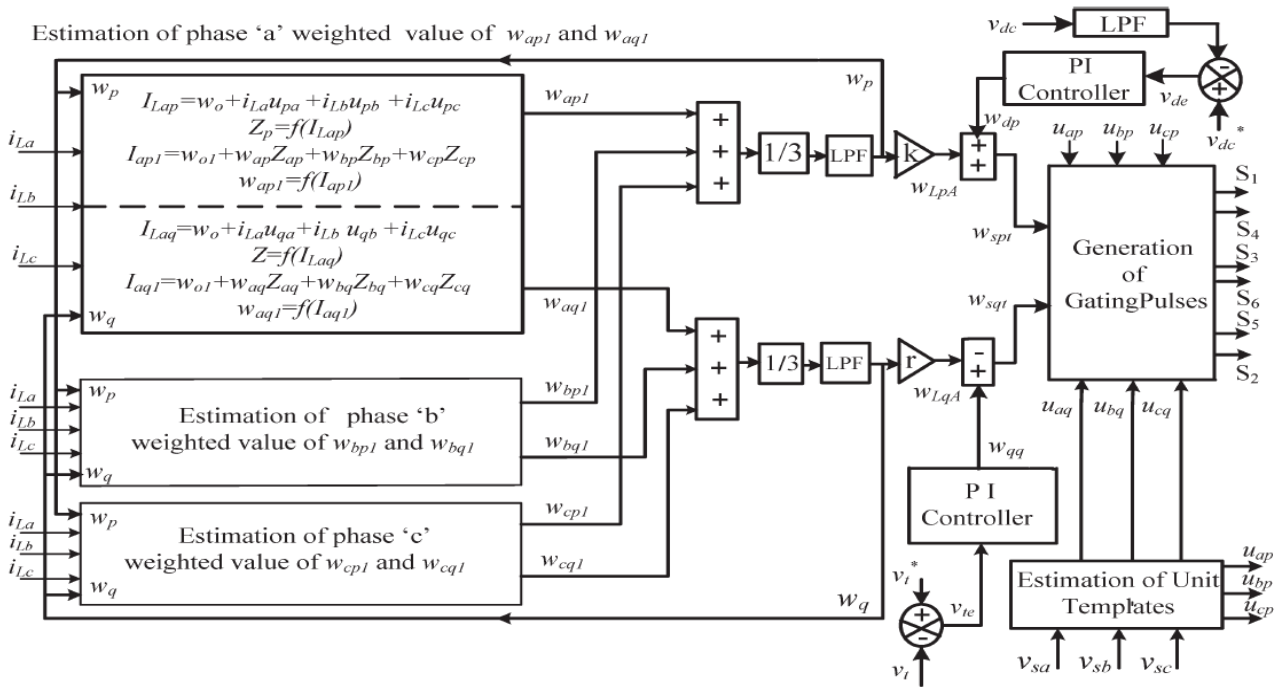$$w_p = (w_{ap1} + w_{bp1} + w_{cp1})/3. \qquad (18)$$

Fig. 2. Estimation of reference currents using BP control algorithm

First order low pass filters are used to separate the low frequency components. "k" denotes the scaled factor of extracted active power components of current in the algorithm which is shown in fig. 2. After separating the low frequency components and scaling to the actual value because the output of activation function is between 0 and 1, it is represented as wLpA.

Similarly the weighted amplitudes of reactive power components of the load currents (waq,wbq, and wcq) of the fundamental load current are extracted as

$$I_{Laq} = w_o + i_{La}u_{aq} + i_{Lb}u_{bq} + i_{Lc}u_{cq} \qquad (19)$$

$$I_{Lbq} = w_o + i_{Lb}u_{bq} + i_{Lc}u_{cq} + i_{La}u_{aq} \qquad (20)$$

$$I_{Lcq} = w_o + i_{Lc}u_{cq} + i_{La}u_{aq} + i_{Lb}u_{bq} \qquad (21)$$

Where wo is the selected value of the initial weight and uaq, ubq and ucq are the quadrature components of the unit template.

The quadrature unit templates (uaq,ubq and ucq) of the phase PCC voltage are estimated as

$$u_{aq} = \frac{(-u_{bp} + u_{cp})}{\sqrt{3}}, \quad u_{bq} = \frac{(3u_{ap} + u_{bp} - u_{cp})}{2\sqrt{3}}$$

$$u_{cq} = \frac{(-3u_{ap} + u_{bp} - u_{cp})}{2\sqrt{3}}. \qquad (22)$$

The extracted values of ILaq, ILbq and ILcq are passed through a sigmoid function as an activation function to the estimation of Zaq,Zbq and Zcq

$$Z_{aq} = f(I_{Laq}) = 1/(1 + e^{-ILaq}) \qquad (23)$$

$$Z_{bq} = f(I_{Lbq}) = 1/(1 + e^{-ILbq}) \qquad (24)$$

$$Z_{cq} = f(I_{Lcq}) = 1/(1 + e^{-ILcq}). \qquad (25)$$

The estimated values of Zaq, Zbq and Zcq are fed to the hidden layer as input signals. The three phase outputs of this

layer (Iaq1,Ibq1, and Iq1) before the activation function can be represented as

$$I_{aq1} = w_{o1} + w_{aq}Z_{aq} + w_{bq}Z_{bq} + w_{cq}Z_{cq} \qquad (26)$$

$$I_{bq1} = w_{o1} + w_{bq}Z_{bq} + w_{cq}Z_{cq} + w_{aq}Z_{aq} \qquad (27)$$

$$I_{cq1} = w_{o1} + w_{cq}Z_{cq} + w_{aq}Z_{aq} + w_{bq}Z_{bq} \qquad (28)$$

Where wo1,waq, wbq, and wcq are the selected value of the initial weight in the hidden layer and the updated three weights using the average weighted value of the reactive power components of currents (wq) as a feedback signal, respectively.

The updated weight of the phase "a" reactive power components of load currents "waq" at the nth sampling instant is expressed as

$$w_{aq}(n) = w_q(n) + \mu \left\{ w_q(n) - w_{aq1}(n) \right\} f'(I_{aq1}) z_{aq}(n) \tag{29}$$

Wq(n) and waq(n) are the average weighted value of the reactive power component of load currents and the updated weight in the nth sampling instant, respectively, and waq1(n) and zaq(n) are the phase "a" weighted amplitude of the reactive power current component of load currents and the output of the feedforward section of the algorithm at the nth instant, respectively. F'(Iaq1) and μ are presented as the derivative of Iaq1 components and the learning rate.

Similarly for phase "b" and "c" the updated weighted values of the reactive power current components of the load current are expressed as

$$w_{bq}(n) = w_q(n) + \mu \left\{ w_q(n) - w_{bq1}(n) \right\} f'(I_{bq1}) z_{bq}(n) \tag{30}$$

$$w_{cq}(n) = w_q(n) + \mu \left\{ w_q(n) - w_{cq1}(n) \right\} f'(I_{cq1}) z_{cq}(n). \tag{31}$$

The extracted values of Iaq1, Ibq1 and Icq1 are passé through an activation function to the estimation of the fundamental reactive component in terms of three phase weights waq1, wbq1 and wcq1 as

$$w_{aq1} = f(I_{aq1}) = 1/(1 + e^{-Iaq1}) \tag{32}$$

$$w_{bq1} = f(I_{bq1}) = 1/(1 + e^{-Ibq1}) \tag{33}$$

$$w_{cq1} = f(I_{cq1}) = 1/(1 + e^{-Icq1}). \tag{34}$$

The average weight of the amplitude of the fundamental reactive power current components(wq) is estimated using the amplitude sum of the three phase load reactive power component of the load current (waq1,wbq1 and wcq1) divided by three. Mathematically it is expressed as

$$w_q = (w_{aq1} + w_{bq1} + w_{cq1})/3. \tag{35}$$

First order low pass filters are used to separate the low frequency component. "r" denotes the scaled factor of the extracted reactive power components in the algorithm which is shown in fig 2. After separating low frequency components and scaling to the actual value because the output of the activation function is between 0 and 1, it is represented as wLqA.

B. Amplitude Of Active Power Current Components Of Reference Source Currents

An error in the dc bus voltage is obtained after comparing the reference dc bus voltage v*dc and the sensed dc bus voltage vdc of a VSC, anad this error at the nth sampling instant is expressed as

$$v_{de}(n) = v_{dc}^*(n) - v_{dc}(n). \tag{36}$$

This voltage error is fed to a PI controller whose output is

required for maintaining the dc bus voltage of the DSTATCOM. At the nth sampling instant, the output of the PI controller is as follows:

$$w_{dp}(n) = w_{dp}(n-1) + k_{pd} \left\{ v_{de}(n) - v_{de}(n-1) \right\} + k_{id}\, v_{de}(n) \tag{37}$$

Where kpd and kid are the proportional and integral gain constants of the dc bus PI controller. Vde(n) and vde(n-1) are the dc bus voltage errors in the nth and (n-1)th instant, and wdp(n) and wdp(n-1) are the amplitude of the active power component of the fundamental reference current at the nth and (n-1)th instant, respectively.

The amplitude of the active power current components of the reference source currnet(wspt) is estimated by the addition of output of the dc bus PI controller (wdp) and the average magnitude of the load active currents (wLpA) as

$$w_{spt} = w_{dp} + w_{LpA}. \tag{38}$$

C. Amplitude of Reactive Power Components of Reference Source Currents

An error in the ac bus voltage is achieved after comparing the amplitudes of the reference ac bus voltage $v_t{}^*$ and the sensed ac bus voltage v_t of a VSC. The extracted ac bus voltage error v_{te} at the nth sampling instant is expressed as

$$v_{te}(n) = v_t^*(n) - v_t(n). \tag{39}$$

The weighted output of the ac bus PI controller wqq for regulating the ac bus terminal voltage at the nth sampling instant is expressed as

$$w_{qq}(n) = w_{qq}(n-1) + k_{pt} \left\{ v_{te}(n) - v_{te}(n-1) \right\} + k_{it}\, v_{te}(n) \tag{40}$$

where $w_{qq}(n)$ is part of the reactive power component of the source current and it is renamed as w_{qq}. k_{pt} and k_{it} are the proportional and integral gain constants of the ac bus voltage PI controller.

The amplitude of the reactive power current components of the reference source current (w_{sqt}) is calculated by subtracting the output of the voltage PI controller (w_{qq}) and the average load reactive currents (w_{LqA}) as

$$w_{sqt} = w_{qq} - w_{LqA}. \tag{41}$$

D. Estimation of Reference Source Currents and Generation of IGBT Gating Pulses

Three phase reference source active and reactive current components are estimated using the amplitude of three phase (a, b, and c) load active power current components, PCC voltage in-phase unit templates, reactive power current

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components, and PCC quadrature voltage unit templates as

$$i_{sap} = w_{spt}\, u_{ap}, i_{sbp} = w_{spt}\, u_{bp}, i_{scp} = w_{spt}\, u_{cp} \quad (42)$$

$$i_{saq} = w_{sqt}\, u_{aq}, i_{sbq} = w_{sqt}\, u_{bq}, i_{scq} = w_{sqt}\, u_{cq}. \quad (43)$$

The addition of reference active and reactive current components is known as reference source currents, and these are given as

$$i_{sa}^* = i_{sap} + i_{saq}, \quad i_{sb}^* = i_{sbp} + i_{sbq}, \quad i_{sc}^* = i_{scp} + i_{scq}. \quad (44)$$

The sensed source currents (i_{sa}, i_{sb}, i_{sc}) and the reference source currents (i_{sa}^*, i_{sb}^*, i_{sc}^*) are compared, and current error signals are amplified through PI current regulators; their outputs are fed to a pulse width modulation (PWM) controller to generate the gating signals for insulated-gate bipolar transistors (IGBTs) S_1 to S_6 of the VSC used as a DSTATCOM.

III. SIMULATION RESULTS AND DISCUSSION

MATLAB with SIMULINK and Sim Power System tool boxes is used for the development of the simulation model of a DSTATCOM and its control algorithm. The performance of the control algorithm is observed under non linear loads. The proposed work is intended to achieve minimized losses in the distribution system. Here data is collected from the standard IEEE data and the allowable harmonic resonance of 5% is also verified. A prototype of DSTATCOM is developed using a digital signal processor, and its performance is studied under various operating conditions. The performance of DSTATCOM is found to be satisfactory with the proposed control algorithm for various types of loads. A Distribution STATic COMpensator (DSTATCOM) is proposed for compensation of reactive power and unbalance caused by various loads in distribution system

In order to find the best suitable control characteristics synchronous detection algorithm is used. The simulation model for load balancing and reactive power compensation is as shown in the figures below. The resulting waveform can be seen in the figures below. The allowable limits as in IEEE standards for harmonic elimination is 5% and this can be observed using the above waveforms.
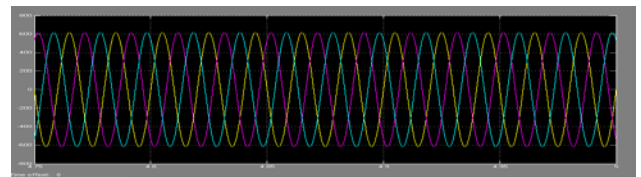

(a)
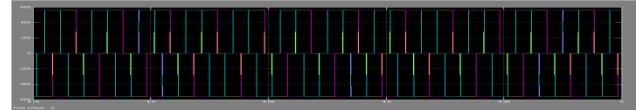
(b)
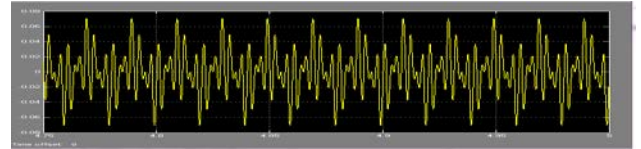
(c)

(d)

Fig 3: performance of DSTATCOM for harmonic elimination

Fig 3(a) shows the source voltage which is approximately 338.8 when the values in the appendix are considered. Fig 3(b) shows the source current which contains harmonics when load is connected. This could be eliminated by connecting the DSTATCOM across the load. Fig 3(c) shows the harmonic component which is estimated using the algorithm, this has to be eliminated. Hence the balanced load current when DSTATCOM is connected is as shown in fig 3(d). These results shows the harmonics elimination when DSTATCOM is connected.
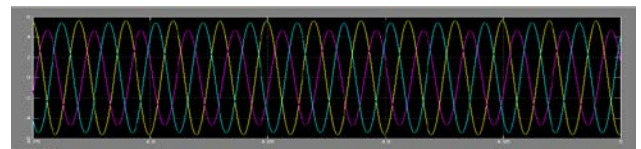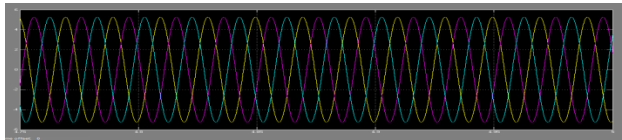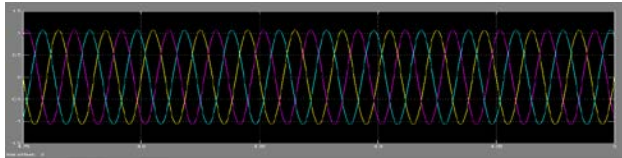

(a)
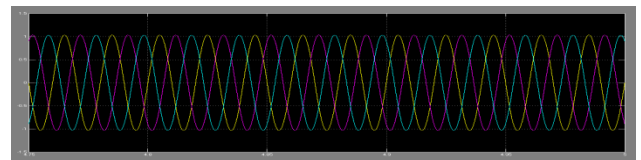
(b)

Fig 4: load balancing with and without DSTATCOM

Fig 4(a) shows the unbalanced load when DSTATCOM is not connected and fig 4(b) represents the source current when DSTATCOM is connected across the PCC. From the above figures we can observe the load balancing is done when DSTATCOM is connected.

(a)

(b)

Fig 4: performance of DSTATCOM for reactive power compensation

Fig 4(a) represents the active power uncompensated which has a magnitude of 5 units thus when DSTATCOM is connected, the active current component will be reduced to 1.029 units. This shows the reactive power compensation which could be done using DSTATCOM.

IV. CONCLUSION

In this work, a fast and cost effective Distribution STATCOM (DSTATCOM) is proposed for mitigating the problem of harmonic elimination, load balancing and reactive power compensation is done in order to mitigate power quality problems. A controller which is based on feed foreword technique is used which utilizes the error signal which is the difference between the reference current and actual measured load current to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. It is clear from the results that the power quality of the system with RL load as in IEEE data can be compensated effectively using the control algorithm and DSTATCOM.

APPENDIX

AC supply source: three-phase, 415 V (L-L), 50 Hz. Source impedance: R_s = 0.04 Ω and L_s = 2 mH. Nonlinear: three phase full bridge uncontrolled rectifier with R = 13 Ω and L = 200 mH. Rating of VSC = 10 kVA (approximately 30% higher than the rated value). Ripple filter: R_f = 5 Ω and C_f = 10 μF. Switching frequency of inverter = 10 kHz. Reference dc bus voltage: 700 V. Interfacing inductor (L_f) = 2.75 mH. Gains of PI controller for dc bus voltage: k_{pd} = 3.1 and k_{id} = 0.9. Gains of voltage PI controller: k_{pt} = 2.95 and k_{it} = 4. Selected initial weights: w_o = 0.4 and w_{o1} = 0.2. Learning rate (μ) = 0.6. Cutoff frequency of low-pass filter used in dc bus voltage = 15 Hz. Cutoff frequency of low-pass filter used in ac bus voltage = 10 Hz.

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