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Enhancement of power quality using U-SOGI based control algorithm for DSTATCOM

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ABSTRACT

The distributed static compensators (DSTATCOM) are connected at the distribution end to enhance the quality of power. The performance of DSTATCOM needs to be improved for better utilization and more ancillary services. In this regard, an upgraded second-order generalized integrator (U-SOGI) based adaptive control structure is developed for DSTATCOM. The proposed control algorithm is much simpler than transformation based techniques because this structure consists of two integrator, three mathematical operators and a damping factor. This control algorithm is utilized to extract the fundamental active and reactive components from the distorted load current. These components are further multiplied with respective voltage templates for generating the reference currents. Moreover, the damping factor is adjusted to mitigate the DC offset and damp out the oscillations presented in weight component during transient conditions. The proposed algorithm successfully performs the power quality tasks namely; a) harmonic mitigation, b) reactive current suppression, c) power factor correction, d) zero voltage regulation, and e) load balancing during various operating scenarios in distribution system. The robustness of proposed control is tested using MATLAB/Simulink results under both steady-state and dynamic conditions. Further, the superiority of the proposed technique is also presented by comparing it with classical techniques. From simulation study, it can be highlighted that the proposed controller successfully mitigates various power quality issues as per IEEE standards and performs way better than its counterparts under all possible operating conditions.

1. Introduction

The continuous proliferation of switching devices and non-linear loads are distorting the quality of power in the distribution system. The power quality (PQ) in any distribution system becomes an important aspect of maintaining various parameters such as superior load capability, utilization of maximum electric equipment, zero voltage regulation, etc. [1]. Various custom power devices such as active power filter (SAPF), static and distributed compensators (DSTATCOM), distributed voltage regulator (DVR) and unified power quality conditioner (UPQC) have been constantly utilized to improve the power quality of the distribution system at various levels [2–4]. More precisely, these devices perform as per the applied control structure when they are connected to the power network. Among these custom power devices, the DSTATCOM is popularly utilized to mitigate the source side harmonic current, reactive power minimization, and load current balancing under various dynamic and static conditions. The control algorithm for these custom power devices requires continuous improvements to the various challenging operating conditions are coming after the fluctuation of distributed energy sources [5].

The most classical and conventional control structures such as instantaneous active and reactive power theory (IRPT) [6], synchronous reference frame theory (SRF) [7], d-q theory [8], instantaneous symmetrical component (ISC) [9], etc. have been frequently utilized in DSTATCOM to overcome the power-quality related issues. In IRPT theory the inclusion of extra inter harmonics during the reference current generation have been a big challenge for the DSTATCOM. In order to overcome this problem, the SRF and d-q theory have been implemented for a three-phase distribution network. However, this theory is more suitable for three-phase balanced network under balanced loading conditions while the slight unbalancing in network conditions disturbs the current generation procedure [10]. Further, the ISC-based strategy has been utilized by several researchers for the DSTATCOM operation in various practical scenarios but the continuous transformations require larger memory and sampling time for the digital controller. This

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will further degrade the overall system performance. A comparative analysis of control techniques for shunt active filter for power quality improvement have been implemented in the case of distributed power supply in the distribution system [11]. A modified id-iq-based control technique has been introduced for time-varying reactive power control and harmonic compensation in distribution system under load fluctuations [12].Under a polluted supply system, a controller for DSTATCOM is proposed based on instantaneous reactive power for load compensation [13]. The fundamental current components of distorted load are computed with imaginary reference source voltage which makes the compensator current closer to sinusoidal. In case of nonlinear load for control of time varying power flow and load compensation under distributed supply system an improved synchronous reference frame base control algorithm is proposed for DSTATCOM [14]. Lyapunov function based controllers have been proposed for DSTATCOM for harmonic compensation in the distribution system owing to the customer side nonlinearity [15]. The use of DSTATCOM using IRPT theory has been implemented in hydropower generation [16]. The quasi type-1 PLL (QT1-PLL)with third order moving average filter (MAF) has been implemented for harmonically distorted grid voltage and frequency deviation [17], and the response of this technique is very fast and very good accuracy at steady state operation as compared to conventional control technique. The fuel cell grid integration through DSTATCOM for reduction of grid harmonic using filter less improved PQ control technique has been proposed in the distribution system to enhance the power quality problems [18]. Savitzky–Golay Filter-Based PLL has been reported for validation of system performance under imbalanced and harmonically distributed condition [19]. An improved control technique for fuel based DSTATCOM for harmonic suppression of supply current in the distribution system has been implemented using an improved Icosθ control technique with Kernel-based training method [20].The different system configuration for distribution system with improved Icosθ control technique for DSTATCOM has been described for power quality improvement in distribution system [21] Reactive power and harmonic elimination in isolated power plant based on diesel engine have been explained in [22]. More importantly, the various applications of DSTATCOM in the DFIG system have been implemented for different control loops such as voltage control, frequency control and harmonic reduction [23]. On the other hand, DSTATCOM has various applications in solar PV systems to address the various performance parameters under day and night time scenarios because the same inverter can be utilized as an active power injector when PV is available and a PQ enhancer when the power is not available at DC-link points [24].

The operation of DSTATCOM depends upon its design components like DC link voltage, coupling inductor, and its control technique which is used for extraction of reference source current among fast response and less computation, gating pulses generation technique and stability problems related to design control technique [25–32]. An adaptive control technique adjusts the gain of the controller automatic and its parameters in real-time, for desired performance level achievement. These controllers are also tuned automatically in a closed loop control and extract the required information from genuine data for tuning a controller [33–34]. An adaptive controller based on the synchronized filtered x-control technique has been developed for harmonic current filtering from loads that produce the harmonic in the system [35]. Artificial immune system-based control technique has been implemented which is based on the immune feedback principle for random, unidentified, and severe disturbances [36]. After clearing the disturbance this controller returns to its normal position which is the characteristic of this controller. A notch filter based adaptive controller has been proposed which is appropriate for the computation of essential frequency signals from polluted signals and also used for changing the notch frequency, according to input signal frequency changes [37].The performance of Fuzzy based adaptive controller depends upon the design of rules for the fuzzy logic controller (FLC) controller [38]. FLC controller also is used for the current controller for switching patterns and regulation of VSC dc-link voltage. The algorithm Variable step size, least mean square (LMS) based on auto-correlation time mean is developed for up-gradation of the step size of a signal [39].

The VSC-based DSTATCOM with capacitor bank has been implemented in transmission line in the distribution system for power quality enhancement [40]. For, mitigation of sag/swell and active/reactive power compensation with DSTATCOM using fused control method based on second order twisting algorithm (STA) and sliding mode control has been developed [41], and drawbacks of SMC technique are eliminated under load variation. For, mitigation of current related power quality in the distribution system, hybrid DSTATCOM has been developed with an RC filter [42]. In the distribution power grid, the power quality problems are mitigated with DSTATCOM by controlling reactive power flow control which are created by unbalanced and variable load [43].Result of Sliding and traditional Proportional-Integrator controller. The LMS-based control technique for DSTATCOM has been proposed for the estimation of active and reactive weight calculation and these weights are used for the computation of reference currents (Active and reactive components of load current). The proposed controller has been with DSTATCOM in distribution for enhancement of power quality [44].

In, a grid integration photovoltaic (GIPV) system an improved multifunctional control technique for DSTATCOM has been proposed for real/reactive power flow control and enhancement of power quality problems [45], and the comparisons of modified instantaneous reactive power(IRP) theory and modified synchronous reference (SRF) theory are carried out in the GIPV system. In a grid-tied solar photovoltaic system, the Kalman filter-based neural network has been presented with perturb and observe based maximum power tracking in the solar photovoltaic system to track maximum power from solar module and used for power quality enhancement in the grid system [46]. The different controller based on phase-locked loop (PLL) like delay PLL, enhanced PLL and SOGI-frequency locked loop (SOGI-FLL) has been presented and results are compared for quality improvement using DSTATCOM in the distribution system [47].These PLL-based techniques have been designed and modeled for synchronization of grid and compensation of grid-tied PV single-phase system. A battery energy storage (BES) system with DSTATCOM in the distribution system has been presented and it becomes a better option to stabilize and meet the grid demand/store the surplus power in case of excess power from the source [48]. The BES with DSTATCOM has become a better option for power quality improvement. Voltage controlled oscillator (VCO) less PLL-based control technique for DSTATCOM has been developed which gives a faster dynamic response under variable conditions [49]. This control technique has been used for power quality improvement in the distribution system. The traditional SOGI technique for DSTATCOM has been reported in [50–51]. This technique was well known for to compute the load current fundamental component and reference supply current generation. DC offsets are present in load current with this control. The dual SOGI technique has been customized in which four integrator are used and six integrator-based dual SOGI technique has also been reported in [52]. These techniques suppress the THD with more no. of the integrator which increase the cost and complexity of the system. The comparison of SOGI, dual SOGI and improved SOGI control technique has been reported in [53].

In the above scientific, it is observed that various control structures related to SOGI, dual SOGI and I-SOGI have been presented to improve the power quality at the distribution end. In SOGI, D-SOGI and I-SOGI the number of integrators required are 2, 4 and 3 respectively. As a result, the memory requirement in SOGI is low as compared to D-SOGI and I-SOGI whereas the DC offsets are more present in SOGI as compared to other types. On the other hand, the complexity of D-SOGI is medium as compared to SOGI and I-SOGI. Therefore, a sophisticated improved method is required to improve and mitigate the trade-off considered in the other generalized-integrator based control techniques.

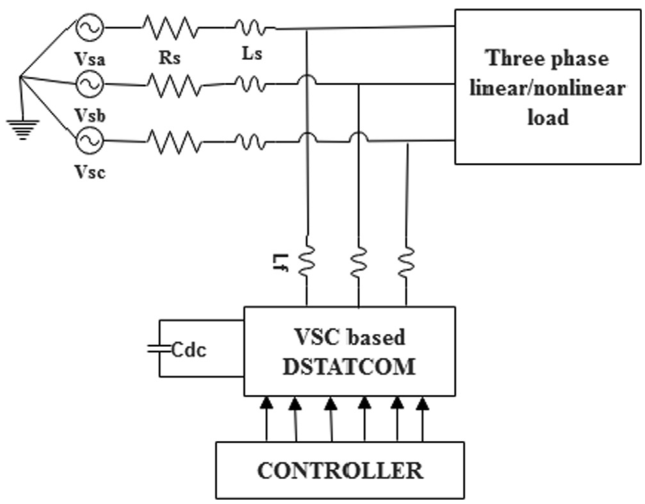

Fig. 1. DSTATCOM in proposed system.

In this paper, an upgraded form of SOGI is designed in MATLAB and implemented for various scenarios utilizing only two integrators. As a result, the proposed structure is giving better performance than SOGI and I-SOGI in terms of memory requirement, complexity and DC component elimination. Moreover, the proposed controller will also give better results in terms of source current harmonic elimination and can be used for DSTATCOM control in the distribution system for enhancement of power quality. The key features of the proposed structure are as follows,

1. In the proposed structure, the existing SOGI method is upgraded using the new deviation parameters such that better voltage regulation can be achieved under sudden load/voltage transitions.
2. The proposed structure requires lesser sampling time requirement and hence provides a fast reference current generation under various operating scenarios.
3. The designed methodology provides various power quality features including current harmonic mitigation, reactive power compensation; load balancing, power factor correction, voltage regulation and DC-link voltage stabilization.
4. The proposed structure is designed in MATLAB/Simulink environment for testing the performance and thereafter validated using a real-time platform in the laboratory.

2. Distribution system architecture

The three-phase AC mains having source impedance Z_s (R_s + L_s) is connected to the three-phase linear/nonlinear loads as shown in Fig. 1. This power network is connected to the three-phase inverter with DC-link capacitor in order to design the system as DSTATCOM. The different parameters the DSTATCOM such as interfacing

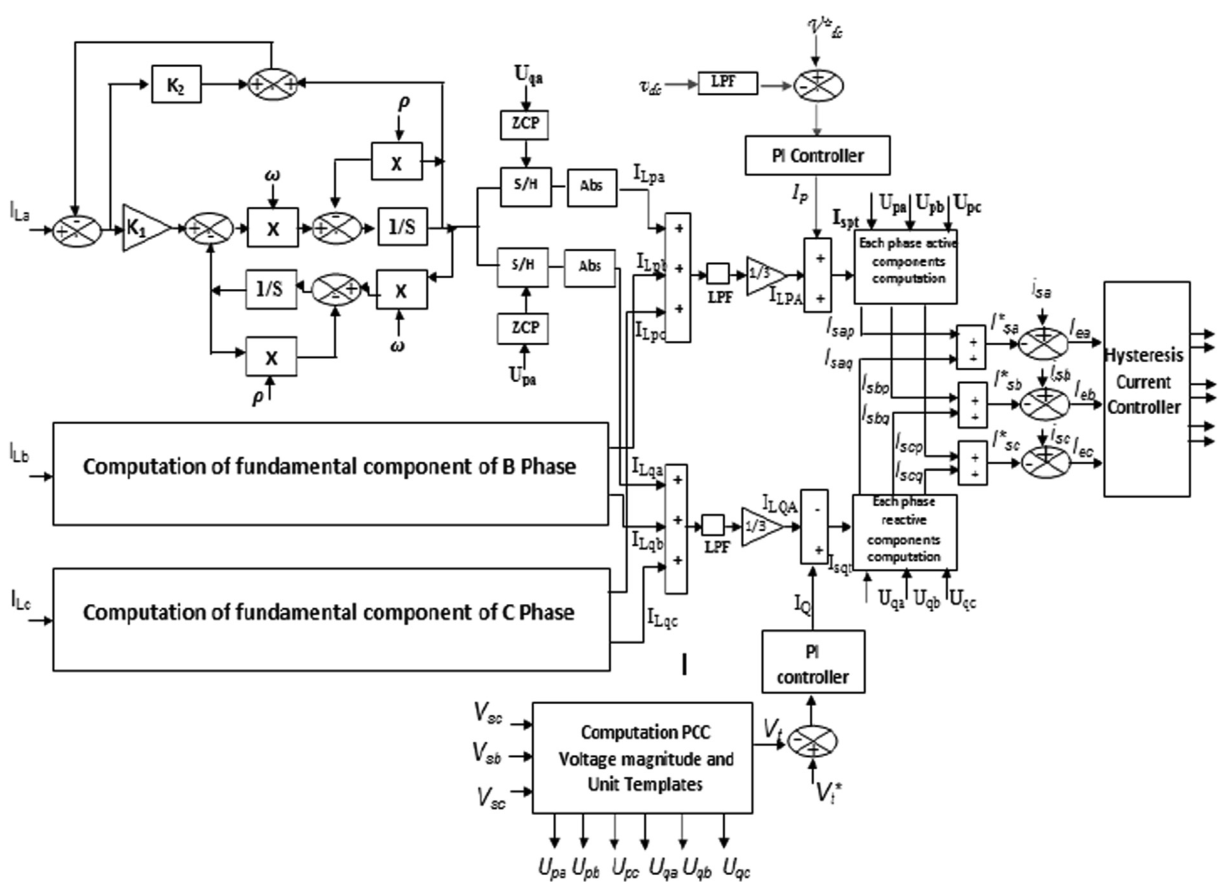

Fig. 2. Computation of reference current with U-SOGI technique.

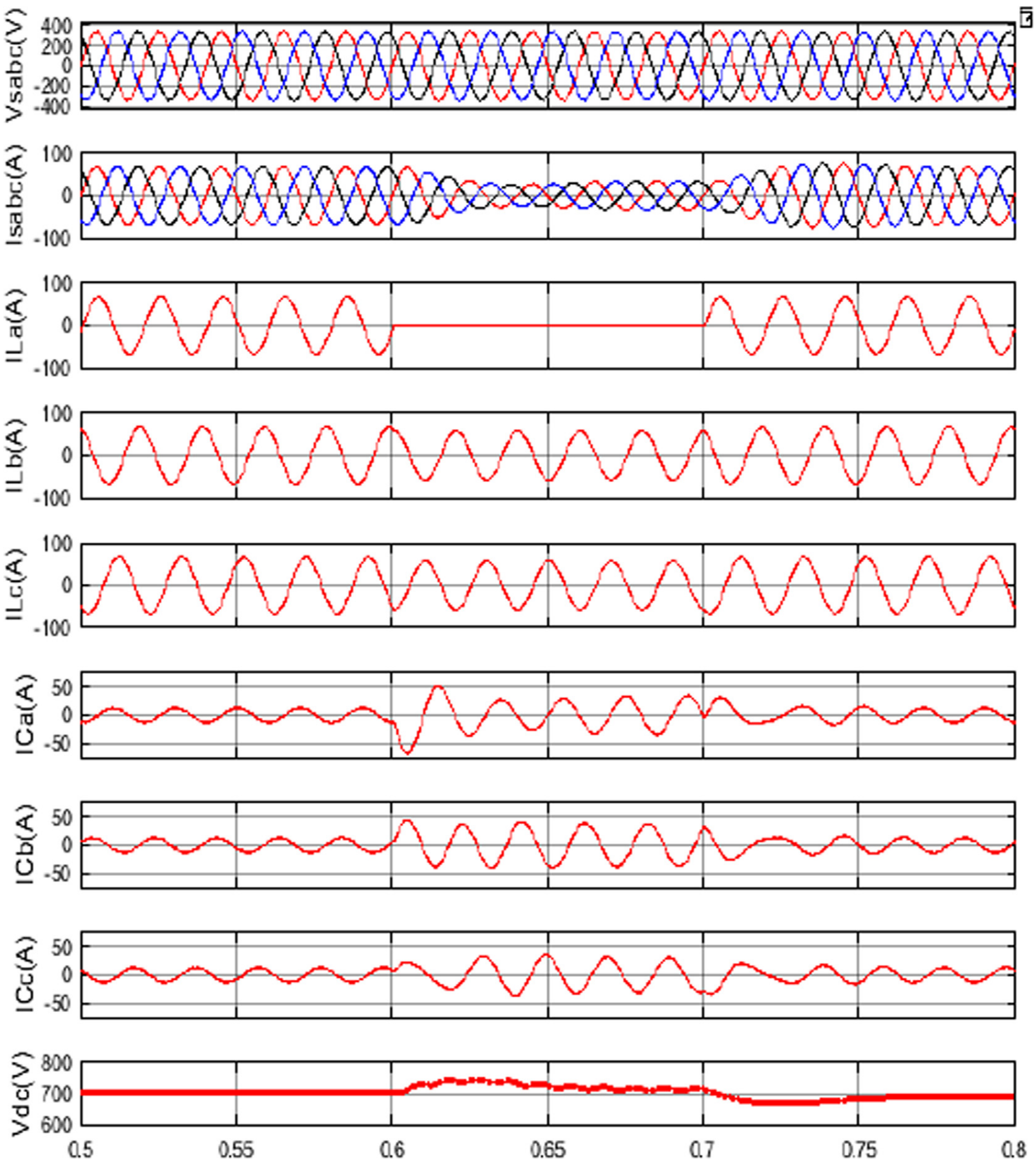

Fig. 3. PFC mode DSTATCOM performances with linear load (x-axis in sec).

inductors, capacitors, and different inverter parameters are designed as per standard procedure. The interfacing inductor L_f coupled to AC output of VSC and the utility grid in order to mitigate the ripples present in the inverter output current. Moreover, the DC side capacitor act as source for the inverter and supports the energy balance for the designed system. Moreover, it helps in supplying the essential compensating current to the coupling point of connection in 180 degree phase shift to reduce the source current harmonics and reactive power compensation of load currents to reduce the burden (harmonic/reactive power) from the distribution system.

3. Inverter control algorithm

The proposed U-SOGI based control technique is designed using various mathematical operators as depicted in Fig. 2. This structure is used to extract the fundamental active and reactive components of the highly distorted load current. These active and reactive current components are further utilized for reference current computation. The generated reference currents are further processed to drive the IGBT-based DSTATCOM. Moreover, unit vector and quadrature vector templates are generated using the coupling point voltage (V_{pcc}) for a smooth grid synchronization process. In the proposed structure, a separated damping factor is designed and integrated with SOGI to improve the damping performance under sudden load varying conditions whereas the SOGI algorithm the quadrature signal generator (QSG) is used as building blocks and to make load current free from frequency and phase error, the feedback circuit is also used to find and transmit the load current to the controller [54]. In the proposed structure of SOGI, an additional integrator is also taken in the existing QSG block to damp-out the DC offsets of load current. The design procedure of the proposed structure requires conventional SOGI algorithm feedback loop transfer function and taken as an orthogonal signal generator (OSG) as,

$$f_{SOGI}(s) = \frac{\omega s}{s^2 + 2\omega s + \omega^2} \tag{1}$$

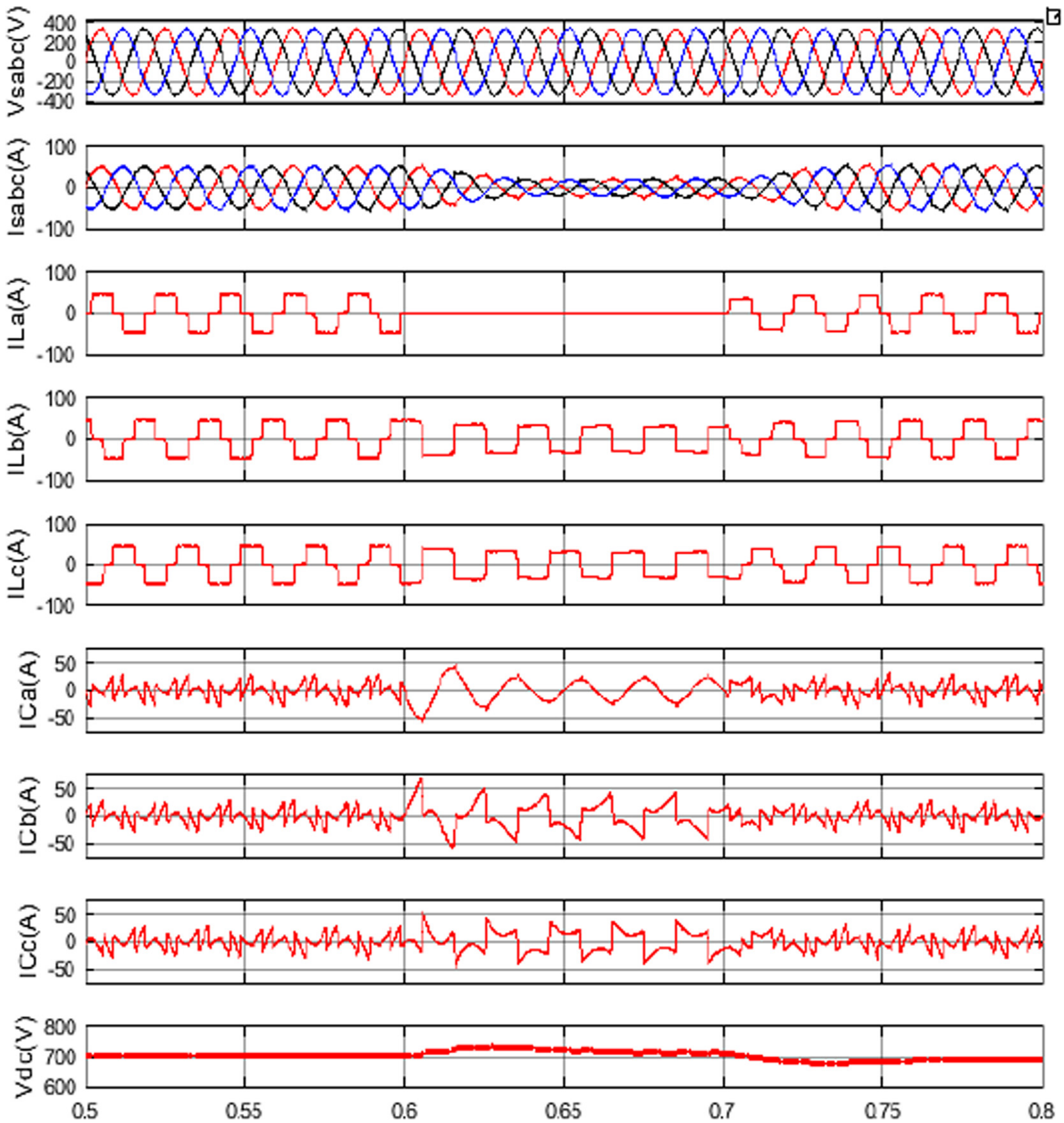

Fig. 4. PFC mode DSTATCOM performances with nonlinear load (x-axis in sec).

In OSG block a damping factor is added to reduce the error between real and sensed value. This factor is used for system oscillation reduction under varying load condition. System oscillation is increased with its higher value [55–56].

The conventional SOGI algorithm with this modification known as U-SOGI and OSG block transfer function for this U-SOGI is given by.

$$f_{USOGI}(s) = \frac{\omega(s+\rho)}{(s+\rho)^2 + \omega^2} \tag{2}$$

The DC offset and inter harmonic from the load current cannot be eliminated with conventional SOGI. A LPF filter can be inserted into the system, for DC offset reduction but due to this the filter efficiency of conventional SOGI is again disrupted [57]. The conventional SOGI has more oscillation and DC offsets than U-SOGI in the magnitude of derived essential active and reactive component of load current. These current components have no oscillation and DC offsets when they are derived from the U-SOGI algorithm. For, the estimation of a different control signal, the following mathematical formulations is used in this control algorithm.

a) Extraction of PCC voltage and its unit template.

Magnitude of (V_t) PCC voltage is computed with the help of phase voltages (V_{sa}, V_{sb} and V_{sc}) and given by.

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

With the help of phase locked loop (PLL), synchronizing angle $\varnothing$ of PCC voltage is computed and which is used for estimation of unit templates [57–58]. Templates of PCC voltage are formulated as.

$$U_{pa} = \sin(\varnothing) \tag{4}$$

$$U_{pb} = \sin\left(\varnothing - 120^{\circ}\right) \tag{5}$$

$$U_{pc} = \sin\left(\varnothing - 240^{\circ}\right) \tag{6}$$

$$U_{qa} = \cos(\varnothing) \tag{7}$$

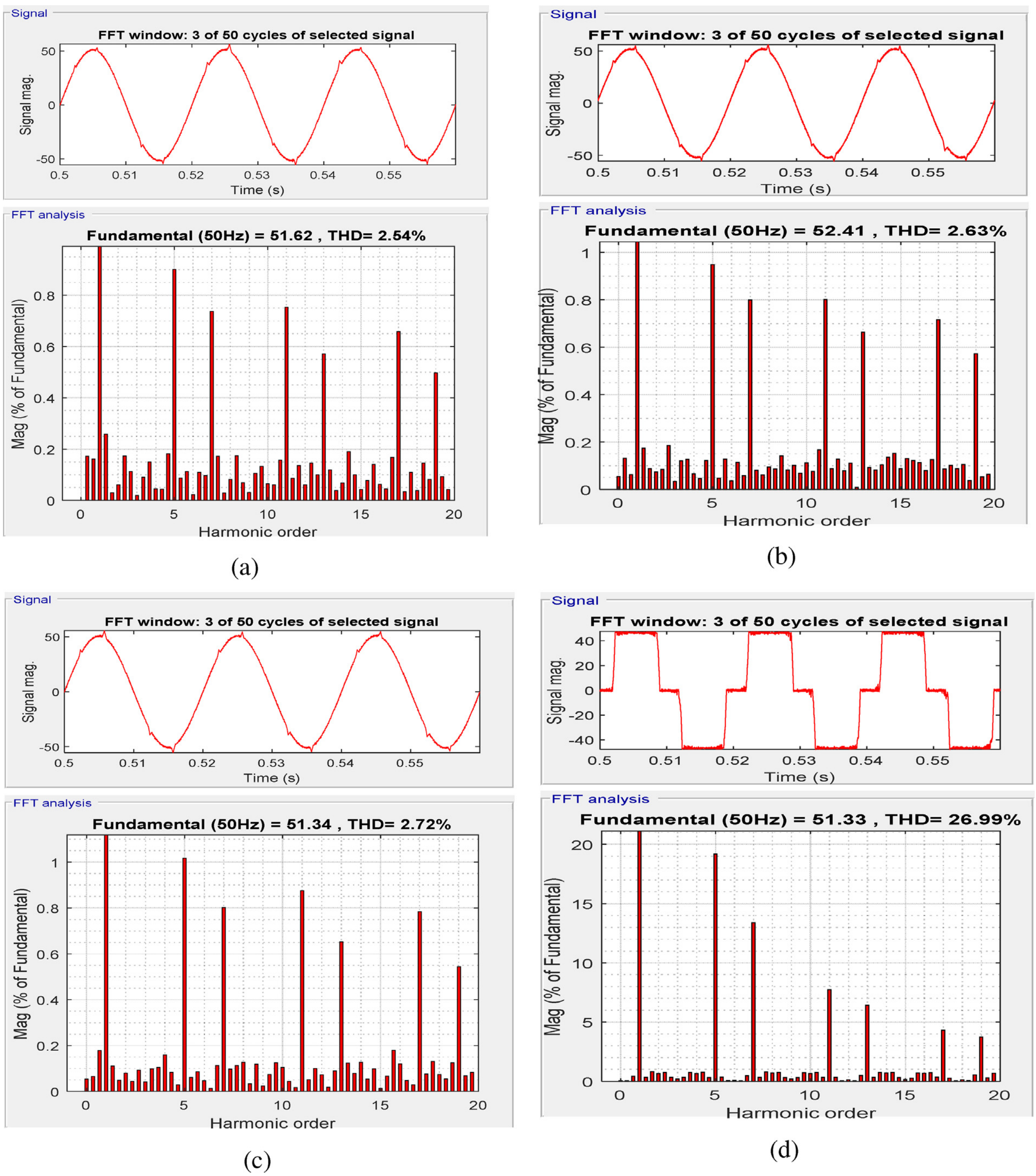

Fig. 5. In PFC mode THD spectrum with nonlinear load, (a) source current with proposed controller, (b) source current with ISOGI controller, (c) source current with SOGI controller,(d) load current.

$$U_{qb} = \cos\left(\varnothing - 120^{\circ}\right) \quad (8)$$

$$U_{qc} = \cos\left(\varnothing - 240^{\circ}\right) \quad (9)$$

b) Reference supply active and reactive current component estimation.

The active and reactive value of each phase load current peak is computed as depicted in Fig. 3. The load current I_{Labc} is supplied to U-SOGI based OSG for generation of load current peak value. The load currents, active (I_{Lpa}, I_{Lpb} and I_{Lpc}) and reactive (I_{Lqa}, I_{Lqb} and I_{Lqc}) value are computed as shown in Fig. 3. The average value of (I_{LpA}) active and (I_{LqA}) reactive, of load current is computed as:

$$I_{LpA} = \frac{I_{Lpa} + I_{Lpb} + I_{Lpc}}{3} \quad (10)$$

$$I_{LqA} = \frac{I_{Lqa} + I_{Lqb} + I_{Lqc}}{3} \quad (11)$$

The DC link voltage (V_{dc}) is subtracted from reference DC voltage (V^{*}_{dc}) for error signal generation and it is passed through DC-PI controller for control DC link voltage [59]. The DC link output

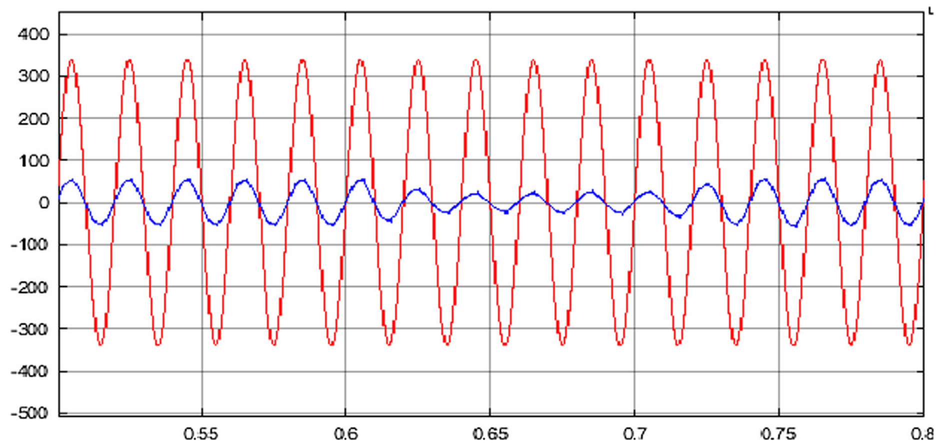

Fig. 6. Represents the source voltage and source current (x-axis in sec).

current I_P is added to the average value of active component of load current for estimation of reference source current, active value which is specified by:

$$I_{Spt} = I_P + I_{LpA} \tag{12}$$

The average value of load current, reactive value is deducted from the output current I_Q of AC link for estimation of source current, reference reactive value which is specified by:

$$I_{Sqt} = I_Q - I_{LqA} \tag{13}$$

To find the each phase active component, the source current, active component is multiplied with in phase unit templates of their respective phase as formulated below.

$$I_{sap} = I_{spt}U_{pa}, I_{sbp} = I_{spt}U_{pb}, I_{scp} = I_{spt}U_{pc} \tag{14}$$

To find the each phase reactive component, the source current reactive component is multiplied with quadrature unit templates of their respective phase as formulated below.

$$I_{saq} = I_{sqt}U_{qa}, I_{sbq} = I_{sqt}U_{qb}, I_{scq} = I_{sqt}U_{qc} \tag{15}$$

Total reference current for each phase is computed as

$$I^*_{sa} = I_{sap} + I_{saq}, I^*_{sb} = I_{sbp} + I_{sbq}, I^*_{sc} = I_{scp} + I_{scq} \tag{16}$$

The computed source reference current are deducted from supply currents for estimation of current error and this current error is given to HCC controller for gating pulse production which are used for DSTATCOM control.

4. Simulation and result discussion

Three phase linear/nonlinear load feeding from three phase AC system is developed and implemented in MATLAB 2018b. The VSC based DSTATCOM performance under dynamic condition of load is presented in time domain as below.

a) DSTATCOM performance in PFC mode under dynamic condition.

The DSTATCOM performance in PFC mode for linear load with one phase out at t = 0.6 to 0.7 s in terms of phase voltage (V_{sabc}), source current (I_{sabc}), load current (I_{La},I_{Lb},I_{Lc}), compensator current (I_{Ca},I_{Cb},I_{Cc}), and DC link DSTATCOM voltage (V_{dc}) respectively shown in Fig. 3 respectively. For dynamic linear load DSTATCOM performance is satisfactory in PFC mode for compensation of reactive power and load balancing. The proposed controller is robust under dynamic linear load condition. DC link voltage and load is balanced during dynamic condition.

The DSTATCOM performance in PFC mode for nonlinear (rectifier based nonlinear load with R = 12 Ω, L = 200mH) load with one phase out at t = 0.6 to 0.7 s in terms of phase voltage (V_{sabc}), source current (I_{sabc}), load current (I_{La}, I_{Lb}, I_{Lc}), compensator current (I_{Ca},I_{Cb}, I_{Cc}), and DC link DSTATCOM voltage (V_{dc}) respectively shown in Fig. 4 respectively. For dynamic nonlinear load DSTATCOM performance with U-SOGI controller is satisfactory in PFC mode for load balancing, reactive power compensation and harmonic compensation. Under dynamic non linear load the proposed controller is robust for regulating dc link voltage and source current THD suppression. THD spectrum for the source current of a phase are 2.54%, 2.63% and 2.72% with U-SOGI, I-SOGI and SOGI respectively and for load current is 26.99% shown in Fig. 5 (a, b, c and d). Fig. 6 represents the source voltage and current shows waveforms from which it is clear that both are in same phase so the power factor is unity.

b) DSTATCOM performance in ZVR mode under dynamic condition.

The (V_{pcc}) PCC voltage is regulated by injecting the required leading reactive power in the system in ZVR mode of DSTATCOM operation. The DSTATCOM performance in this mode, for linear load with one phase out at t = 0.6 to 0.7 s in terms of phase voltage (V_{sabc}), source current(I_{sabc}), load current (I_{La},I_{Lb},I_{Lc}), compensator current (I_{Ca},I_{Cb},I_{Cc}), PCC voltage amplitude(V_{pcc}) and DC link DSTATCOM voltage(V_{dc}) respectively shown in Fig. 7 respectively. For dynamic load DSTATCOM performance is satisfactory for load balancing, voltage regulation and reactive power compensation. The proposed controller with dynamic linear load is also robust in ZVR mode for DC link voltage regulation, PCC voltage regulation and load current balancing.

The DSTATCOM performance in this mode for nonlinear (rectifier based nonlinear load with R = 12 Ω, L = 200mH) load with one phase out at t = 0.6 to 0.7 s in terms of phase voltage (V_{sabc}), source current (I_{sabc}), load current (I_{La},I_{Lb},I_{Lc}), compensator current (I_{Ca},I_{Cb},I_{Cc}), PCC voltage amplitude(V_{pcc}) and DC link DSTATCOM voltage(V_{dc}) respectively shown in Fig. 8 respectively. Under nonlinear dynamic load the proposed controller is robust in terms of PCC voltage and DC link voltage regulation and source current THD suppression. THD spectrum for source a phase current are 2.71%, 2.96% and 2.97 % with U-SOGI,I-SOGI and SOGI respectively and for load current is 26.93% shown in Fig. 9(a, b, c and d). For dynamic nonlinear load DSTATCOM performance is satisfactory in this mode for load balancing, voltage regulation, reactive power compensation and harmonic compensation. Fig. 10 represents

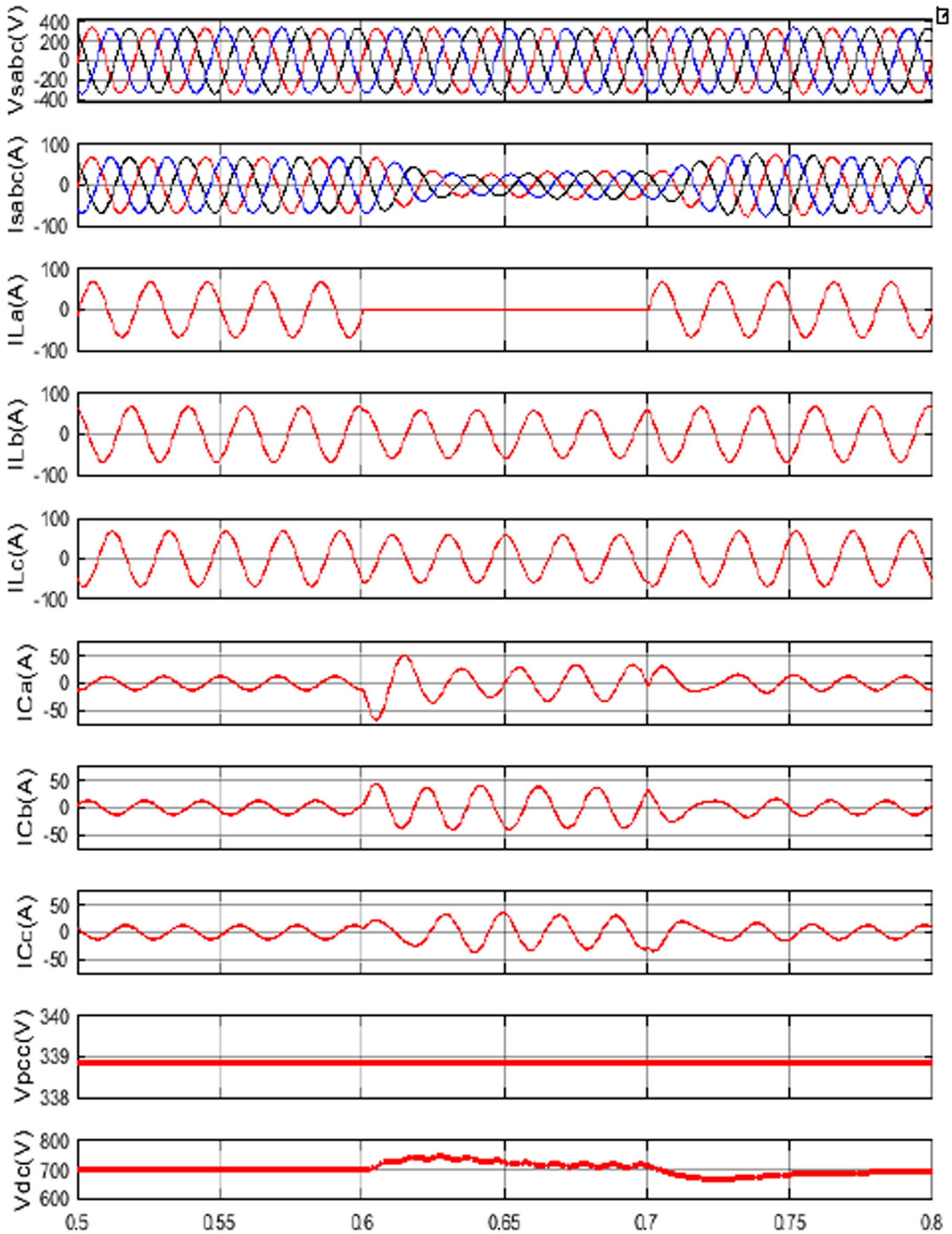

Fig. 7. ZVR mode DSTATCOM performances with linear load (x-axis in sec).

source voltage and current waveforms, from which it is clear that both are in same phase so the power factor is unity..

c) Proposed controller stability analyses and DC offset removal capability study.

In the proposed control technique, the gains K1 and K2 are added in the conventional SOGI structure for removal of DC offset current and a damping factor ρ is also added to conventional SOGI structure to reduce the between true and sensed value. This ρ damping factor also reduces the oscillations during dynamic load conditions. Here, ω is the frequency in radian per second. The ρ is selected for positive and negative values, for negative values the system is unstable as in S-plane pole-zeros are lie in right which is presented in Fig. 11a.. The larger value of ρ increases the oscillations in the proposed system. The value of damping factor is tuned to 0.9 and this value works satisfactory for all type of load currents.

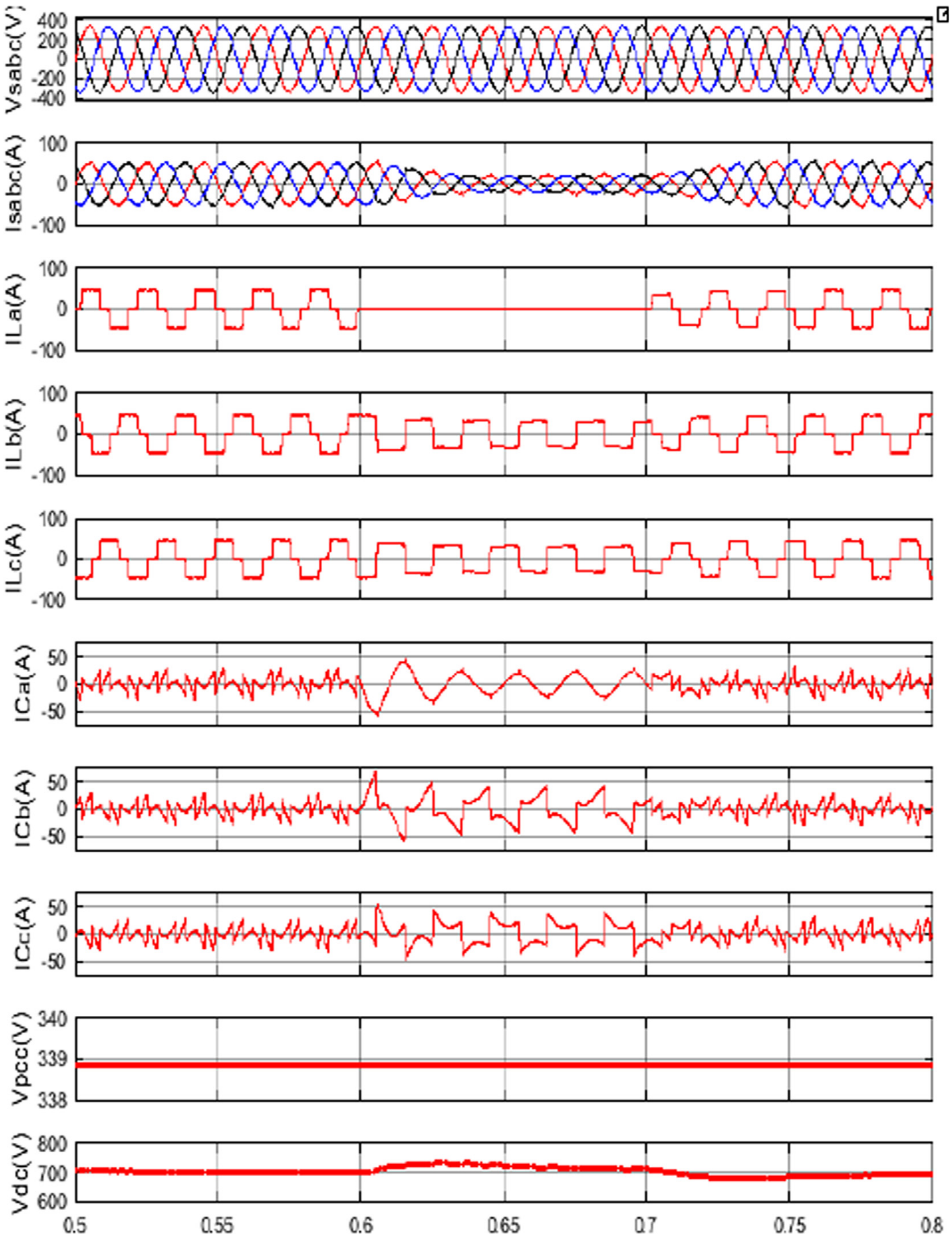

Fig. 8. ZVR mode DSTATCOM performances with nonlinear load (x-axis in sec).

Bode plot for the conventional SOGI and proposed SOGI controller is depicted in Fig. 11(b). From bode plot their stability are compared with the help of gain and phase margin. It is observed from bode plot both the controller are stable. Moreover the stability of U-SOGI is better than the conventional SOGI as the gain margin of U-SOGI is infinity and the conventional SOGI is incapable for the removal of DC offset from the input load current which is presented in Fig. 11(c).

d) Comparative Analysis of proposed controller with the existing controllers.

The detailed comparative analysis of the proposed controller with classical controllers is presented in tabular form as well as

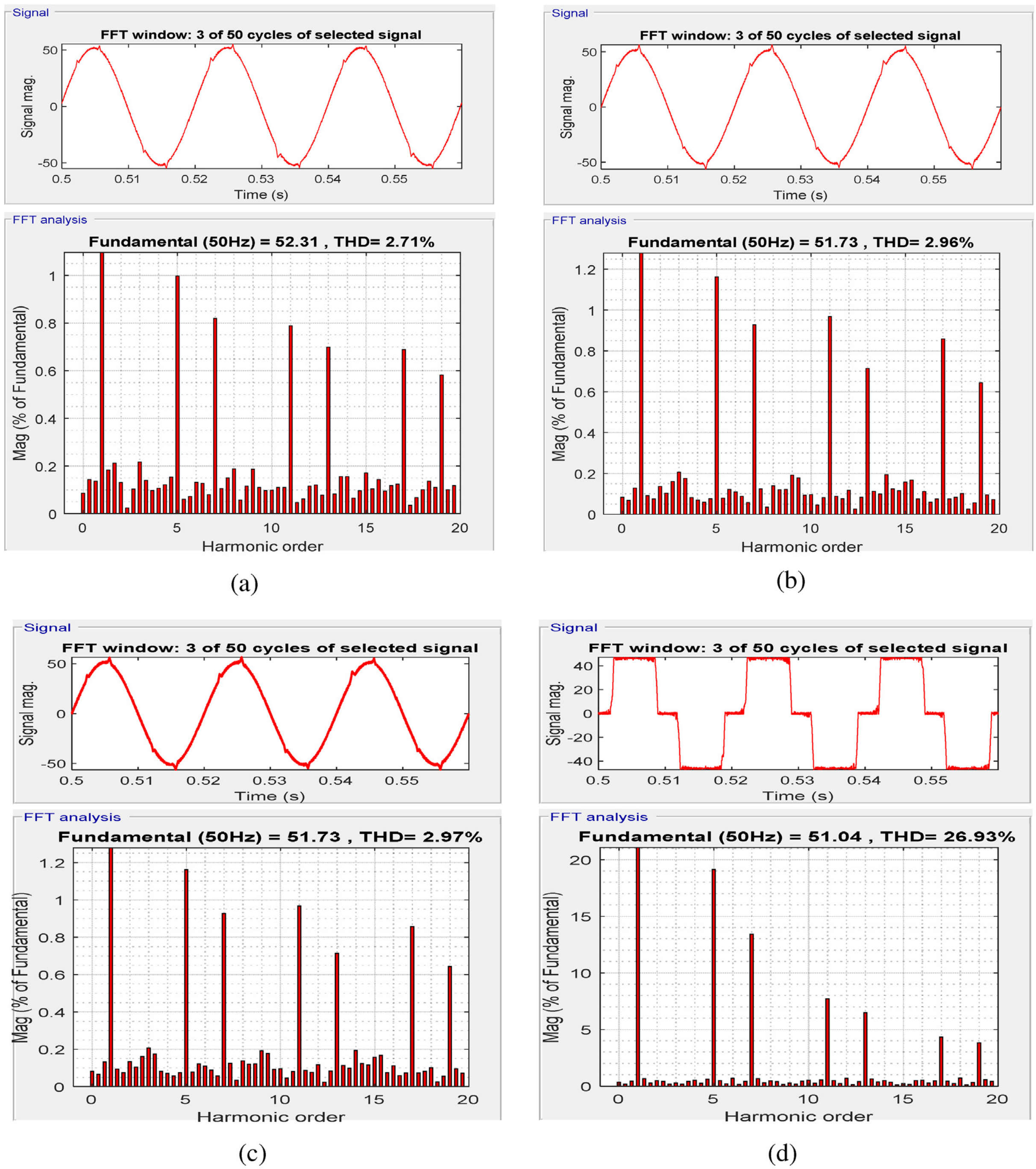

Fig. 9. In ZVR mode THD spectrum with nonlinear load, (a) source current with proposed controller, (b) source current with ISOGI controller, (c) source current with SOGI controller, (d) load current.

graphical form. In the proposed structure, the overall complexity reduces the stress on the digital controller. In the comparative study, the THD level under different modes of operation, complexity level, reference current generation speed, sampling time requirement and DC offset level are considered for all the three control structures namely; SOGI, I-SOGI and U-SOGI.

The THD comparison for the controllers in PFC and ZVR mode of DSTATCOM operation are discussed and presented in part (a & b) of result section. Now the Fig. 12 (a, b and c) describe the performance of SOGI, ISOGI and U-SOGI under unbalanced grid voltage condition and from the Fig. 13 (a, b, c &d) it is clear that the proposed controller is for harmonic elimination. Table 1 shows the numerical value analysis of different parameters for all three structures whereas Furthermore, the proposed controller is more suitable for practical implementation under different practical scenario and works superior to the I-SOGI and SOGI controller in

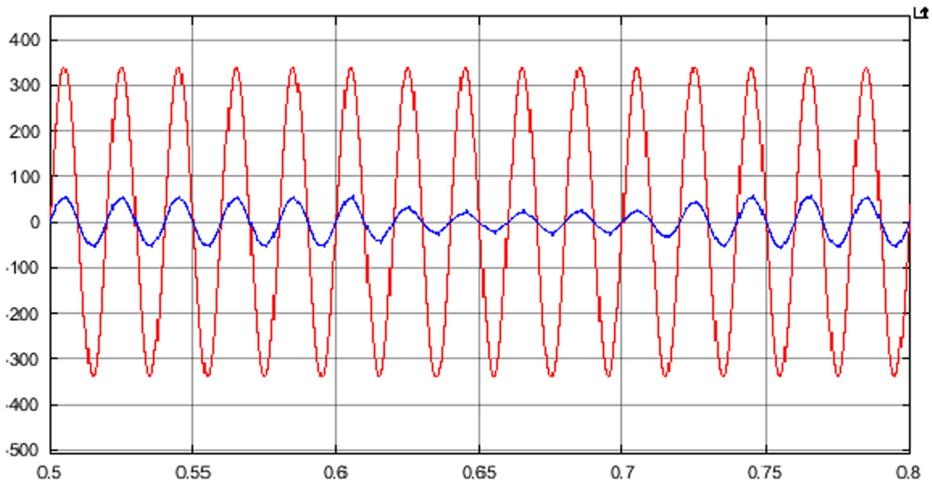

Fig. 10. Waveforms source voltage and source current (x-axis in sec).

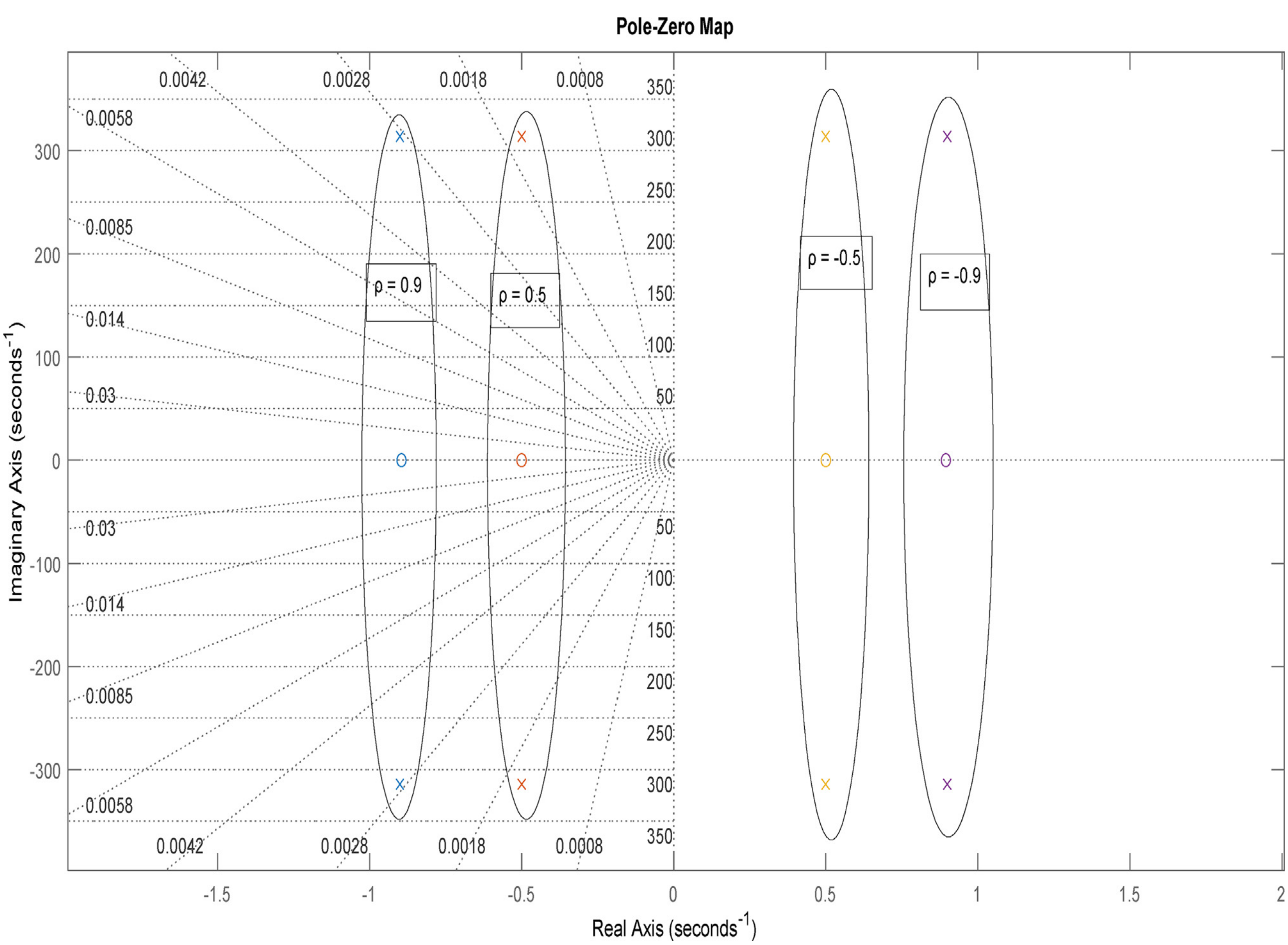

Fig. 11a. Pole zero plot of U-SOGI.

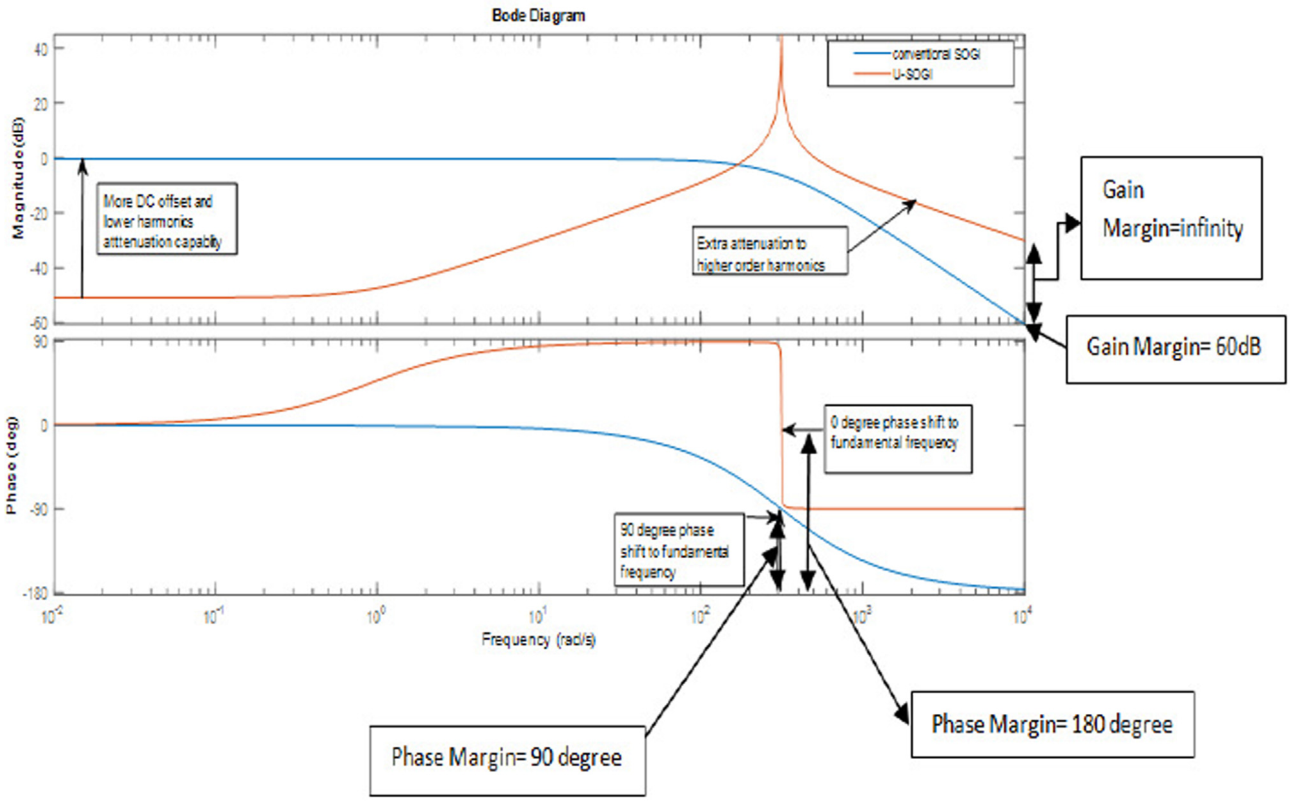

Fig. 11b. Bode plot for SOGI and U-SOGI controller.

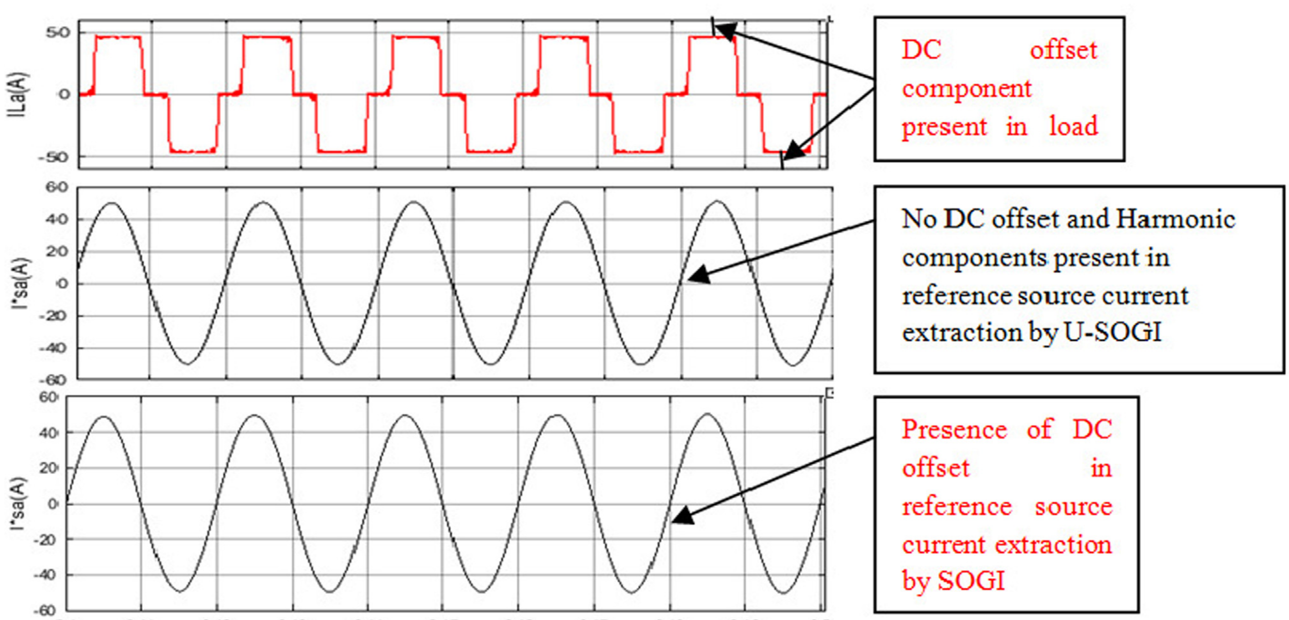

Fig. 11c. Shows the DC offsets removal capability of U-SOGI over the SOGI (x-axis in sec).

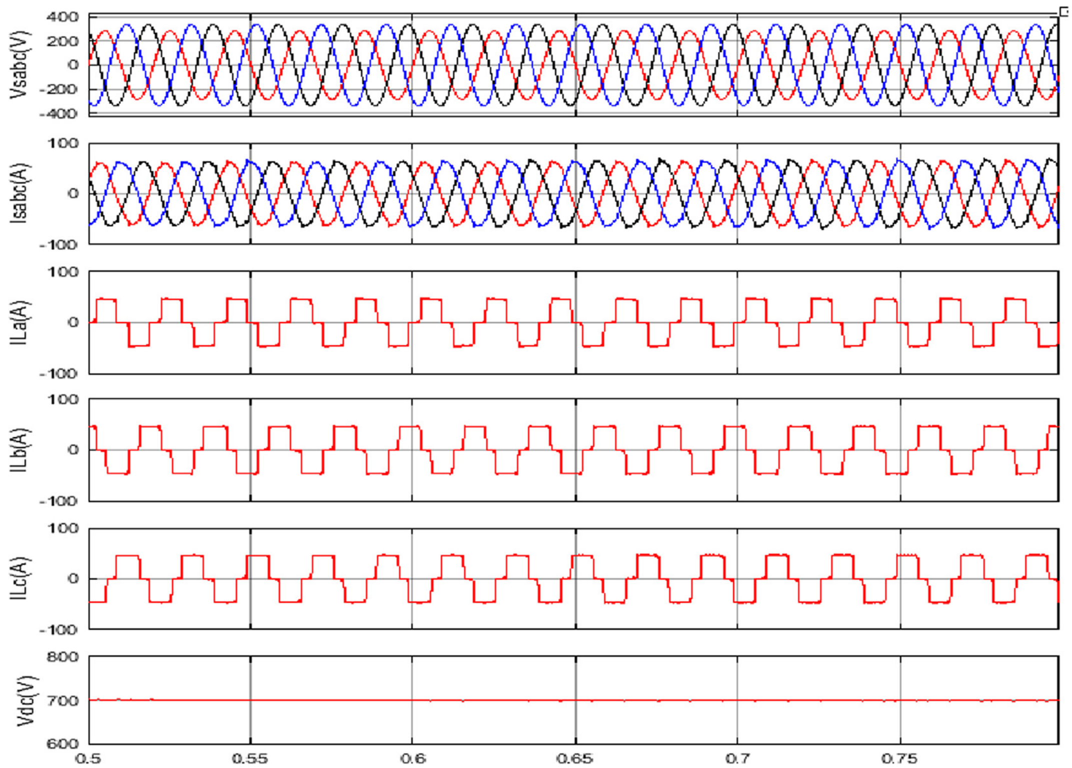

Fig. 12a. Performance of DSTATCOM under unbalanced grid voltage with SOGI controller (x-axis in sec).

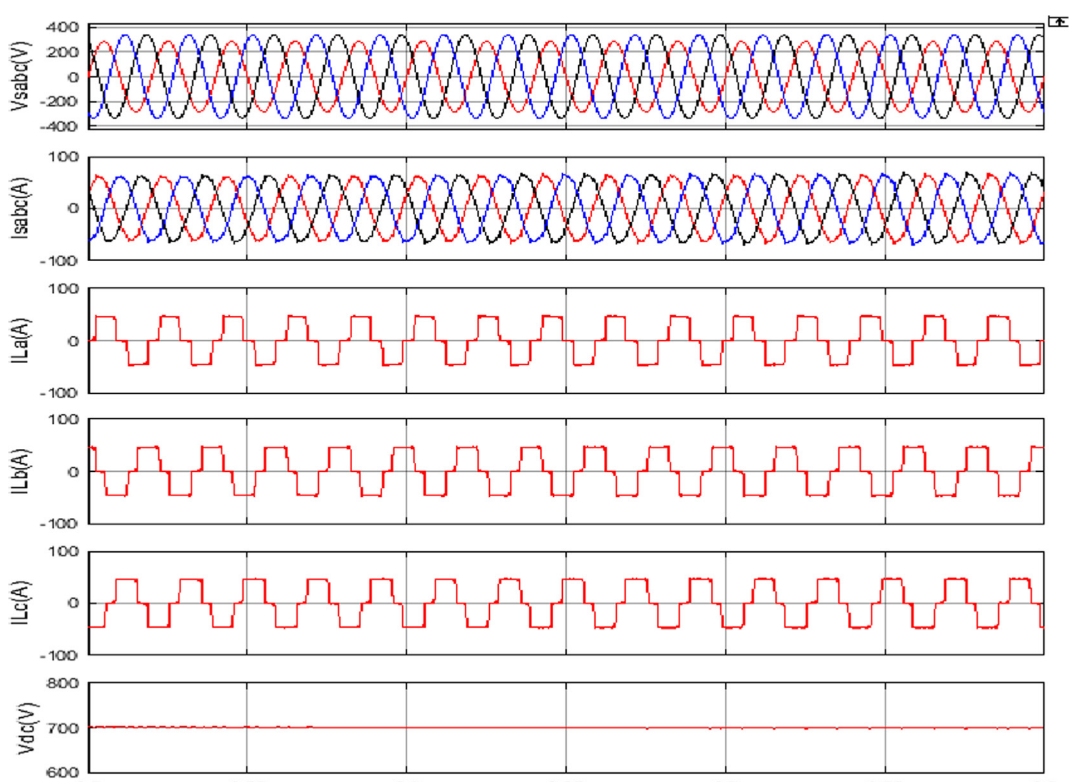

Fig. 12b. Performance of DSTATCOM under unbalanced grid voltage with ISOGI controller (x-axis in sec).

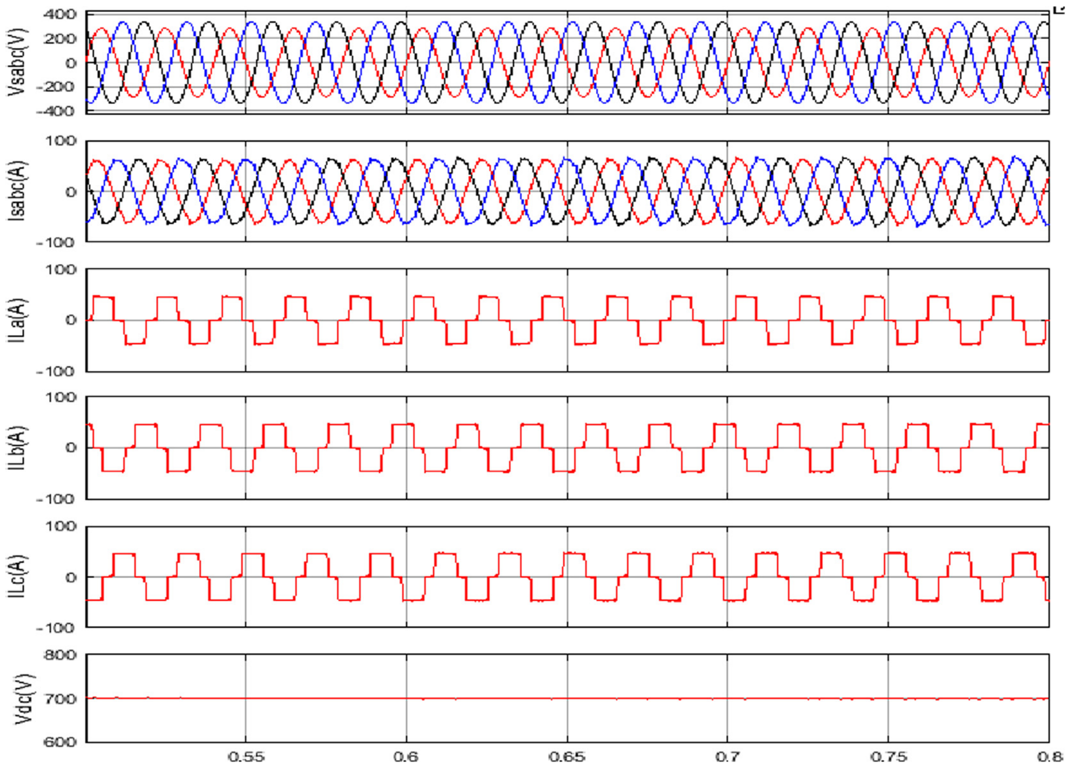

Fig. 12c. Performance of DSTATCOM under unbalanced grid voltage with U-SOGI controller (x-axis in sec).

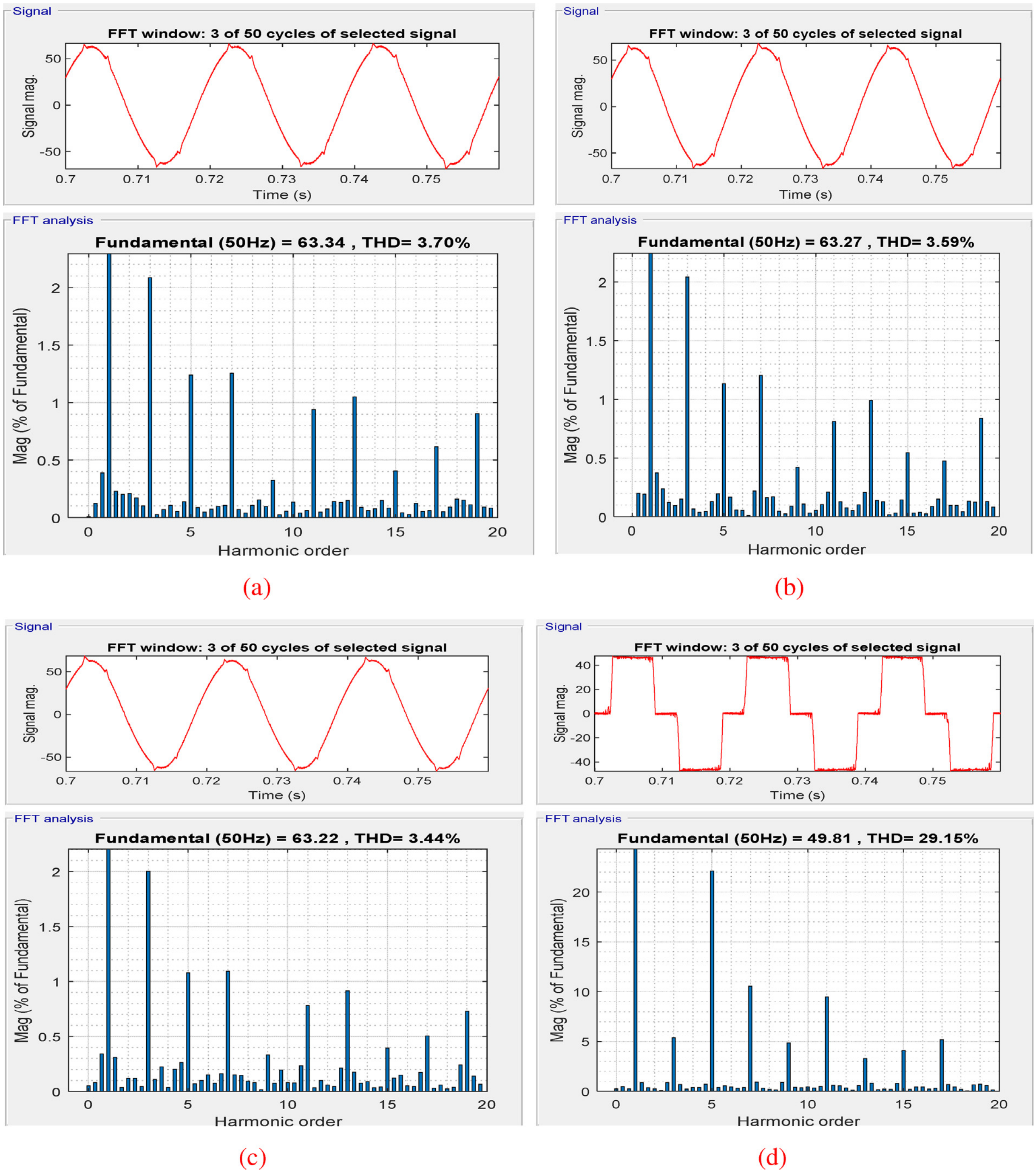

Fig. 13. Source current THD spectrum with (a) SOGI, (b) I-SOGI, (c) U-SOGI controller and (d) load current THD spectrum.

Table1
Comparison of existing control techniques with proposed technique.

Parameters	SOGI	I-SOGI	U-SOGI
Source Current THD (PFC mode)	2.72%	2.63%	2.54%
Source Current THD ZVR Mode	2.97%	2.96%	2.71%
Source current THD under grid voltage unbalanced condition	3.70%	3.59%	3.44%
Complexity Level	+++	++	+
Reference Current Generation Speed	Medium	Medium	High
Sampling Time Requirement	85 µsec	71 µsec	65 µsec
Percentage DC-offset	10%	8%	5%

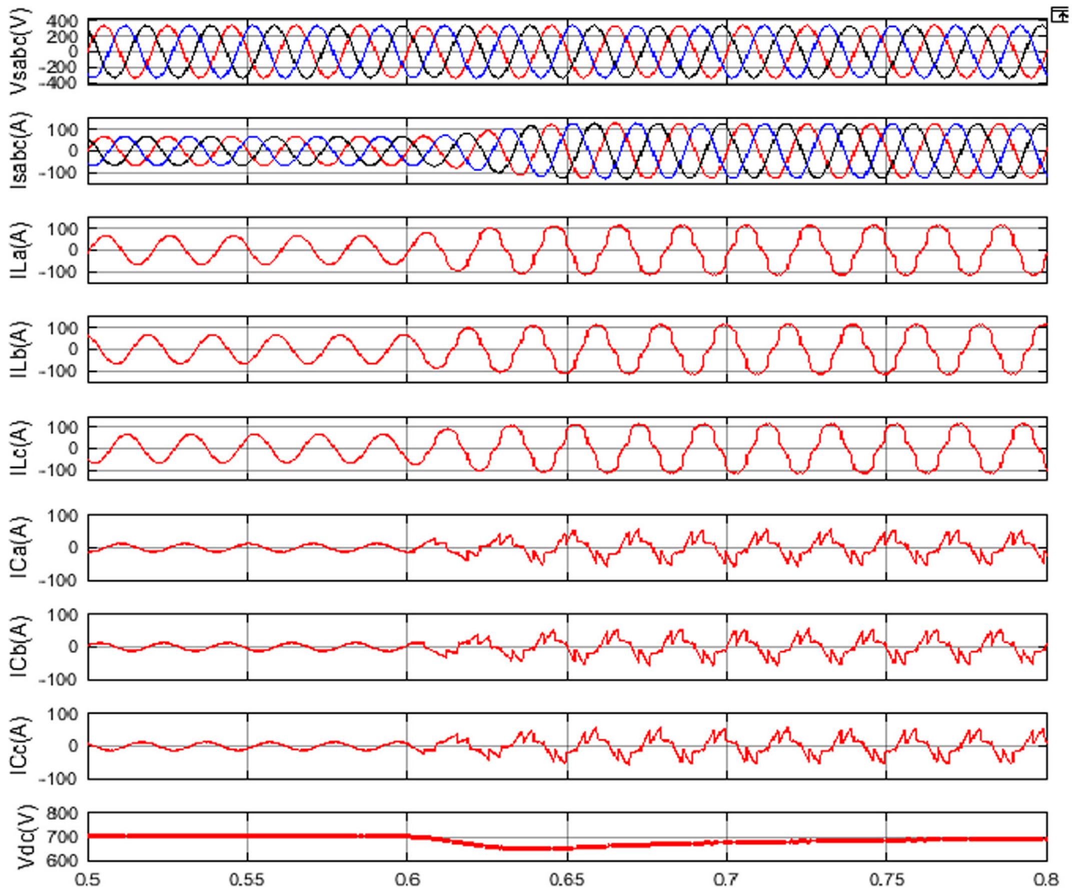

Fig. 14. Robustness of controller with DSTATCOM in PFC mode (x-axis in sec).

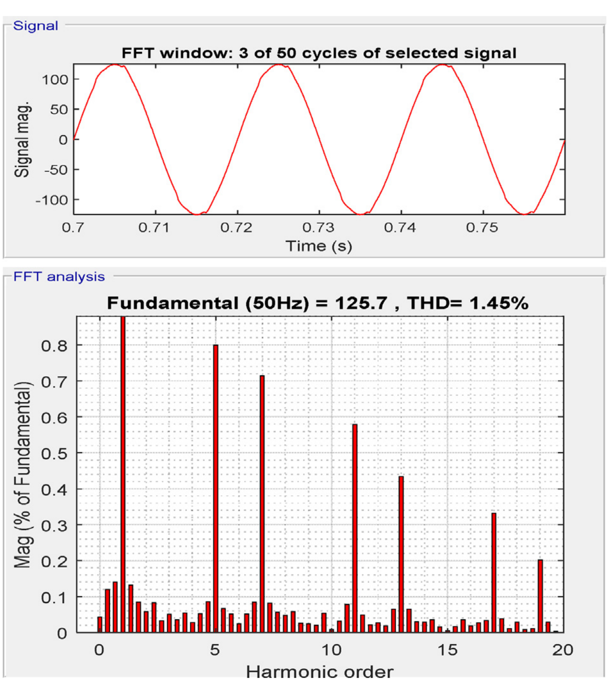

Fig. 15. THD spectrum of, (a) source current, (b) load current.

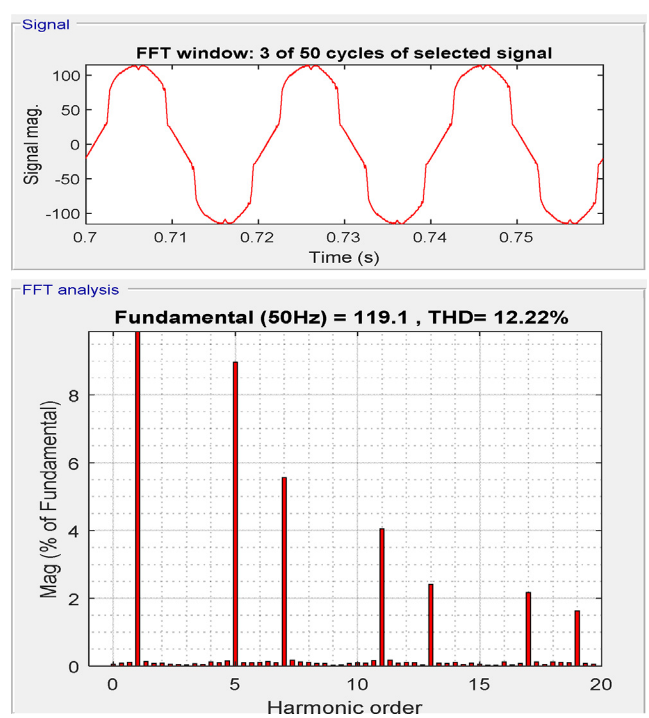

Fig. 15 (*continued*)

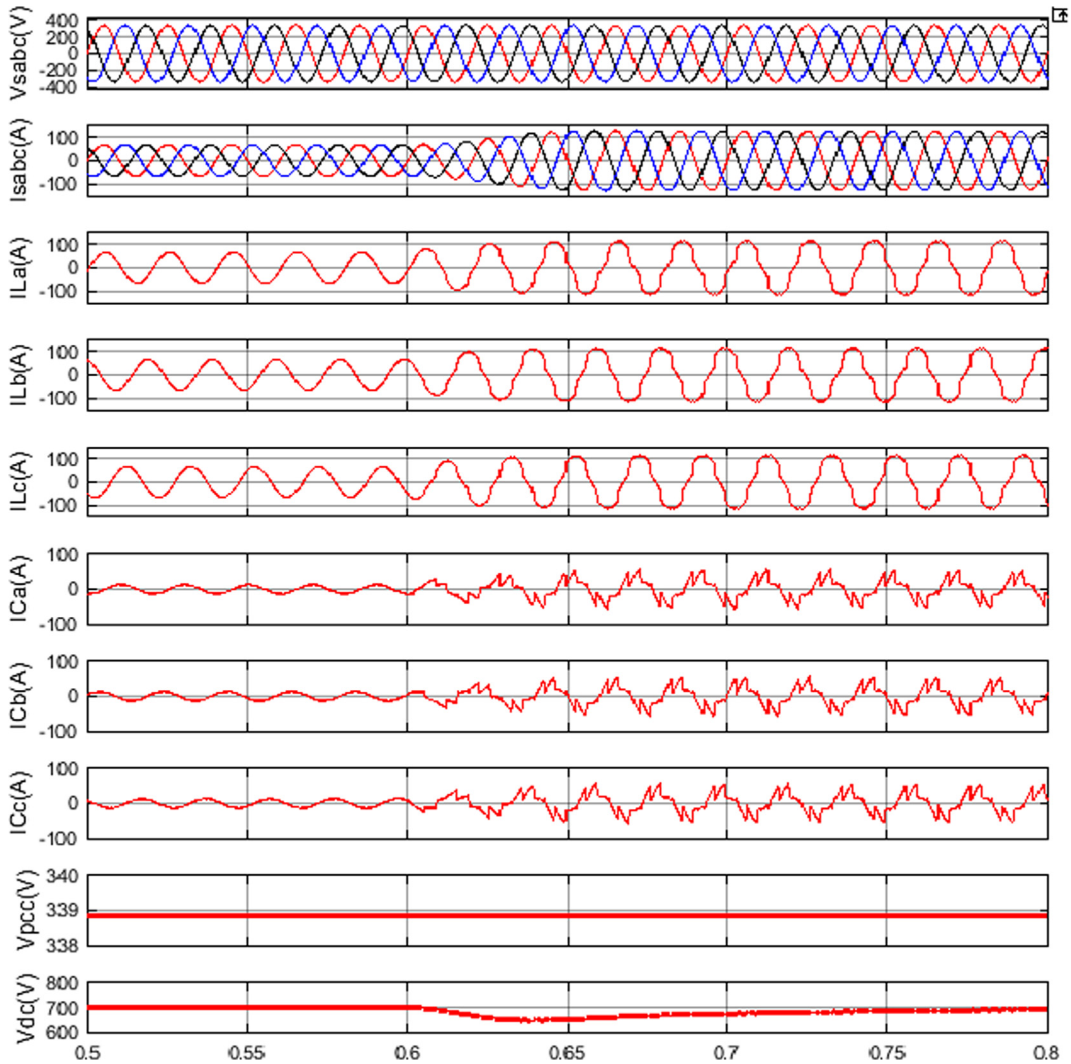

Fig. 16. Robustness of proposed controller with DSTATCOM in ZVR mode (x-axis in sec).

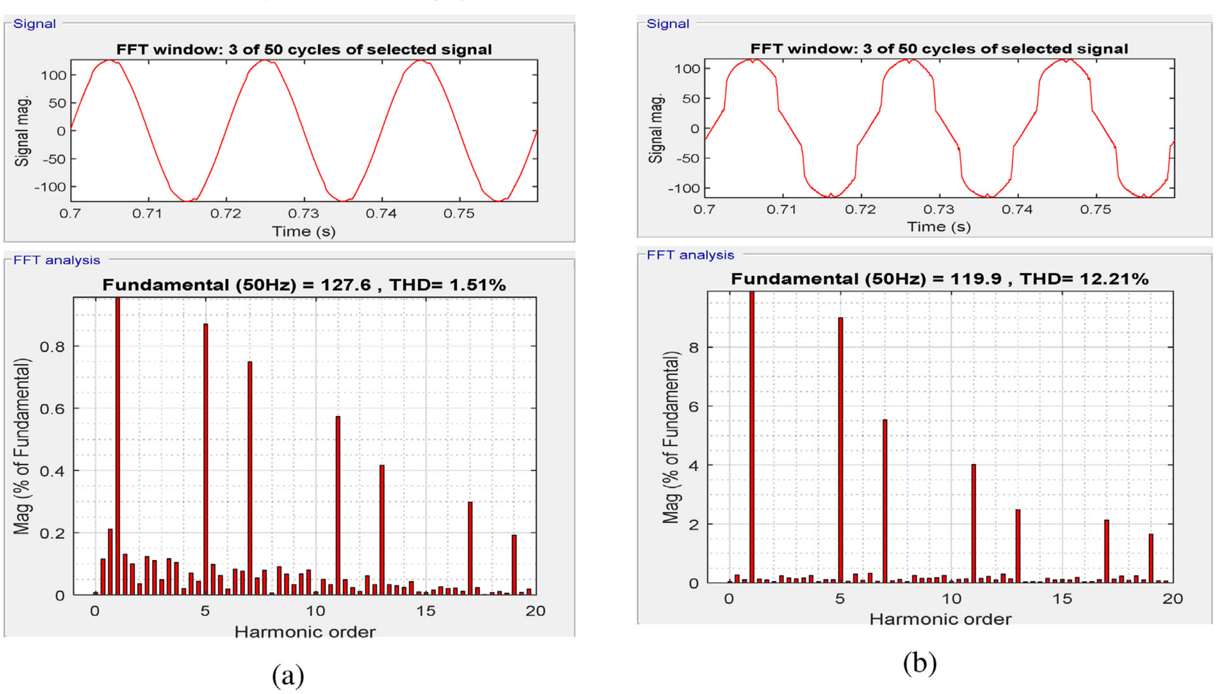

Fig. 17. THD spectrum of, (a) source current, (b) load current.

terms of DC offsets elimination, memory requirement and source side harmonic elimination.

e) Robustness of Proposed controller.

To check the robustness of proposed controller and it is also tested with the combination of linear as well as nonlinear load.

1 Nonlinear is added in existing linear load in PFC mode of DSTATCOM.

In PFC mode of DSTATCOM with linear load (40kVA, 0.8 pf) and an additional nonlinear load (rectifier based nonlinear load with R = 12 Ω, L = 200mH) is added at t = 0.6 s, the results are analyse in terms of phase voltage (V_{sabc}), source current(I_{sabc}), load current (I_{La},I_{Lb},I_{Lc}), compensator current (I_{Ca},I_{Cb},I_{Cc}), and DC link DSTATCOM voltage(V_{dc}) respectively shown in Fig. 14 respectively. The source current is sinusoidal and DC link voltage is also maintained constant even at t = 0.6 s when the additional load is added in the distribution system. Source THD is also within the IEEE standard which is 1.45% and load THD is 12.22% as shown in Fig. 15 (a & b) respectively. DSTATCOM performance is satisfactory in PFC mode for compensation of reactive power and load balancing.

2 Nonlinear is added in existing linear load in ZVR mode of DSTATCOM.

In ZVR mode of DSTATCOM with linear load(40kVA, 0.8 pf) and an additional nonlinear load (rectifier based nonlinear load with R = 12 Ω, L = 200mH) is added at t = 0.6 s, the results are analyze in terms of phase voltage (V_{sabc}), source current(I_{sabc}), load current a,b,c phase (I_{La},I_{Lb},I_{Lc}), compensator current a,b,c phase(I_{Ca},I_{Cb},I_{Cc}), coupling point voltage(V_{pcc}) and DC link DSTATCOM voltage(V_{dc}) respectively shown in Fig. 16 respectively. The source current is sinusoidal and DC link voltage is also maintained constant even at t = 0.6 s when the additional load is added in the distribution system. Source THD is also within the IEEE standard which is 1.51% and load THD is 12.21% as shown in Fig. 17 (a & b) respectively. DSTATCOM performance is satisfactory in this mode for load balancing, voltage regulation, reactive power compensation and harmonic compensation.

The proposed controller is robust in terms of source current harmonic mitigation, DC link voltage regulation, reactive power compensation and load balancing in distribution system with different load combination.

5. Conclusions

In this manuscript, an upgrade SOGI based control structure has been implemented to generate the inverter reference current for estimation of desired harmonic content. The proposed structure has been designed with help of simple mathematical operators such that the sampling time reduced to a substantially low level. In view of this, the speed of the reference current generation increased to very good level and provides a better dynamic response. The proposed controller has improved the source current wave shape and reduces the THD level to well below 5% to comply with the IEEE standard. Moreover, this structure has been beneficial in the practical situation in order to provide load balancing; reactive power compensation, PCC voltage regulation and DC link voltage regulation. Furthermore, the comparative study has been included to show the superiority of U-SOGI based controller over SOGI and ISOGI in terms of cost, harmonic elimination, less memory requirement and DC offset elimination. Finally, it can be aptly conclude that the proposed controller is much simpler in structure, robust and very effective for controlling the harmonics, voltage levels and DC offsets for various operating conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Three phase line to line voltage 415 V, 50 Hz, with resistance R_s = 0.07 Ω and inductance L_s = 2mH.Load, (a) linear load of 40kVA, 0.8 pf and (b) rectifier based nonlinear load with R = 12 Ω, L = 200mH.DSTATCOM parameters V^*_{dc} reference DC voltage 700 V, coupling inductor 4mH, DC bus capacitance = 10000μF. Parameters for U-SOGI controller K_1 = 4, K_2 = 5 and ρ = 0.9.

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