A Comparitive Study on Different Control Algorithms of Distribution Static Compensator for Power Quality Improvement

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***Abstract*- DSTATCOM (Distribution STATic COMpensator) is used for reactive power compensation, harmonics elimination, zero voltage regulation, power factor correction, neutral current compensation and unbalance caused by various loads in the distribution system. This paper presents a comparative study of the performance of different control algorithms for the control of DSTATCOM which are named as Character of Triangle Function control algorithm(CTF), IcosineΦ based Isolated Topology with Unipolar Switching control algorithm and Adaptive Theory Based Improved Linear Sinusoidal Tracer control algorithm(ILST). These algorithms are used for extraction of load fundamental active and reactive power components of currents which are used for estimation of reference source currents. These schemes are simulated under the MATLAB environment using SIMULINK and PSB toolboxes. Simulation and experimental results represents the performance of these schemes for the control of DSTATCOM.**

***Keywords*- Character of Triangle Function(CTF), IcosineΦ, Adaptive Theory based Improved Linear Sinusoidal Tracer (ILST).**

I. INTRODUCTION

In the present scenario of AC transmission network, the mitigation of power quality problems is the major challenge due to increase of power electronic devices [1]. Static power converters such as rectifiers, large number of low-power electronic-based appliances, induction heating, switch mode power supplies, adjustable speed drives, electric traction, cyclo-converters etc. are nonlinear loads that generate considerable distortions in the ac mains current and causing power quality problems [2, 3]. A control algorithm should have good detection accuracy, wide range of adjustment of internal parameters, stability performance, and fast dynamic response. The performance of DSTATCOM depends largely on the right and accurate real-time detection of harmonics and reactive currents etc. [4-8]. Sawant and Chandorkar [6] have described multifunction active filter using instantaneous p-q-r theory. One of the new application of active filter is described by Crosier and Wang [7] where it is applied for grid connected electric vehicle charging station. Bueno *et al.* [8] have described application of active filter for railway supply system. DSTATCOM (Distribution Static Compensator) is also used for power quality improvement in pico-hydro based power generation [9], isolated wind power generation system [10] etc. Singh [11] has described different configurations of DSTATCOM such as three leg, four leg and characteristics of nonlinear loads. Active filters needs to detect the total distortion current outside the fundamental active source component of currents. A widely used method is the detection algorithm based on the theory of instantaneous reactive power [12]. Because it is easy to calculate and has good robustness and self-learning ability, adaptive harmonic detection algorithm has been paid wide attention in recent years [13, 14]. Based on the adaptive noise cancelling method some adaptive detection techniques for harmonic compensation are introduced for active power filter application [15, 16]. Rocher *et. al* [17] have discussed adaptive filters with fixed-point arithmetic which improves the computation quality. Karuppanan and Mahapatra [18] have discussed Proportional Integral (PI) or Fuzzy Logic Controller (FLC) to extract the required reference current from the distorted load currents. Masand *et. al* [19] have discussed phase shift control, indirect decoupled current control algorithm for DSTATCOM application. In recent years, the adaptive linear neural network (ADALINE) have been widely used in so many research fields, such as signal detection, noise canceling, and harmonic compensation [20, 21]. An active shunt compensator can be treated as a variable conductance for different order of harmonics corresponding to voltage harmonics distortion such that this technology is also useful for suppression of harmonics resonance in the distribution system [22]. Various configurations and

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topologies of DSTATCOM are used for reduction of distortions with acceptable level of performance according to the IEEE-519 standard with an optimal use of dc bus of a voltage source converter (VSC) used as DSTATCOM and in cost-effective manner [23]-[25]. Effective use of DSTATCOM is directly related to the design of power circuit components such as dc-bus capacitor, interfacing inductors, and VSC, control algorithm used for the estimation of reference source currents with increased speed and less calculation, switching scheme for gating pulses, and stability issues of a designed control algorithm [26]–[28].

This paper presents a comparative study of different control algorithms for the control of DSTATCOM. The comparison is on the basis of signal conditioning required dynamic performances under varying linear and non-linear load in PFC and ZVR mode, total harmonic distortion and its multi functionality. A dynamic model of DSTATCOM has been studied using various control algorithms in MATLAB/SIMULINK environment to observe their performance and comparison. Simulation results demonstrate the effectiveness of these three control algorithms of DSTATCOM for compensation of reactive power and unbalanced loading.

II. SYSTEM CONGURATION

A VSC-based DSTATCOM is shown in Fig. 1. It is connected to a three-phase AC mains feeding three-phase linear/nonlinear loads with grid source impendence Z_s. For reducing ripple in compensating currents, interfacing inductors L_f are used at an AC side of the VSC. A zig-zag/ three single-phase transformer is used for neutral current compensation. A three-phase series combination of capacitor (C_a , C_b , C_c) and a resistor (R_a , R_b, R_c) represent the passive ripple filter, which is connected at point of common coupling (PCC) for filtering the high frequency switching noise of the VSC. Generally, the same value of series-connected capacitor and resistance as a ripple filter is used in all the three phases. 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. The rating of the insulated gate bipolar transistor (IGBT) switches of the VSC is based on the voltage and current rating for the required compensation. For a considered load of 50 kVA (0.8 lagging), the compensator data are given in Appendix A. The rating of the VSC for the reactive power compensation/harmonics elimination is found to be 35 kVA (approximate 15% higher than the reactive power from rated value). The designed value of different auxiliary components of DSTATCOM such as interfacing ac inductors, dc-bus voltage, and value of dc-bus capacitor are also given in Appendix A.

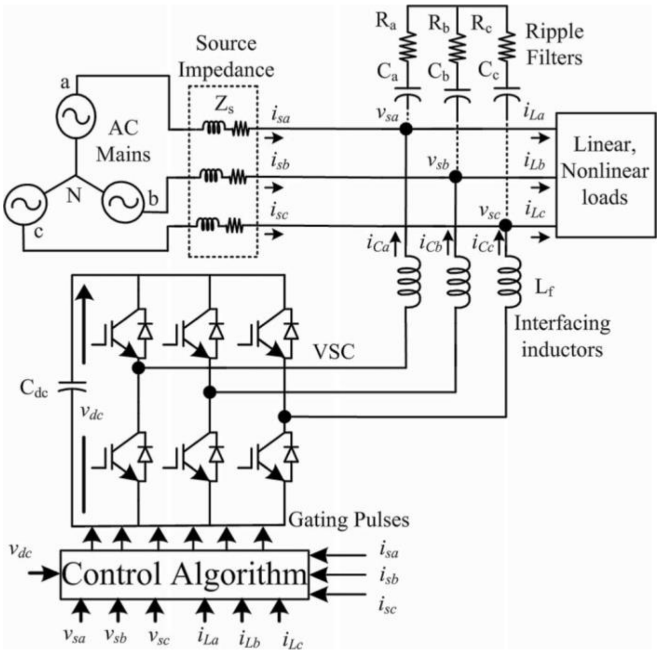

Fig1. Schematic diagram of VSC based DSTATCOM

III. CONTROL ALGORITHMS

A. CTF Control Algorithm [33].

The main aim of this algorithm is to get the fundamental active and reactive power component. Fig 2 shows a block diagram of a CTF based control algorithm based on CTF time domain for estimating of reference source currents.

The load fundamental active (i_{1Lp}) and reactive (i_{1Lq}) can be estimated by considering the phase voltage ($v_s(t)$ of AC mains at PCC distortion free sinusoidal wave as,

$$v_s(t) = v_{ms}\sin(wt) \qquad (1)$$

Where v_{ms} *is* the peak value of phase voltage.

The polluted load current $i_{LD}(t)$ is the mixture of fundamental load current $i_{LD}(t)$ is the mixture of the fundamental load current (i_{L1}) and the harmonic current i_H. It can be written as,

$$i_{LD(t)} = \sum_1^\infty \sqrt{2I_{Ln}}\sin(nwt + \theta_n) + i_{dc}(t) \qquad (2)$$

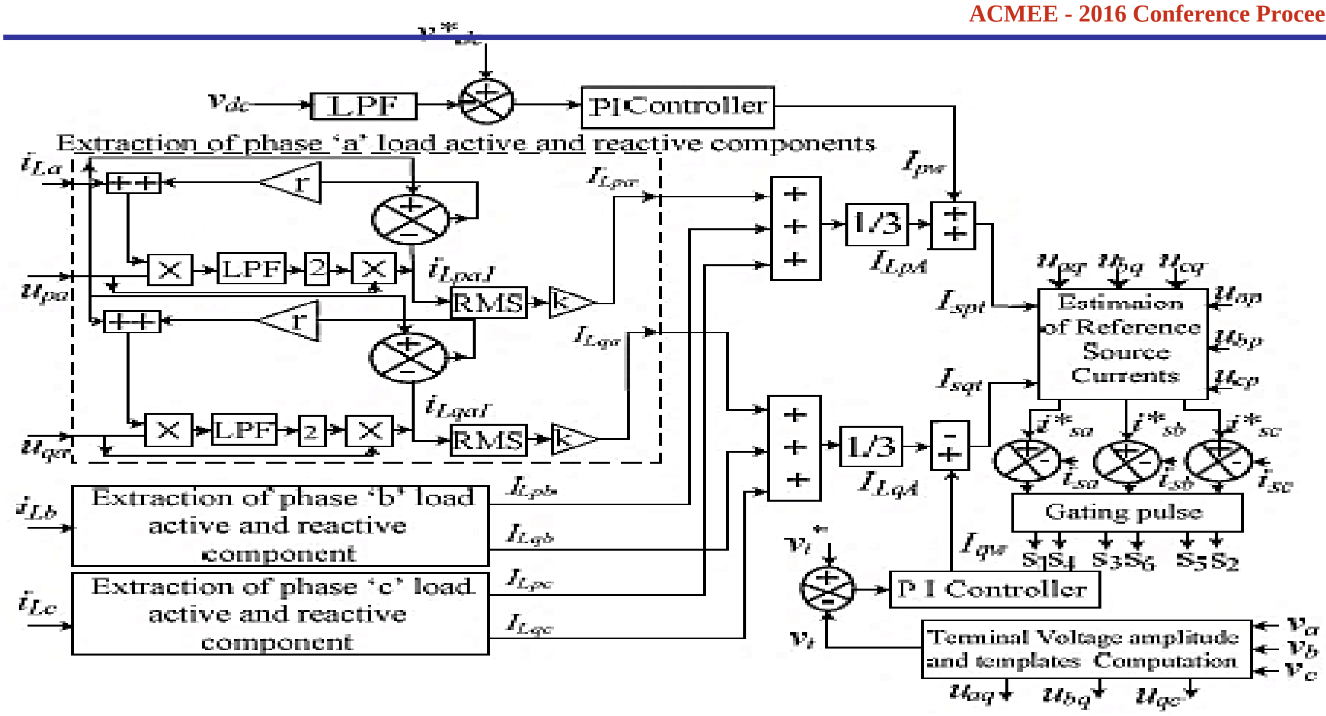

Fig2 .Generation Of reference source currents using CTF based control algorithm[33]

Where $I_{Ln} and\ \theta_n$ are the RMS value of n^{th} order harmonics current and phase angle of the n^{th} order harmonic,$i_{dc}(t)$ is the dc component presence in the load which is very small in case of the symmetrical loads and ω represents frequency in radian per second.Eqn(2) can be expressed as,

$$i_{LD(t)}=\sum_1^\infty \sqrt{2I_{L1}\sin(\omega t+\theta_1)} + \sum_2^\infty I_{Ln}\sin(\omega t+\theta_n) + i_{dc}(t) \quad (3)$$

$$i_{LD(t)} = i_{(t)} + I_{LH(t)} + i_{dc(t)} \quad (4)$$

Where $I_{L1}$is the fundamental value of the RMS load current and its phase angle is θ_1.

The fundamental load current can be expressed as ,

$$i_{L1(t)} = i_{1Lp(t)}+i_{1Lq(t)} \quad (5)$$

From eqn. (5),the load current can be expressed as,

$$i_{LD(t)} = i_{iLp(t)} + i_{1Lq(t)} + i_{LH(t)} + i_{dc(t)} \quad (6)$$

Where $i_{LD(t)}, i_{iLp(t)}, i_{1Lq(t)}, i_{LH(t)}, i_{dc(t)}$are the load fundamental active current ,reactive current harmonics current and DC component presence in due to load respectively.

Maximum value of active current

$$(I_{Lp})=\sqrt{2I_{L1}\cos(\theta_1)} \quad (7)$$

Maximum value of the reactive current

$$(I_{Lq})= \sqrt{2I_{L1}\sin(\theta_1)}$$

From eqn. (6-7) and (3),

$$i_{LD(t)} = I_{Lp}\sin(\omega t) + I_{Lq}\cos(\omega t) + \sum_2^\infty I_{Ln}\sin(\omega t+\theta_n) \quad (8)$$

Where $i_{1Lp(t)} = I_{Lp}\sin(\omega t)\ and\ i_{1Lq(t)} = I_{Lp}\cos(\omega t)$

Multiply by {2(sinωt)} in eq. (8) and according to character of triangle function is as,

$$2i_{LD}(t)\sin(\omega t) = I_{Lp}(1-\cos 2\omega t) + I_{Lq}\sin 2(\omega t) + \sum_2^\infty I_{Ln}\sin(\omega t+\theta_n) \quad (9)$$

Eqn. (9) shows $i_{LD(t)}$ is the mixture of DC and AC components which is seprated by low pass filter. Following relations from above eqn. are:-

$$i_{1Lp}(t) = i_{LD}(t) - \{i_{LH}(t) + i_{1Lq}(t)\} \quad (10)$$

Similarly

$$i_{1Lq}(t) = i_{LD}(t) - \{i_{LH}(t) + i_{1Lp}(t)\}$$

Basic equations for the estimation of different control variables of control algorithms are discussed below

For the estimation of in phase and quadrature unit templates of AC mains the in phase voltage unit templates (u_{ap}, u_{bp}, u_{cp}) are estimated from respective phase voltages (v_a,v_b and v_c) divided by amplitude of the terminal voltage (v_t) at PCC as [29].

$$\mathbf{v_t} = \sqrt{\frac{2(v_{sa}^2+v_{sb}^2+v_{sc}^2)}{3}} \quad (11)$$

Unit template in phase with phase voltages(w_{pa},w_{pb} and w_{pc})are estimated as

$$w_{pa} = \frac{v_{sa}}{v_t}, w_{pb} = \frac{v_{sb}}{v_t}, w_{pc} = \frac{v_{sc}}{v_t} \quad (12)$$

Similarly, the quadrature unit templates (w_{qa},w_{qb} and w_{qc}) are given as:

$$w_{qa} = \frac{(-w_{pb}+w_{pc})}{\sqrt{3}};$$
$$w_{qb} = \frac{(3w_{pa}+w_{pb}-w_{pc})}{2\sqrt{3}}; \quad (13)$$
$$w_{cq} = \frac{(-3w_{ap}+w_{bp}-w_{cp})}{2\sqrt{3}}$$

Major components in the distorted load currents are fundamental active power, reactive power, harmonics components, and the dc components. Fundamental active power, reactive power and harmonics component of load currents are the primary components in the polluted distorted current loads.

In this control algorithm phase 'a' load, fundamental active power component are subtracted from original load currents and reactive and harmonic current are estimated. After taking constant factor 'r' which is the % of harmonic and reactive current are added with polluted load current (i_{La}).Added value is multiplied with inphase voltage unit template(u_{pa}).

After suppressing the harmonic an other components using low pass filter this component is again multiplied with a factor of 2 in closed loop control system .Thus phase 'a' load fundamental active component (i_{Lpa1}) is extracted from original load current using above procedure. After extraction of load fundamental active power component of current, its root mean square value is estimated and converted to peak value using factor 'k=1.414' as a gain.

An amplitude of phase 'a' load active power component of current is considered as I_{Lpa}.Similaraly phase 'b' and phase 'c' amplitude of load active component of current I_{Lpb} , I_{Lpc} are also estimated.

For the extraction of load reactive current component ,harmonic and active currents are estimated after subtracting fundamental reactive current component from the polluted load currents .After taking factor 'r' which is the % of harmonic and active current are added with polluted current (i_{La}) and it is multiplied with quadrature phase unit template (u_{pa}).After suppressing the harmonics and other components using low pass filter ,this component is again multiplied with a factor of 2 in closed loop control system. Thus phase 'a' load current reactive component(i_{Lqa1}) is extracted from original load current using above procedure.

After extraction of load reactive power current component ,its root mean square value is estimated and converted to peak value using 'k=1.414' gain. An amplitude of phase 'a' load reactive power current component is I_{Lqa}.Similarly phase 'b' and phase 'c' amplitude of load reactive current component ofI_{Lqb}, I_{Lqc} are also estimated.

The average of amplitudes of fundamental active and reactive power components of load currents of the three phase loads are estimated using the amplitude of the load active and reactive power component of each phase and its average value is calculated for the extraction of three phase reference source current as

$$I_{LpA} = \frac{(i_{Lpa}+i_{Lpb}+i_{Lcp})}{3} \quad (14)$$
$$I_{LqA} = \frac{(i_{Lqa}+i_{qb}+i_{Lcq})}{3} \quad (15)$$

Reference dc-bus voltage v_{dc}^{*} and sensed dc-bus voltage v_{dc} of a VSC are compared and error in dc-bus voltage at the kth sampling instant is expressed as:

$$v_{de}(k) = v_{dc}^{*}(k) - v_{dc}(k) \quad (16)$$

This dc-bus voltage error v_{de} is fed to a proportional–integral (PI) regulator whose output is required for maintaining dc-bus voltage of the DSTATCOM. Its output at the kth sampling instant

is given as:-

$$I_{pw}(k) = I_{pw}(k-1)$$
$$+k_{pd}\{v_{de}(k) - v_{de}(k-1)\} + k_{id}v_{de}(k) \quad (17)$$

where $k_{pd}$and k_{id} are the proportional and integral gain constants of the dc bus PI controller. $v_{de}(k)$ and $v_{de}(k-1)$ are the dc-bus voltage errors at kth and $(k-1)^{th}$ instants and $I_{pw}(k)$ and $I_{pw}(k-1)$ are the amplitudes of the active power component of the fundamental reference current at kth and (k–1)th instants.

The amplitude of active power current components of the reference source current I_{spt} is calculated by an addition of output of dc-bus PI controller I_{pw} and an average magnitude of the load active power component of currents I_{LpA} as:

$$I_{spt} = I_{pw} + I_{LpA} \quad (18)$$

Similarly, AC bus voltage PI controller is used to regulate the PCC terminal voltage. The output signal of AC bus voltage PI controller is considered as I_{qw}. The amplitude of the reference source current is calculated by subtracting the output of voltage PI controller (I_{qw}) and average load reactive current (I_{LqA}) as

$$I_{sqt} = I_{qw} - I_{LqA} \quad (19)$$

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

$$i_{sap} = I_{spt}u_{pa} \text{ ,} \quad i_{sbp} = I_{spt}u_{pb} \text{ ,} \quad i_{scp} = I_{spt}u_{pc} \qquad (20)$$

$$i_{saq} = I_{sqt}u_{qa} \text{ ,} \quad i_{sbq} = I_{sqt}u_{qb} \text{ ,} \quad i_{scq} = I_{sqt}u_{qc} \qquad (21)$$

Reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are estimated by the addition of reference active and reactive power components of currents as:

$$i^*_{sa} = i_{sap} + i_{saq} \text{ ,} \quad i^*_{sb} = i_{sbp} + i_{sbq} \text{ ,} \quad i^*_{sc} = i_{scp} + i_{scq} \qquad (22)$$

The sensed source currents (i_{sa}, i_{sb} *and* i_{sc}) and these reference source currents (i^*_{sa}, i^*_{sb} *and* i^*_{sc}) are compared for the respective phases and each phase current error is amplified using PI current regulators and their outputs are compared with a carrier signal of 10 kHz to generate the gating signals for IGBT switches of VSC used as DSTATCOM.

B. IcosineΦ Algorithm based Isolated Topology with Unipolar Switching [34]

In this control algorithm a designed a new isolated topology based on zig-zag/ three single-phase transformers is used in DSTATCOM to select optimum dc voltage for proper utilization of solid state devices. An advantage of a zigzag transformer is to mitigate the zero sequence currents and triplen harmonics in its primary windings. Thus, it helps in the reduction of the devices rating of VSC connected in the secondary windings. In this control algorithm we used the six–leg VSC. The six-leg VSC of the proposed DSTATCOM operated with six gating signals has an advantage of doubling the PWM voltage frequency compared to devices switching frequency with unipolar switching as compared to bipolar switching which is used in three-leg VSC for a given switching frequency. Moreover, the dc bus voltage of VSC is also reduced as compared to three-leg VSC topology.

The load currents (i_{La}, i_{Lb}, i_{Lc}), voltages at the PCC (point of common coupling) (v_a, v_b, v_c) and dc bus voltage (v_{dc}) of VSC are sensed as feedback control signals. Distorted load currents can be expressed as-

$$i_{La} = \sum_{n=1}^{\infty} I_{Lan} \sin(n\omega t - \Phi_{an}) \qquad (23)$$

$$i_{Lb} = \sum_{n=1}^{\infty} I_{Lbn} \sin(n\omega t - \Phi_{bn} - 120^0) \qquad (24)$$

$$i_{Lc} = \sum_{n=1}^{\infty} I_{Lcn} \sin(n\omega t - \Phi_{cn} - 240^0) \qquad (25)$$

where $\Phi_{an}, \Phi_{bn}, \Phi_{cn}$ are phase angles of nth harmonic current in three phase load currents with their phase volatges. I_{Lan},I_{Lbn}, I_{Lcn} are amplitude of nth harmonic current in these phases.

In this control approach,the amplitude of active power component of current (I_{Lpa}) of phase 'a' is extracted from filtered value of distorted load current (i_{Lfa}) at the zero crossing of the in-phase unit template ($cos\Phi_{pa}$) of three phase PCC voltages.

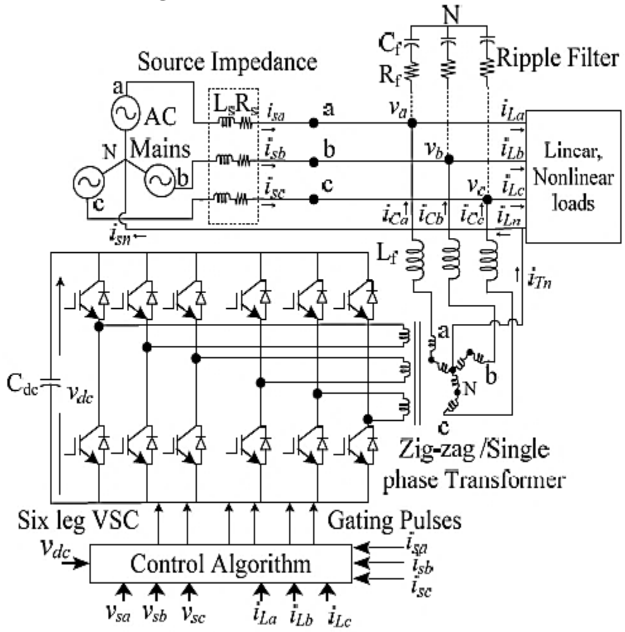

Fig 3. Schematic diagram of DSTATCOM with zig zag transformer and six leg VSC[34].

A zero crossing detector and a "sample and hold" circuit are used to extract the I_{Lpa}(amplitude of filtered load current at zero crossing of corresponding in-phase unit template). Similarly, other two phase's amplitude of active power component of current I_{Lpb} and I_{Lpc} are also extracted. In the case of balanced system, the amplitude of active component of load currents can be expressed as,

$$I_{LpA} = \frac{(I_{Lpa}+I_{Lpb}+I_{Lpc})}{3} \qquad (26)$$

where $I_{Lpa}, I_{Lpb}, I_{Lpc}$ are the amplitude of the load active power component of currents.

For self supporting dc bus of VSC, the error in dc bus voltage of VSC $v_{de}(n)$) of DSTATCOM at nth sampling instant is as,

$$\mathrm{v_{de}(n) = v^*_{dc}(n) - v_{dc}(n\,)} \qquad (27)$$

where $\mathrm{v^*_{dc}(n)}$) is the reference dc voltage and $\mathrm{v_{dc}(n\,)}$is the sensed dc bus voltage of the VSC.

The output of the proportional integral (PI) controller which is used for regulating dc bus voltage of the VSC at the n^th sampling instant can be expressed as,

$$\mathrm{I_{cd}}(\mathrm{n}) = \mathrm{I}_{cd}(\mathrm{n}-1) + \mathrm{k_{pd}}\{\mathrm{v_{de}}(n) - \mathrm{v_{de}}(\mathrm{n}-1)\} + \mathrm{k_{id}}\mathrm{v_{de}}(n) \quad (28)$$

where $\mathrm{I_{cd}}(\mathrm{n})$ is considered as part of active power component of reference source current. $\mathrm{k_{pd}}$ and $\mathrm{k_{id}}$ are the proportional and integral gain constants of the dc bus PI voltage controller. Un-sampled value of $\mathrm{I_{cd}}(\mathrm{n})$) is represented as I_{cp}. The amplitude of active power component (I_{sp}) of reference source currents can be expressed as: $I_{sp} = I_{LpA} + I_{cp}$ (29)

The PCC phase voltages (v_a, v_b, v_c) are considered sinusoidal and their amplitude is estimated as:

$$\mathbf{v_t} = \sqrt{\frac{2(\mathrm{v_a^2+v_b^2+v_c^2})}{3}} \quad (30)$$

The unit vectors in phase with v_a, v_b and v_c are derived as-

$$cos\Phi_{pa} = \frac{v_a}{v_t}; cos\Phi_{pb} = \frac{v_b}{v_t}; cos\Phi_{pc} = \frac{v_c}{v_t} \quad (31)$$

In-phase components of reference source currents are estimated as:

$$i_{sap}^* = I_{sp}\cos\Phi_{pa};$$
$$i_{sbp}^* = I_{sp}\cos\Phi_{pb}; \quad (32)$$
$$i_{scp}^* = I_{sp}\cos\Phi_{pc}$$

The unit vectors $(\sin\Phi_{qa}, \sin\Phi_{qb}, \sin\Phi_{qc})$ in quadrature with three phase PCC voltages $(v_a, v_b \; and \; v_c)$ may be derived using a quadrature transformation of the in-phase unit vectors($cos\,\Phi_{pa}, cos\,\Phi_{pb} \; and \; cos\,\Phi_{pc}$) as [30]:

$$\sin\Phi_{qa} = \left(\frac{-\cos\Phi_{pb}}{\sqrt{3}}\right) + \left(\frac{\cos\Phi_{pc}}{\sqrt{3}}\right), \quad (33)$$

$$\sin\Phi_{qb} = \left(\frac{\sqrt{3}\cos\Phi_{pa}}{2}\right) + \left(\frac{\cos\Phi_{pb}-\cos\Phi_{pc}}{2\sqrt{3}}\right), \quad (34)$$

$$\sin\Phi_{qc} = \left(\frac{-\sqrt{3}\cos\Phi_{pa}}{2}\right) + \left(\frac{\cos\Phi_{pb}-\cos\Phi_{pc}}{2\sqrt{3}}\right) \quad (35)$$

The amplitude of reactive power component of current (I_{LqA}) of phase ‘a’ filtered load current (i_{Lfa}) is extracted at the zero crossing of the unit template quadrature-phase of the PCC voltage ($sin\Phi_{qa}$). A zero crossing detector and a “sample and hold” circuit has been used to extract the i_{Lqa} (amplitude of filtered load current at zero crossing of corresponding quadrature - phase unit template). Similarly, the amplitude of reactive power component of phase ‘b’ (i_{Lqb}) and phase ‘c’ (i_{Lqc}) are also estimated. The amplitude of reactive power component of load currents can be expressed as:

$$I_{LqA} = \left(\frac{i_{Lqa}+i_{Lqb}+i_{Lqc}}{3}\right) \quad (36)$$

Reference AC-bus voltage v_t^* and sensed AC-bus voltage v_t of a VSC are compared and error in AC-bus voltage at the n^th sampling instant is expressed as:

$$\mathrm{v_{te}}(\mathrm{n}) = \mathrm{v_t^*}(\mathrm{n}) - \mathrm{v_t}(\mathrm{n}) \quad (37)$$

This AC-bus voltage error $\mathrm{v_{te}}$ is fed to a proportional–integral (PI) regulator whose output is required for maintaining dc-bus voltage of the DSTATCOM. Its output at the n^th sampling instant is given as:-

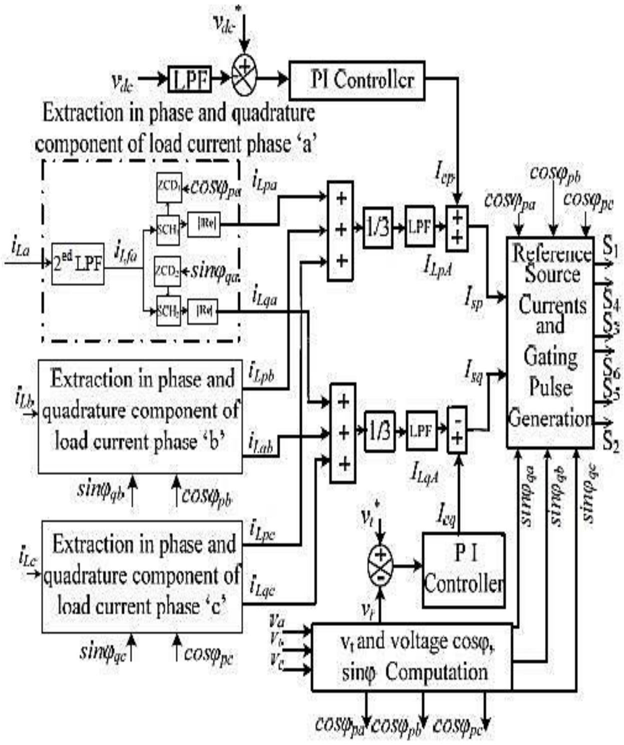

fig 4.Estimation of reference source current using IcosΦ algorithm[34]

$$\mathrm{I_{cq}}(\mathrm{n}) = \mathrm{I_{cq}}(\mathrm{n}-1) + \mathrm{k_{pq}}\{\mathrm{v_{te}}(\mathrm{n}) - \mathrm{v_{te}}(\mathrm{n}-1)\} + \mathrm{k_{iq}}\mathrm{v_{te}}(\mathrm{n}) \quad (38)$$

where $\mathrm{k_{pq}}$ and k_{iq} are the proportional and integral gain constants of the AC bus PI controller. $\mathrm{v_{te}}(\mathrm{k})$ and $\mathrm{v_{te}}(\mathrm{k}-1)$ are the AC-bus voltage errors at n^th and $(\mathrm{n}-1)^{th}$ instants and $\mathrm{I_{cq}}(n)$ and $\mathrm{I_{cq}}(\mathrm{n}-1)$ are the amplitudes of the reactive power component of the fundamental reference current at n^th and (n–1)^th instants. $\mathrm{I_{cq}}(n)$ is the part of amplitude of reactive power component of the reference source current at n^th instant. $\mathrm{I_{cq}}(n)$ is represented as $\mathrm{I_{cq}}$ in steady state.

The amplitude of reactive power current components of the reference source current $\mathrm{I_{sq}}$ is calculated by an addition of output of AC-bus PI controller $\mathrm{I_{pw}}$ and an average magnitude of the load reactive power component of currents I_{LqA} as: $I_{sq} = I_{cq} - I_{LqA}$ (39)

The quadrature or reactive power components of reference source current are estimated as:

$$i^*_{saq} = I_{sq} \sin \Phi_{qa} , \quad (40)$$

$$i^*_{sbq} = I_{sq} \sin \Phi_{qb}, \quad (41)$$

$$i^*_{scq} = I_{sq} \sin \Phi_{qc} \quad (42)$$

Total Reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are estimated by the addition of reference active (in phase) and reactive(quadrature) power components of currents as:

$$i^*_{sa} = i^*_{sap} + i^*_{saq}, \quad (43)$$

$$i^*_{sb} = i^*_{sbp} + i^*_{sbq}, \quad (44)$$

$$i^*_{sc} = i^*_{scp} + i^*_{scq} \quad (45)$$

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C. Adaptive ILST Control Algorithm[36]

An area of adaptive control provides an automatic adjustment of the controller gains and parameters in real time, in order to achieve a desired level of performance. It provides an automatic tuning procedure in a closed loop for the controller parameters. Characteristics of this control algorithms are the ability to extract necessary information from real online data in order to tune the controller, and also used for grid synchronization.

In this control approach, error detection accuracy and dynamic response both are related to each other. An error in the linear sinusoid tracer algorithm is affected by the high-order harmonics. Thus, this algorithm is not able to detect harmonics current accurately. For removal of this limitation, a low-pass filter (LPF) is used and this modification is named as an adaptive theory-based improved linear sinusoid tracer (ILST) where source current and reference current both are tracing each other without any change even at unbalance loads.

Three-phase voltages at the PCC are sensed and their amplitude is calculated using PCC phase voltages (v_{sa},v_{sb} and v_{sc})

$$\mathbf{v_t} = \sqrt{\frac{2(v_{sa}^2+v_{sb}^2+v_{sc}^2)}{3}} \quad (46)$$

Unit template inphase with phase voltages(w_{pa},w_{pb} and w_{pc}) are estimated as

$$w_{pa} = \frac{v_{sa}}{v_t}, w_{pb} = \frac{v_{sb}}{v_t}, w_{pc} = \frac{v_{sc}}{v_t} \quad (47)$$

Similarly, the quadrature unit templates (w_{qa},w_{qb} and w_{qc}) are given as:

$$w_{qa} = \frac{(-w_{pb}+w_{pc})}{\sqrt{3}}; w_{qb} = \frac{(3w_{pa}+w_{pb}-w_{pc})}{2\sqrt{3}};$$

$$w_{cq} = \frac{(-3w_{ap}+w_{bp}-w_{cp})}{2\sqrt{3}} \quad (48)$$

Major components in the distorted load currents are fundamental active power, reactive power, harmonics components, and dc components. An adaptive theory-based ILST [54] with selectable frequency and bandwidth is used to estimate the phase "a" load fundamental current i_{Lfa} as shown in the block diagram of Fig. 6(b).

In this control algorithm, phase 'a' fundamental load current is subtracted from the load current to estimate the current error signal. The filtered value of a current error signal with the combination of band-pass filter (ψ) is added with the output signal, which is multiplied by the power frequency signal (–ρ). After integration of this signal, phase "a" fundamental load current i_{Lfa} is estimated. Similar procedure is adapted for phase 'b' and phase 'c' to extract to fundamental components of load currents. The amplitudes of three-phase fundamental load active power current components (i_{Lpa},i_{Lpb} and i_{Lcp}) are extracted at the zero crossing of the unit template in- phase of PCC voltages.An output of zero crossing detector (ZCD_1) works as a trigger pulse of signal and hold logic (SCH_1) and fundamental current as an input signal of SCH_1 . The real

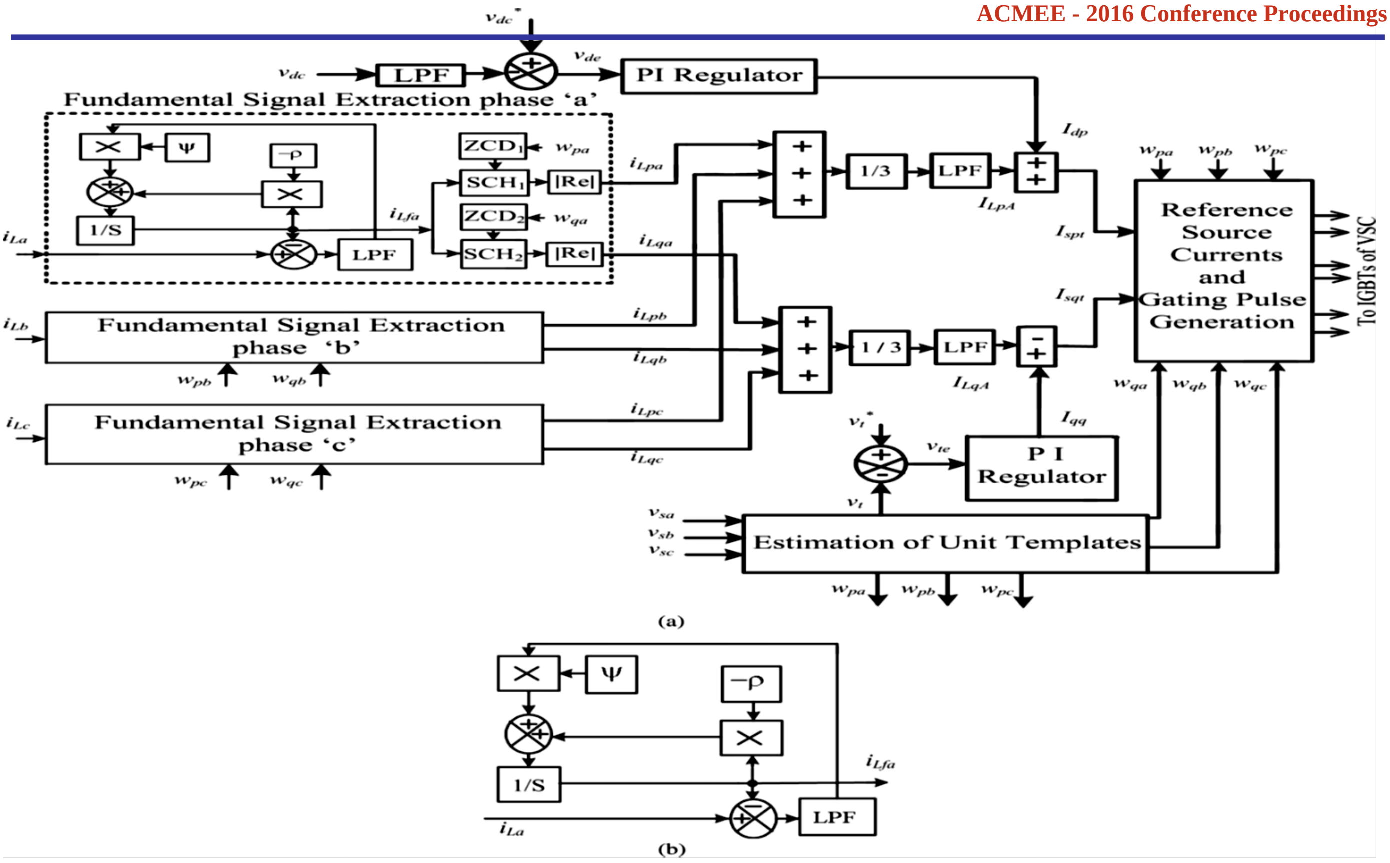

Fig 6. a) Generation of reference source currents using an adaptive theory-based ILST control algorithm. (b) Estimation of the fundamental signal using an adaptive theory-based ILST control algorithm[35].

component of the SCH_1 output is known as the amplitude of fundamental active power components.

The average amplitude of fundamental active power components (I_{LpA}) is estimated using amplitude sum of three-phase load active power components (i_{Lpa},i_{Lpb} and i_{Lcp}) divided by three for load balancing.

First-order low-pass filters are used to separate the low-frequency components. Mathematically, it is expressed as:

$$I_{LpA} = \frac{(i_{Lpa}+i_{Lpb}+i_{Lcp})}{3} \quad (49)$$

Similarly, amplitudes of reactive power components (i_{Lqa},i_{Lqb} and i_{Lcq}) of fundamental load currents are extracted at the zero crossing of the quadrature unit template phase of PCC voltages using zero-crossing detector (ZCD_2) and signal and hold logic (SHC_2). An output signal of SHC2 is known as the amplitude of fundamental reactive power components of load current.

The average amplitude of the fundamental reactive power component I_{LqA} is estimated using load fundamental reactive power current components i_{Lqa},i_{Lqb} and i_{Lcq}.Alow-pass filter is used to extract its smooth or ripple-free component. Mathematical expression of the average amplitude of the fundamental reactive power current component I_{LqA} is given as:

$$I_{LqA} = \frac{(i_{Lqa}+i_{Lqb}+i_{Lcq})}{3} \quad (50)$$

Fig. 6(b) shows the subsection of an adaptive theory-based ILST control algorithm. The transfer function $G_1(s)$ of a lowpass filter is as:

$$G_1(s) = \frac{1}{\tau s+1} \quad (51)$$

where τ is the time constant of a L.P.F. and it is greater than zero.

The transfer function in Fig. 6(b) in terms of phase 'a', extracted fundamental current $i_{Lfa}$and load current i_{La} canbe written as:

$$C(s)=\frac{i_{Lfa}}{i_{La}}(s) = \frac{G(s)}{1+G(s)H(s)} \quad (52)$$

where forward path transfer function :

$G(s)=\frac{\psi}{\tau s^2+(\tau\rho+1)s+\rho}$; and feedback transfer function $H(s) = 1$.

The characteristics equation of the transfer function is written as:

$$\tau s^2 + (\tau\rho + 1)s + (\rho + \psi) = 0 \quad (53)$$

where τ = time constant of a low-pass filter, ρ = power frequency, ψ = frequency band of a band-pass filter.

Stability of characteristic equation is analyzed using a Rough–Hurwitz criterion. Details of this analysis are given in the Appendix B.

Reference dc-bus voltage v^*_{dc} and sensed dc-bus voltage v_{dc} of a VSC are compared and error in dc-bus voltage at the kth sampling instant is expressed as:

$$v_{de}(k) = v^*_{dc}(k) - v_{dc}(k) \quad (54)$$

This dc-bus voltage error v_{de} is fed to a proportional–integral (PI) regulator whose output is required for maintaining dc-bus voltage of the DSTATCOM.Its output at the kth sampling instant is given as:-

$$I_{dp}(k) = I_{dp}(k-1)$$
$$+k_{pd}\{v_{de}(k) - v_{de}(k-1)\}k_{id}v_{de}(k) \quad (55)$$

where k_{pd} and kid are the proportional and integral gain constants of the dc bus PI controller. $v_{de}(k)$ and $v_{de}(k-1)$ are the dc-bus voltage errors at kth and $(k-1)$th instants and $I_{dp}(k)$ and $I_{dp}(k-1)$ are the amplitudes of the active power component of the fundamental reference current at kth and (k–1)th instants.

The amplitude of active power current components of the reference source current I_{spt} is calculated by an addition of output of dc-bus PI controller I_{dp} and an average magnitude of the load active power component of currents I_{LpA} as:

$$I_{spt} = I_{dp} + I_{LpA} \quad (56)$$

A reactive power component of reference source currents is required for the operation of DSTATCOM in the ZVR mode. In the ZVR mode, source currents are slightly leading from the ac mains voltages because extra leading reactive power component is required for regulating the voltage at PCC. It is zero in the operation of DSTATCOM in the PFC mode.

The voltage error between reference PCC voltage v^*_t and its sensed value v_t is fed to the PCC voltage PI controller. The voltage error v_{te} of ac voltage at the kth sampling instant is given as:

$$v_{te}(k) = v^*_t(k) - v_t(k) \quad (57)$$

The output of the PCC voltage PI controller I_{qq} for maintaining PCC terminal voltage to a constant value at the kth sampling instant is given as:

$$I_{qq}(k) = I_{qq}(k-1)$$
$$+k_{pt}\{v_{te}(k) - v_{te}(k-1)\} + k_{it}v_{te}(k) \quad (58)$$

where $I_{qq}(k)$ is a part of the reactive power component of source current and it is named as I_{qq}. k_{pt} and k_{it} are the proportional and integral gain constants of the PCC voltage PI controller.Gains of PI controller for dc-bus voltage: k_{pd} = 2.4, k_{id} = 1.54; gains of the PCC voltage PI controller: k_{pt} = 3.1, k_{it} = 0.95.

The amplitude of reactive power current components of the reference source current I_{sqt} is calculated by subtracting average load reactive currents i_{LqA} from the output of voltage PI controller I_{qq} as

$$I_{sqt} = I_{qq} - I_{LqA} \quad (59)$$

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

$$i_{sap} = I_{spt}w_{pa}\ ,\quad i_{sbp} = I_{spt}w_{pb}\ ,\quad i_{scp} = I_{spt}w_{pc} \quad (60)$$

$$i_{saq} = I_{sqt}w_{qa}\ ,\quad i_{sbq} = I_{sqt}w_{qb}\ ,\quad i_{scq} = I_{sqt}w_{qc} \quad (61)$$

Reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are estimated by the addition of reference active and reactive power components of currents as:

$$i^*_{sa} = i_{sap} + i_{saq}\ , i^*_{sb} = i_{sbp} + i_{sbq}\ , \quad (62)$$

$$i^*_{sc} = i_{scp} + i_{scq} \quad (63)$$

The sensed source currents (i_{sa}, i_{sb} *and* i_{sc}) and these reference source currents (i^*_{sa}, i^*_{sb} *and* i^*_{sc}) are compared for respective phases and each phase current error is amplified using PI current regulators and their outputs are compared with a carrier signal of 10 kHz to generate the gating signals for IGBT switches of VSC used as DSTATCOM.

IV. SIMULATION RESULTS AND DISCUSSIONS

MATLAB with Simulink and sim power system (SPS) toolboxes is used for the development of simulation model of a DSTATCOM and its control algorithm. The performance of various algorithms in time domain for the three phase DSTATCOM is simulated for PFC and ZVR modes of operation at linear and nonlinear loads using developed MATLAB model. The performance of a control algorithm is observed for time-varying linear/nonlinear loads.

A. Performance of DSTATCOM in the PFC Mode

The dynamic performance of a VSC-based DSTATCOM for the PFC mode at linear load is shown in Fig. 7. The performance indices are as phase voltages at PCC (v_s), balanced source currents (i_s), load currents (i_{La}, i_{Lb}, and i_{Lc}), compensator currents (i_{Ca}, i_{Cb}, and i_{Cc}), and dc-bus voltage (v_{dc}), which are shown under varying loads (at *t* = 1.35–1.45 s) conditions. It shows the functions of DSTATCOM and its control algorithm for reactive power compensation and load balancing. Similarly, an uncontrolled rectifier as a nonlinear load is connected to the supply system. The dynamic performance of DSTATCOM and waveforms of phase "a" voltage at PCC v_{sa} , source current i_{sa} , and load current i_{La} are shown in Figs. 8 and 6(a)–(c), respectively.

CTF Control Algorithm[33]

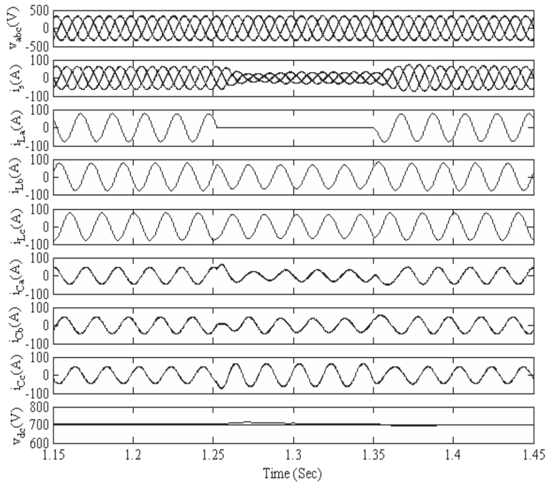

Fig7. Dynamic Performance of DSTATCOM under varying linear load in PFC mode [33]

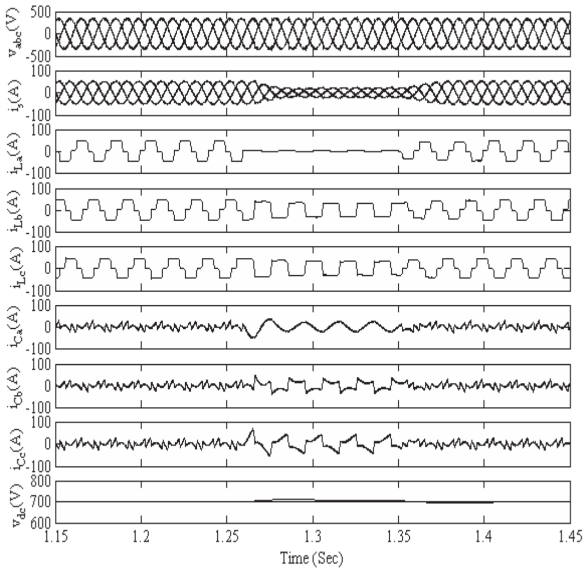

Fig8.. Dynamic Performance of DSTATCOM under varying nonlinear load in PFC mode[33]

IcosΦ based Algorithm[34]

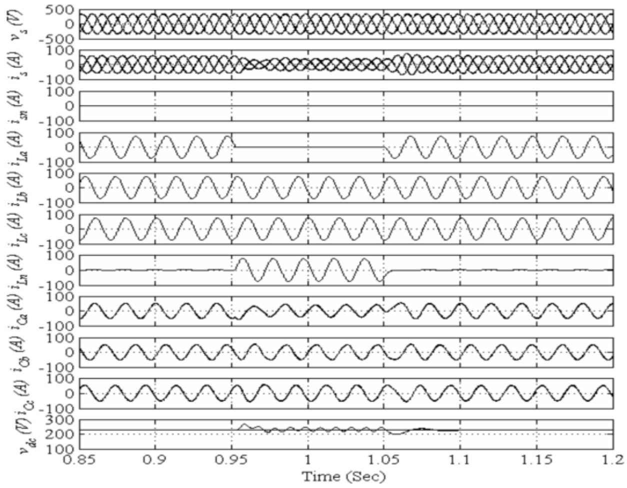

Fig9.. Dynamic Performance of DSTATCOM under varying linear load in PFC mode [34]

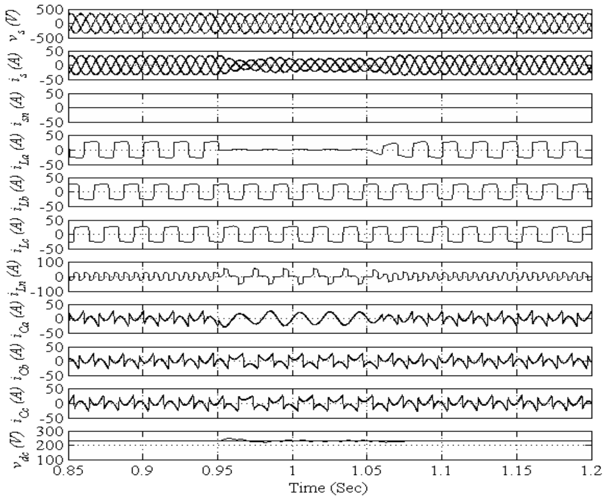

Fig10. Dynamic Performance of DSTATCOM under varying nonlinear load in PFC mode[34]

ILST Algorithm[35]

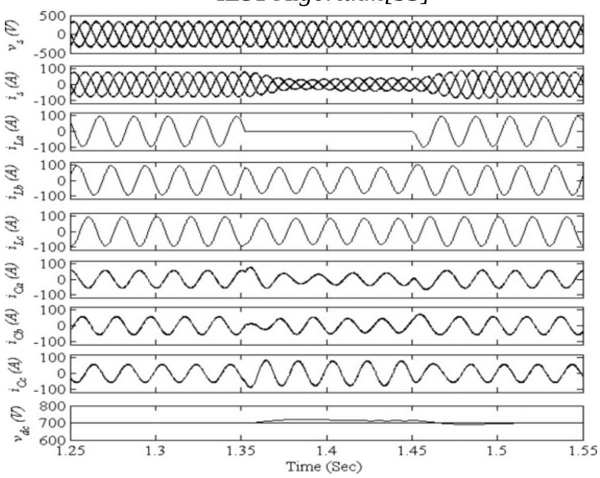

Fig13. Dynamic Performance of DSTATCOM under varying linear load in PFC mode [35]

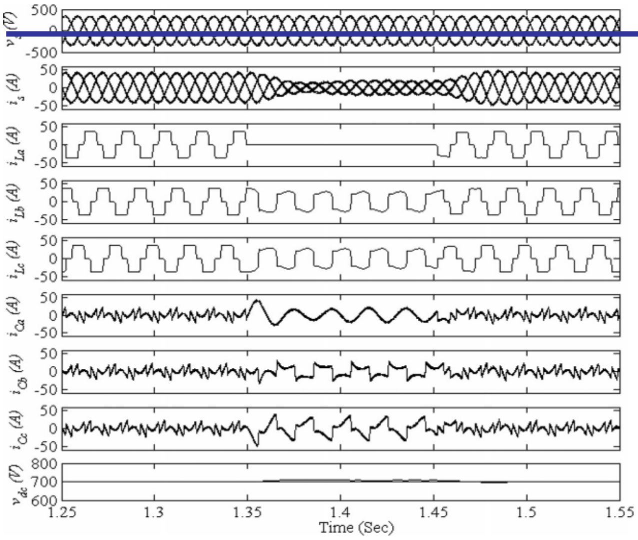

Fig14. Dynamic Performance of DSTATCOM under varying nonlinear load in PFC mode[35]

C. Performance of DSTATCOM in the ZVR Mode

In the ZVR mode, the amplitude of PCC voltage is regulated to the reference amplitude by injecting the leading reactive power components. Fig. 7 shows the dynamic performance of the DSTATCOM used for reactive power compensation to achieve ZVR and load balancing under linear loads (at t = 1.35– 1.45 s). The performance indices are as PCC phase voltages (v_s), balanced source currents (i_s), load currents (i_{La}, i_{Lb}, and i_{Lc}, compensator currents (i_{Ca}, i_{Cb}, and i_{Cc}), amplitude of voltages at PCC (v_t), and dc-bus voltage (v_{dc}) under time-varying linear loads. The performance of DSTATCOM is also studied under uncontrolled rectifier-based nonlinear loads. The dynamic performance of DSTATCOM in terms of waveforms and harmonics spectra of phase "a" voltage at PCC v_{sa} , source current i_{sa}, and load current i_{La} are shown in Figs. 8 and 9(a)–(c), respectively.

CTF Control Algorithm[33]

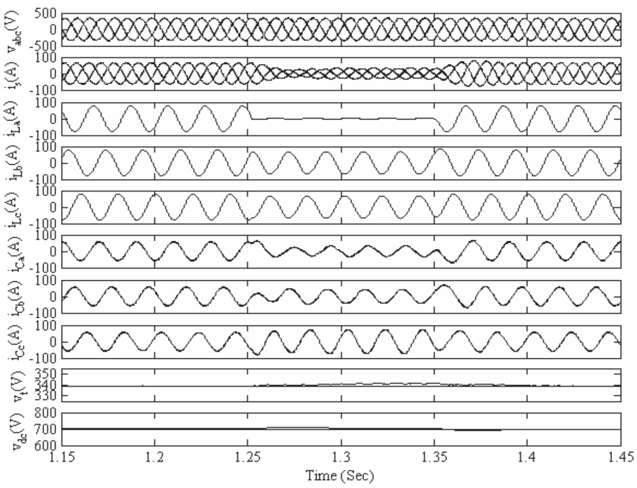

Fig15. Dynamic Performance of DSTATCOM under varying linear load in ZVR mode [33].

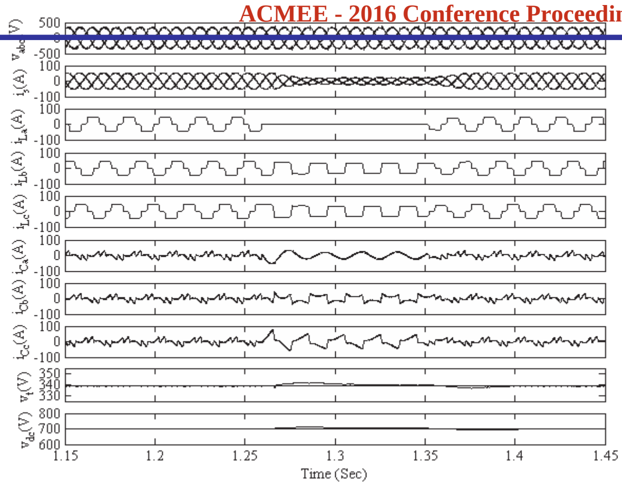

Fig16. Dynamic Performance of DSTATCOM under varying non linear load in ZVR mode [33]

IcosΦ based Algorithm [34]

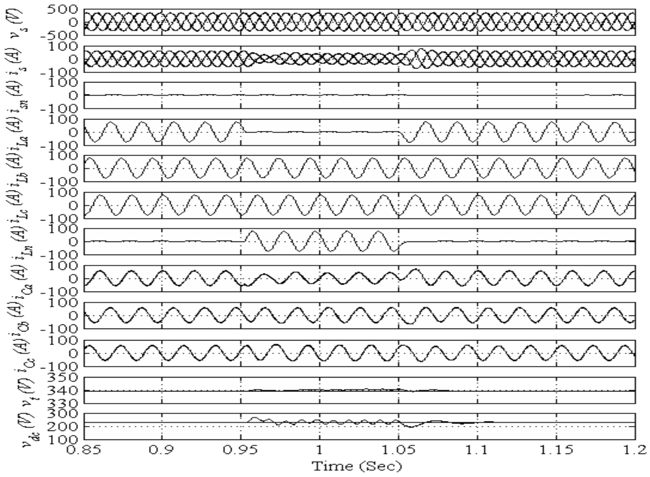

Fig17. Dynamic Performance of DSTATCOM under varying linear load in ZVR mode [34].

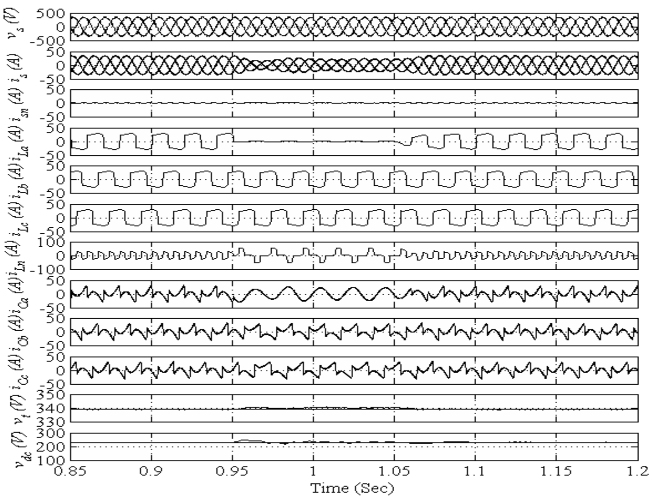

Fig18. Dynamic Performance of DSTATCOM under varying nonlinear load in ZVR mode [34]

ILST Algorithm [35]

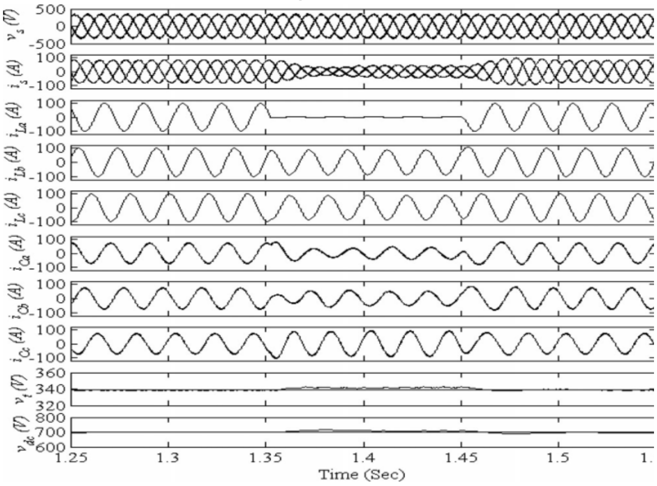

Fig21. Dynamic Performance of DSTATCOM under varying linear load in ZVR mode [35].

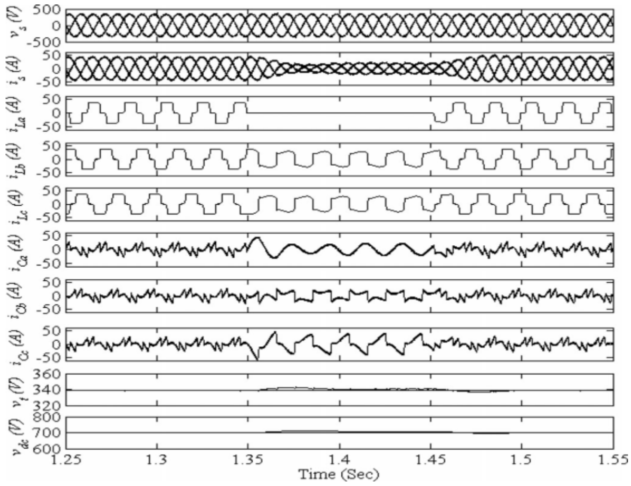

Fig22. Dynamic Performance of DSTATCOM under non varying linear load in ZVR mode [35].

It may be seen that the THD of the source current and PCC voltage are within IEEE519-1992 standard limit of 5%. PCC voltage is also regulated even at unbalanced loads. Table I shows the summarized results demonstrating the performance of STATCOM. These results shows satisfactory performance of DSTATCOM for reactive power compensation, harmonic elimination, and load balancing of linear and nonlinear loads.

CTF Control Algorithm [33]

TABLE I

TABLE PERFORMANCE OF DSTATCOM

Operating Mode	Performance parameters	Nonlinear load (3Φ uncontroled rectifier with R-L load)
PFC mode	PCC voltage (V),%THD	236.38V,3.45%
	Supply current (A),%THD	36.03A,3.06%
	Load current (A),%THD	35.39A,25.56%
ZVR mode	PCC voltage (V),%THD	239.49V,3.84%
	Supply current (A),%THD	36.71 A,3.26%
	Load current (A),%THD	35.87A,25.43%
	DC bus voltage (V)	700v

IcosΦ based Algorithm [34]

TABLE II

TABLE PERFORMANCE OF DSTATCOM

Operating Mode	Performance parameters	Linear Load	Nonlinear load (3Φ uncontroled rectifier with R-L load)
PFC mode	PCC voltage (V),%THD	237.3V,1.15%	237.72V,2.39%
	Supply current (A),%THD	41.64A,0.99%	23.75A,2.13%
	Load current (A),%THD	52.83A,0.07%	24.06A,40.75%
ZVR mode	PCC voltage (V),%THD	239.6V,1.44%	239.63V,2.88%
	Supply current (A),%THD	42.41A,0.96%	24.03 A,2.25%
	Load current (A),%THD	53.34A,0.10%	24.23A,40.83%
	DC bus voltage (V)	700v	700v

ILST Algorithm [35]

TABLE IV

TABLE PERFORMANCE OF DSTATCOM

Operating Mode	Performance parameters	Linear Load	Nonlinear load (3Φ uncontroled rectifier with R-L load)
PFC mode	PCC voltage (V),%THD	233.6V,2.43%	237.23V,2.86%
	Supply current (A),%THD	55.07A,1.55%	29.21A,3.19%
	Load current (A),%THD	67.7A,0.17%	28.53A,25.98%
ZVR mode	PCC voltage (V),%THD	239.5V,2.37%	239.56V,3.14%
	Supply current (A),%THD	57.14 A,1.48%	29.67 A,3.27%
	Load current (A),%THD	69.4A,0.19%	28.77A,26.15%
	DC bus voltage (V)	700v	700v

V. CONCLUSION

In this paper, a comparative performance evaluation of the

V. CONCLUSION

In this paper, a comparative performance evaluation of the CTF, IcosineΦ based Isolated Topology with Unipolar Switching control algorithm and adaptive theory based Improved Linear Sinusoidal Tracer control algorithm(ILST**)** is presented. The results are analyzed considering the THD (%) in PFC and in the ZVR mode. The target for all these compensation techniques is to achieve the sinusoidal source current in phase with positive sequence component of the supply fundamental voltage. A three-phase DSTATCOM has been implemented for compensation of linear and nonlinear loads using CTF, IcosineΦ based Isolated Topology with Unipolar Switching control algorithm, and adaptive theory based Improved Linear Sinusoidal Tracer control algorithm (ILST**)**. Various functions of DSTATCOM such as reactive power compensation, harmonic elimination, and load balancing have been demonstrated in PFC and ZVR modes for all the algorithms. From these results, it is concluded that ILST control algorithm have been found most suitable for time-varying loads among all discussed algorithms. PCC and DC bus voltages of the DSTATCOM have also been regulated to reference values under unbalanced loads.

APPENDIX A

AC supply source: three-Phase, 415 V (*L–L*), 50 Hz; source impedance: R_s = 0.07 Ω, L_s = 2 mH; Load: 1) Linear: 50 kVA, 0.8 p.f. lagging; 2) Nonlinear: three-phase full-bridge uncontrolled rectifier with R = 15 Ω and L = 100 mH; ripple filter: R_f = 5 Ω, C_f = 7 μF; dc-bus capacitance: 12000 μF; reference dc-bus voltage: 700 V; interfacing inductor Lf = 2.5 mH; gains of PI controller for dc-bus voltage: k_{pd} = 2.4, k_{id} = 1.54; gains of the PCC voltage PI controller: k_{pt} = 3.1, k_{it} = 0.95.

APPENDIX B

The stability of the ILST control algorithm is analyzed using eq (72) .
Its Routh array formation is shown as:-

TABLE V

S^2	τ	ρ+ψ
S^1	τρ+1	0
S^0	ρ+ψ	

TABLE:- ROUTH ARRY FORMATION

In Table, there are no changes in the sign of the elements in the first column for any positive value of ρ, ψ, and τ. For this condition, it is concluded that there is none of roots in the characteristic equation with a positive real number. This condition satisfies the stability of the controller. For this application, consider values of time constant τ = 0.1 s, power frequency ρ = 314.15 rad/sec, and frequency band of band-pass filter ψ = 250 rad/sec. After putting these values in Table II, there are no changes in the sign of the elements in the first column and it is observed that the control algorithm is stable with a wide range of internal parameter variations.

Design of DSTATCOM

The design of DSTATCOM with transformer configuration based new topology is given in this section.

A. Selection dc Voltage

DC bus voltage $(v_{dc}) = \sqrt{2}V_{LL}/\mathrm{m}$ (64)

where, m (modulation index) considered as 1 and $V_{LL}L$ (138.33 V) is the ac line output voltage of VSC used in STATCOM. Calculated value of dc bus voltage is 195.63 V and its selected value is 230V.

B. Selection of dc bus Capacitor

The value of dc bus of VSC of DSTATCOM is computed as,DC bus capacitor

$$(C_{dc}) = \frac{2r\{v_{ph}(ki_c)t\}}{(v_{dc}^2 - v_{dc1}^2)} \quad (65)$$

where, v_{dc} is the nominal dc voltage and v_{dc1} is the minimum voltage level of dc bus, 'k' is the over loading factor, v_{ph} is the supply phase voltage, factor 'r' is varying between 0.04 to 0.15. i_c is the phase current of the VSC and t is time for which dc bus voltage is to be recovered. Calculated value of dc bus capacitor is 7160.01µF and its selected value is 8500 µF.

C. Selection of ac Inductor

The value of interfacing inductor is estimated as,
AC inductance

$(L_f) = V_{dc}$ / (8*k*fs*i_{crpp} (66)

where v_{dc} is the dc bus voltage, k=1.2, m=1, fs is the switching frequency and i_{crpp} is the acceptable % range of current ripple.

For a considered value of 2% of current ripple in DSTATCOM current. Calculated value of ac inductor is 1.77
mH and its selected value is 2 mH.

D. Voltage Rating of the IGBTs

The voltage rating (v_{sw}) of IGBT under dynamic conditions as,$v_{sw} = v_{dc} + v_d$ *(67)*

where v_d is the 15% overshoot in the dc bus voltage under dynamic condition. The voltage rating of switch is calculated as 264.45 V.

E. Current Rating of the IGBT

The current rating (i_{sw}) of IGBT under dynamic conditions as,i_{sw}=1.2(i_{cr}+ i_{sp}) (68)

where i_{sp} ($\sqrt{2}i_c$) and i_{cr} (5% of i_c) are the peak value of DSTATCOM current and value of allow ripple currents. The minimum current rating of switch is 73.32 A

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