Power Quality Improvement in Distribution System by Using DSTATCOM with Predictive ANN

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Abstract: This paper presents a control algorithm based on enhanced phase-locked loop (EPLL) for distribution static compensator (DSTATCOM) to compensate reactive power, to provide load balancing, to eliminate harmonics, to correct power factor, and to regulate point of common coupling (PCC) voltages under linear and nonlinear loads. In this approach, an extraction of fundamental active and reactive power components of load current for the estimation of source currents includes a signal-processing algorithm based on the EPLL scheme. The proposed control algorithm is implemented using a digital signal processor. Test results on a developed DSTATCOM are presented to validate the proposed control algorithm for compensation of reactive power, load balancing, harmonics elimination, power factor correction, and zero voltage regulation at PCC. A DSTATCOM injects a current into the system to provide for the reactive component of the load current. The validity of proposed method and achievement of desired compensation are confirmed by the results of the simulation in MATLAB/ Simulink.

Keywords: Distribution static compensator (DSTATCOM), enhanced phase-locked loop (EPLL), load balancing, reactive power compensation, zero voltage regulation (ZVR).

I. INTRODUCTION

Three-phase four-wire distribution systems are facing severe power quality problems such as poor voltage regulation, high reactive power and harmonics current burden, load unbalancing, excessive neutral current, etc. Three-phase four-wire distribution systems are used in commercial buildings, office buildings, hospitals, etc. Most of the loads in these locations are nonlinear loads and are mostly unbalanced loads in the distribution system. This creates excessive neutral current both of fundamental and harmonic frequency and the neutral conductor gets overloaded. The voltage regulation is also poor in the distribution system due to the unplanned expansion and the installation of different types of loads in the existing distribution system. In order to control the power quality problems, many standards are proposed, such as the IEEE-519 standard.

There are mitigation techniques for power quality problems in the distribution system and the group of devices is known by the generic name of custom power devices (CPDs). The distribution static compensator (DSTATCOM) is a shunt-connected CPD capable of compensating power quality problems in the load current. Some of the topologies of DSTATCOM for three-phase four-wire system for the mitigation of neutral current along with power quality compensation in the source current are four-leg voltage source converter (VSC), three single-phase VSCs, three-leg VSC with split capacitors, three-leg VSC with zigzag transformer and three-leg VSC with neutral terminal at the positive or negative of dc bus. The voltage regulation in the distribution feeder is improved by installing a shunt compensator. There are many control schemes reported in the literature for control of shunt active compensators such as instantaneous reactive power theory, power balance theory, synchronous reference frame theory, symmetrical components based, etc. The synchronous reference frame theory is used for the control of the proposed DSTATCOM.

In this paper, proposed control algorithm based on enhanced phase-locked loop (EPLL) scheme is implemented for compensation of reactive power, harmonics elimination, load balancing in power factor correction (PFC) and zero voltage regulation (ZVR) modes of operation of DSTATCOM in three phase distorted voltage supply system under unbalanced nonlinear loads. The EPLL is used as the basic structure for harmonic and inter harmonic estimation, and several of such sections are arranged together. Each one is adjusted to estimate a single sinusoid waveform. This control algorithm has the following features:

a. It is adaptive in nature and adopts the variations in amplitude, phase angle and frequency of the input signals.
b. Speed and accuracy of its response are under control, and performance is not affected due to noise and distortion.
c. The structure of EPLL is simple due to this reason; its implementation in real time using DSP or any other embedded controllers is easy.
d. It is a continuous time non window-based approach and offers regular adjustment to the frequency variation; also, performance does not depend upon internal parameter settings.

e. It is also able to extract accurate fundamental components from polluted utility or supply systems.
f. It is not affected from the existence of double frequency ripples in the loop.

II. DSTATCOM AND SYSTEM CONFIGURATION

Before going to discuss about DSTATCOM, we need to know about STATCOM.A STATCOM system is nothing but a three phase inverter connected to the grid through a reactor and a connecting transformer. In the three phase inverter instead of a DC battery, a capacitor is used to provide the DC link voltage. A controller is used to control the voltages, phase and the frequency of the STATCOM to maintain synchronism with the grid.

The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across this reactance. The STATCOM is connected in shunt with the power networks at customer side, where the load compensation. All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs closed loop feedback control and outputs a set of switching signals to drive the main semiconductor switches (IGBT's, which are used at the distribution level) of the power converter accordingly. By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled.

In this way the inverter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the capacitor voltage at the desired level. The mechanism of phase angle adjustment can also be used to control the var generation or absorption by increasing or decreasing the capacitor voltage, and thereby the amplitude of the output voltage produced by the inverter. A STATCOM used in the distribution system is generally called as a DSTATCOM.

The DSTATCOM consists of a voltage source converter (VSC) based on self commutating semiconductor valves and a capacitor on the dc bus. This compensating device is connected at point of common coupling (PCC) through interfacing inductances. In general, the functions of DSTATCOM are reactive power compensation, harmonics elimination, along with load balancing in the distribution system in PFC and ZVR modes of operation.

Fig. 1 shows a schematic diagram of a DSTATCOM connected to a three phase ac mains having a source impedance (Rs, Ls) feeding variety of three phase loads. Interfacing inductors (Lf) are used at ac side of the VSC for reducing ripple in compensating currents. A series connected capacitor (Cf) and a resistor (Rf) represent the ripple filter installed at PCC in parallel with the loads and the DSTATCOM to filter the high frequency switching noise of the voltages at PCC. The compensating currents (i_{Ca}, i_{Cb}, i_{Cc}) are injected by DSTATCOM to cancel harmonics/reactive power components of load currents.

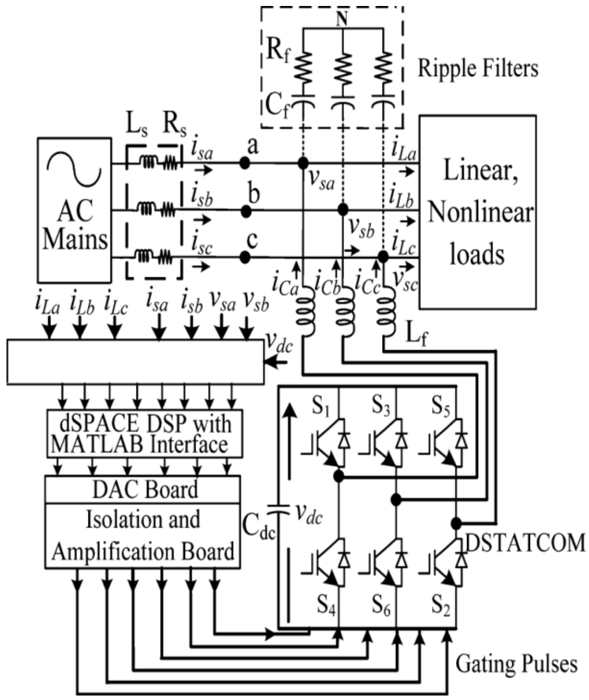


Fig. 1. Schematic diagram of DSTATCOM.

III. CONTROL ALGORITHM OF DSTATCOM

Fig. 2 shows a block diagram of proposed control algorithm based on EPLL scheme for extraction of reference source currents Basic equations for estimation of different control signals of control algorithm are given as.

A. Estimation of In- Phase and Quadrature Unit Voltage Templates

Three phase sensed PCC voltages (Vsa, Vsb, Vsc) may consist of harmonics and negative sequence components. These PCC voltages are processed through band pass filters (BPFs) to filter noise and harmonics. These filtered PCC voltages may also be unbalanced. The individual amplitude of each of these three phase voltages are estimated through squaring them and then processed through low passed filters (LPFs) as follows:

$$v'_{ta}=\sqrt{[2\left(\frac{v_{sa}^2}{2}\right)]}\ ,$$

$$v'_{tb}=\sqrt{\left[2\left(\frac{v_{sb}^2}{2}\right)\right]}\quad and\quad v'_{tc}=\sqrt{[2\left(\frac{v_{sc}^2}{2}\right)]}$$

After processing, these voltages (v'_{ta}, v'_{tb} and v'_{tc}) through LPFs, these are constant valued amplitudes represented as Vta ,Vtb , and Vtc for phases a, b, and c.

Inphase unit templates of PCC voltages are estimated as

$$u_{sap} = \frac{v_{sa}}{V_{ta}} \quad , \quad u_{sbp} = \frac{v_{sb}}{V_{tb}} \quad , u_{scp} = \frac{v_{sc}}{V_{tc}}$$

Moreover, the quadrature unit templates are estimated as

$$u_{saq} = \frac{(-u_{sbp} + u_{scp})}{\sqrt{3}} \quad ,$$

$$u_{sbq} = \frac{(3u_{sap} + u_{sbp} - u_{scp})}{2\sqrt{3}}$$

$$u_{scq} = \frac{(-3u_{sap} + u_{sbp} - u_{scp})}{2\sqrt{3}}$$

The amplitude of PCC voltages is estimated as

$$v'_t = \sqrt{\frac{2(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}{3}}$$

This amplitude v'_t may have ripples because of fundamental negative sequence voltage present in PCC voltages. This v'_t is processed through LPF to achieve amplitude of fundamental positive-sequence PCC voltages and it is represented as for the control of PCC voltages

B. Estimation of Fundamental Active and Reactive Power

Components of Load Currents The fundamental active and reactive power components of load currents are estimated by using proposed control algorithm based on EPLL scheme in each phase. EPLL used in phase ‘a’ receives the input signal as the load current i_{La} . Difference between i_{La} and i_{Lfa} is the total distortion in the applied signal. It is denoted as

C. Estimation of Average Amplitude of Active and Reactive Power Components of Load Currents

The average amplitude of fundamental active and reactive powers components of the three phase load currents are estimated using the amplitude of active and reactive power components of load currents. An average value of amplitudes is estimated for load balancing and to be used in the extraction of three phase reference source current as

$$I_{LpA} = \frac{I_{Lpa} + I_{Lpb} + I_{Lpc}}{3}$$

$$I_{LqA} = \frac{I_{Lqa} + I_{Lqb} + I_{Lqc}}{3}$$

D. Estimation of Amplitude of Active Power Component of Reference Source Currents

To estimate another component of the reference active power component of source currents, the reference dc bus voltage is compared with sensed dc bus voltage of DSTATCOM. The dc bus voltage is regulated through PI (proportional-integral) controller which is required to maintain dc bus voltage. It is represented as Icd . The amplitude of active power component of the reference source current Ispt is estimated as the addition of required active power component of current for the self supporting dc bus of the DSTATCOM and average magnitude of active power components of load currents as

$$I_{spt} = I_{cd} + I_{LqA}$$

E. Estimation of Amplitude of Reactive Power Component of Reference Source Currents

The amplitude of another component of reactive power component of the reference source current is calculated using a voltage PI controller over the amplitude of the PCC voltage V_t and its reference value V_t^*. The voltage error V_{ter} of ac voltage at the sampling instant is given as

$$V_{ter}(r) = V_t^*(r) - V_t(r)$$

The output of the PCC voltage PI controller I_{cq} for regulating PCC voltage to the reference or rated value at the sampling instant is given as

$$I_{cq}(r) = I_{cq}(r-1) + k_{pt}\{V_{ter}(r) - V_{ter}(r-1)\} + k_{it} V_{ter}(r)$$

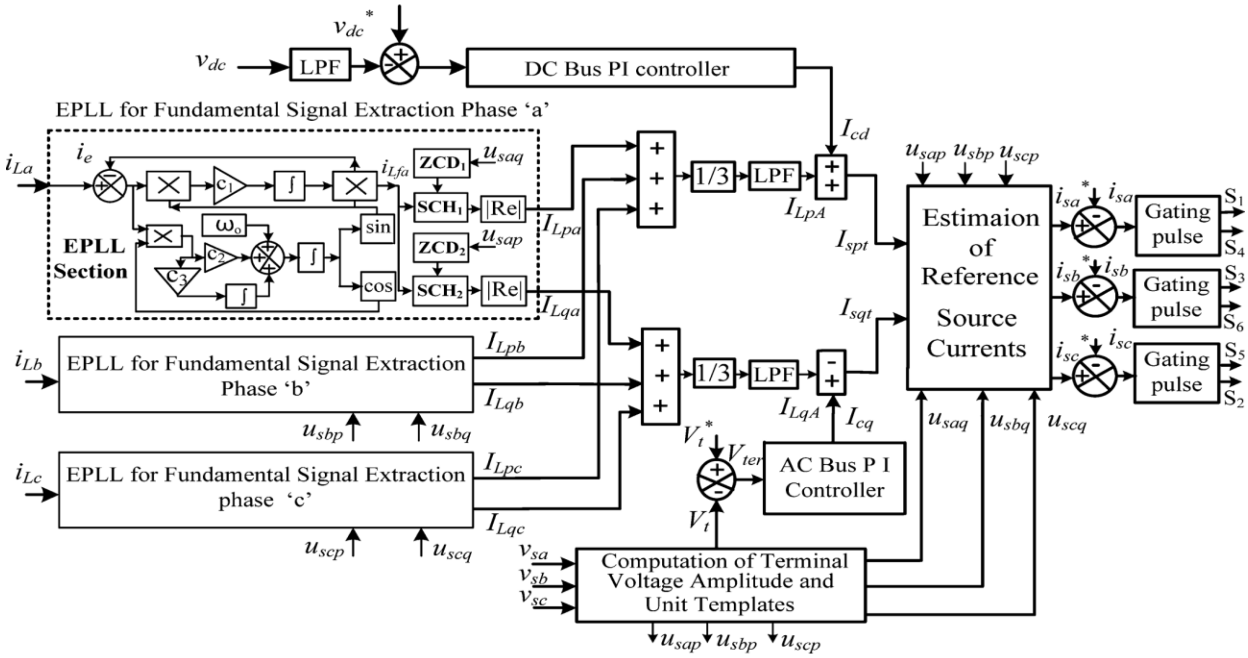


Fig. 2. Generation of reference source currents using the EPLL-based control algorithm

where $I_{cq}(r)$ is a part of the reactive power component of source current and it is named I_{cq}, k_{pt} and k_{it} are the proportional and integral gain constants of the PCC voltage PI controller.

The amplitude of reactive power component of the reference source current I_{spt} is estimated as the difference of output of the voltage PI controller I_{cd} and the average of reactive power component of load currents I_{LqA} as

$$\mathrm{I_{spt}} = \mathrm{I_{cd}} - \mathrm{I_{LqA}}$$

F. Estimation of Reference Source Currents and Generation of Gating Pulses

Three phase reference source currents are estimated using amplitude of active power components of currents, reactive power components of currents, in phase unit voltage templates, and quadrature unit voltage templates. Three phase reference source active and reactive power components of currents are estimated as

$$i_{sap} = I_{spt}\, u_{sap},\ \ i_{sbp} = I_{spt}\, u_{sbp},\ i_{scp} = I_{spt}\, u_{scp}$$

$$i_{saq} = I_{sqt}\, u_{saq},\ \ i_{sbq} = I_{sqt}\, u_{sbq},\ i_{scq} = I_{sqt}\, u_{scq}$$

Total reference source currents are estimated after the addition of reference active and reactive power components of source currents as

$$i_{sa}^{*} = i_{sap} + i_{saq}\ ,\ i_{sb}^{*} = i_{sbp} + i_{sbq}\ ,$$

$$i_{sc}^{*} = i_{scp} + i_{scq}$$

These estimated three phase reference source currents (i_{sa}^{*} ,i_{sb}^{*}, i_{sc}^{*}) are compared with sensed source currents (i_{sa} , i_{sb}, i_{sc}) to estimate the current errors. Using PI controllers, these current errors are amplified and outputs of PI current controllers are compared with carrier signals to generate PWM pulses for switching devices insulated-gate bipolar transistors (IGBTs) (S1 to S6) of VSC.

IV. RESULTS AND DISCUSSION

A prototype of DSTATCOM is developed in the laboratory using a VSC. For sensing the currents and voltages signals, ABB makes Hall Effect current sensors (EL50P1 BB) and Hall Effect voltage sensors (EM010 BB) are used with scaling circuits. An EPLL-based control algorithm of the DSTATCOM system is realized using a DSP (dSPACE 1104) with MATLAB and its SIMULINK interface. For recording tests results, a Fluke 43B power analyzer and a four-channel digital storage oscilloscope (DSO) of Agilent Technology make are used. The estimation of the unit templates in the proposed control algorithm is modified using band-pass filters in sensed PCC voltages and low-pass filters in amplitude of PCC voltage to solve harmonics and unbalanced problems in PCC voltages. It is tested in PFC and ZVR modes of operation of DSTATCOM.

Here we are going to discuss the performance of the proposed algorithm and performance of the linear and non-linear algorithms using DSTATCOM technique.

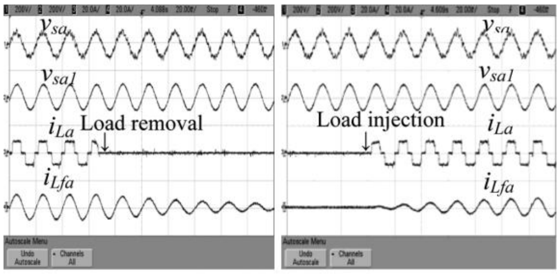
A. Performance of the Proposed Control Algorithm

Fig. 3(a)–(f) shows the various intermediate signals of the proposed control algorithm of DSTATCOM as outputted through digital-to-analog converters from DSP and recorded on the DSO which includes phase "a" distorted voltage waveform Vsa, filtered voltage waveform Vsa1 , load current i_{La} , fundamental load current i_{Lfa} , average amplitude of active power component of three load currents i_{LpA} , output of the dc bus voltage PI controller I_{cd} , amplitude of reference active power component of source current I_{spt} , active power component of reference source current I_{stp} , average amplitude of reactive power component of three load currents I_{LqA} , output of the ac bus PI controller I_{cq}, amplitude of reference reactive power component of source current I_{sqt} , and reactive power component of the reference source current I_{saq} , respectively.

B. Steady State Performance of DSTATCOM under Linear and Nonlinear Loads in PFC Mode

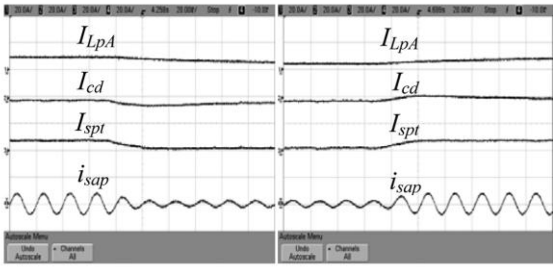
The source power (Ps) and load power (Pl) is shown in Fig. 4(a) and (b) for a 0.85-pf lagging three phase linear loads. The values of source and load apparent powers are 690 VA and 740 VA, respectively. The power factor on source side is improved to unity as the reactive power demand of the load is compensated by the DSTATCOM. Waveforms of PCC voltages (v_{ab} , v_{bc}, v_{ca}) and source currents (i_{sa}, i_{sb}, i_{sc})are shown in Fig. 4(c)–(e).

These results show satisfactory performance of the proposed control algorithm used in DSTATCOM for reactive power compensation and harmonics elimination under linear and nonlinear loads.



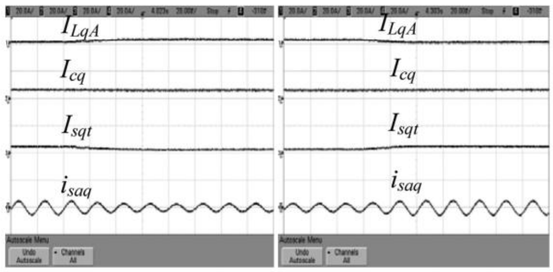
(a) (b)

Waveform v_{sa}, v_{sa1}, i_{La} and i_{Laf} after (a) load removal (b) load injection (Ch.1,2 -200V/div, Ch. 3 and 4- 20A/div, Time axis-20ms/div)



(c) (d)

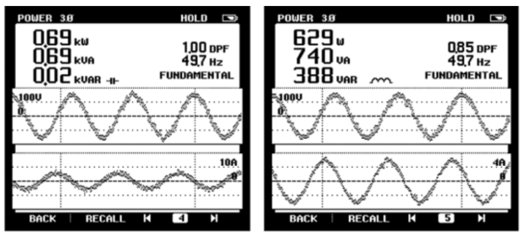
I_{LpA}, I_{cd}, I_{spt} and i_{sap} after (c) load removal (d) load injection (Ch.1,2, 3 and 4- 20A/div, Time axis-20ms/div)



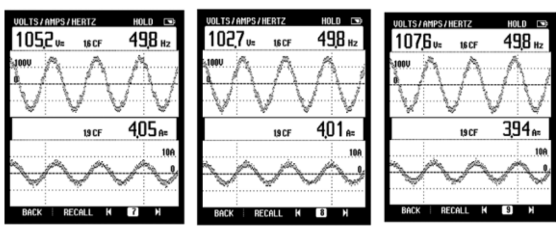
(e) (f)

I_{LqA}, I_{cq}, I_{sqt} and i_{saq} after (e) load removal (f) load injection (Ch.1, 2, 3 and 4- 20A/div, Time axis-20ms/div)

Fig. 3. (a)- (f) Various intermediate signals of the control algorithm at load removal and load injection.



(a) (b)



(c) (d) (e)

Fig. 4. Steady state performance of DSTATCOM under linear lagging pf load in PFC mode.

V. CONCLUSION

The design and control of a DSTATCOM have been carried out for a three phase distribution system. A control algorithm based on correlation and cross correlation function has been found suitable for generating the switching signals of DSTATCOM in a three phase system. A new control algorithm of DSTATCOM has been implemented for compensation of three phase linear and nonlinear loads. The performance of DSTATCOM and its control algorithm has been demonstrated for reactive power compensation, harmonics elimination, and load balancing in PFC and ZVR modes of operation under linear, nonlinear, and mixed loads. Test results have shown that the proposed control algorithm has a fast response for the extraction of fundamental components of load currents under noisy and distorted supply voltages. In all operating conditions, the THD of source current has been observed within an IEEE 519‑1992 standard limit of 5%. The performance of DSTATCOM and its control has been found satisfactory under varying load conditions. The dc bus voltage of the DSTATCOM has also been regulated without any overshoot to the desired value under varying load conditions.

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