An Fundamental Current Reference Control Strategy for DSTATCOM under Various Load Situations

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Abstract
Effort for power quality enhancement is gradually raised in power transmission and distribution system. In a distribution system, it is a pre-requisite consumer related concern which is addressed by evading the mis-operation of massive power electronic load apparatus. Due to this, voltage/current harmonic distortions are acquired at common coupling point, which influences the disruption of quality power in a distribution system. A reliable and efficient active power conditioner is utilized for acquiring the power quality features in a three phase distribution system with attractive control objective. Over the classical conditioning techniques, a D-STATCOM plays a key role in a distribution system for power quality enhancement. Formal control objectives are adversed with incredible switching losses due to extreme harmonized frequencies in a reference current component. This paper proposes the imperative reference current extraction scheme for optimal functioning of DSTATCOM with reduced switching losses and gaining the incredible efficiency. The validation of DSTATCOM with proposed control strategy under several load situations (linear/non-linear & balanced/un-balanced) is evaluated by using Matlab/Simulink platform and simulation results are conferred.

Keywords: D-STATCOM, Fundamental Reference Current Extraction Id-Iq Control Scheme, Power Quality Improvement, Several Load Situations

1. Introduction

The utilization of electrical power is intensified by several bounds and leaps in order to enhance the standard living at present days. The eminent provocations are required for generation of highly qualified energy with respect to greater reliability and standard limits at decent consequences. Now-a-days the increased attention on power quality (PQ) concerns is affected the end-user level commercial and industrial consumers. Majorly, power distribution system is deteriorated from the current/voltage related power quality concerns, which includes current harmonics, reactive power compensation, power factor correction, un-balance loading effects, and sag/swell. In that harmonic content creates major effects, due to the presence of non-linear characterization of power-electronic load apparatus [1].

These power quality concerns in power distribution systems are not new, but the awareness of these issues has been increased recently by end-user consumers. Non-linear load devices stimulus the impressive harmonized current components with non-unity power factor, which initiates the crucial obstacles at PCC level. Classical, power quality mitigation schemes are available in older days consisting of passive power filters and static capacitors, which are integrated in parallel to the PCC/load. Several demerits are illustrated in [1-3], such as only fixed harmonic mitigation, massive size, low response and may form the resonance issues with the line impedances. An advanced custom power device based active compensation scheme is utilized for enhancement of abovementioned power quality concerns [4].

The custom power devices plays a crucial role in power distribution systems consisting of power semi-conductor technology to regulate the power quality, better reliable function, as well value-add on to end-user level consumers. Various custom power devices (CPD) strategies are used to furnish the power quality issues such as static synchronous compensator (STATCOM) used in greater than 11KV transmission line to compensate the reactive power in [5], the efficient static compensation is integrated in distribution level called as D-STATCOM

used in under/below 11KV rating. In that DSTATCOM plays a crucial role in distribution system interfaced as shunt device to compensate the current related issues such as current harmonics, compensation of reactive power, power factor correction, unbalanced loading effect etc.

The D-STATCOM injects the related harmonics components of distorted current based on generation of reference current signals coming from control objective such that harmonized, reactive, unbalanced devices are transformed into equivalent balanced resistive linear load apparatus as explored in [6]. The main theme of control scheme performs the optimal functioning & proper behaviour of a respective compensation scheme to generate attractive switching states to attain the definite compensation task [7, 8]. Several control strategies are already reviewed by several literatures, such as instantaneous real-reactive power theory [9], synchronous reference frame (Id-Iq) theory [10], symmetrical power component theory [11], etc. The classical control objectives generates the reference current signal to DSTATCOM which consisting of very high switching frequencies. Due to these the switching losses are increased with respect to switch stress and reducing the over-all compensation efficiency.

This paper illustrates the implementation of novel control strategy for active compensation of DSTATCOM in a three phase distribution system. The modified fundamental reference Id-Iq control strategy is designed to extract the superlative reference current signal to improve the power quality features as well as overcome the problems coming from the classical Id-Iq control strategy. The validation of proposed control strategy fed DSTATCOM compensation under several load conditions like balanced/unbalanced, linear/non-linear situations are evaluated with the help of Matlab/Simulink tool and results are conferred which evaluates the effectiveness of the proposed control strategy.

2. Proposed DSTATCOM Configuration

A DSTATCOM is distributed static compensator is interfaced at PCC level to enhance the PQ features employed in a three phase power distribution system. It consists of three phase 2-level voltage source inverter (VSI), DC-link capacitor, control objective, gate-drive configuration, LC filter units, loads used in this configuration are linear and non-linear load devices which may be integrated as both balanced and un-balanced elements [12]. The circuit configuration of proposed DSTATCOM scheme is depicted in Figure 1; it is integrated at the PCC in a three phase power distribution system. The elements V_{sabc}, I_{sabc}, V_{Labc}, and I_{Labc} are the source voltage, source current, load voltage and load current as well Z_{sabc} constitute the source impedances in a three phase sequences respectively. The load treated as both linear as well non-linear load devices as diode bridge rectifier supported the RL-load with a balanced/unbalanced load situation [13]. The DC-link capacitor is used to withstand the PCC voltages as a constant and acts the input of voltage source inverter which is represented as C_{dc}, voltage sustains across the DC-link capacitor is V_{dc}.
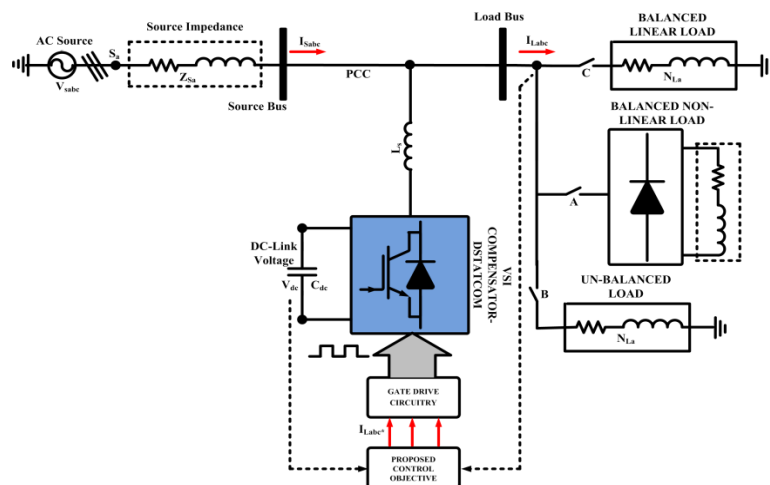

Figure 1. The Circuit Configuration of Proposed DSTATCOM Compensation Scheme

Significant filter units are connected at the front-end of the VSI to attain the standard voltage and compensation current at the PCC. The performance of DSTATCOM is well-defined based on the active-filtering technique with respect to attractive control objective. It is highly needed for riddling the harmonic switching which is produced by VSI compensation. In order to acquire the perfect compensation principle, the DSTATCOM administers the currents at PCC for proper harmonic suppression, reactive power compensation, power factor correction, etc., based on in-phase compensation principle. Provoking the current injection process with maintaining the voltages as constant based on DC-link capacitor as well control objectives [14-16]. The appropriate control objective furnishes the switching states for DSTATCOM by precise sensing of source voltage and load currents. Generally, various control objectives are used in DSTATCOM compensation scheme, in that synchronous reference frame (I_d-I_q) theory plays a prominent role to generate the reference current signal. It comprising of high switching frequency, these high range switching frequencies influences the high switch stress, greater switching losses, accomplishes the un-speculated efficiency. Moreover, the attained issues in classical i_d-i_q control objective are overcome by proposed fundamental switching frequency technique, the generation of switching states in proposed scheme at fundamental frequency which effectuates the low switch stress, low switching losses, incredible efficiency.

3. Proposed Fundamental Frequency Based Id-Iq Control Strategy Fed DSTATCOM

The evaluation of modified fundamental frequency I_d-I_q technique is generally developed based on I_d-I_q theory by the use of instantaneous reactive and active current integrants with the favour of desired current sequences generated from the load apparatus. The formation of proposed control theory is same as regular synchronous reference frame (SRF) theory as direct and quadrature axis. A dual transformation process is provoked by optimum inter-relation in between the stationary and rotating reference switching sequences. At first the phase quantities of load current (I_{Labc}) is transformed into stationary reference frame methodology ($I_{L\alpha}$-$I_{L\beta}$) by using Clarke's transformation process as well; the rotating frame sequence as direct axis and quadrature axis of load current (I_{Ld}, I_{Lq}) components are positioned from the stationary reference frame technique by using Park's transformation process by utilizing the angle (θ). The pertained transformation equations of three phase quantities to two-axis quantities as shown in (1), (2) and (3) are illustrated by the Clarke's & Park's transformation process which are applied to certain phase sequences.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} cos\omega t & sin\omega t \\ -sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \overline{i_{Ld}} + \widetilde{i_{Ld}} \\ \overline{i_{Lq}} + \widetilde{i_{Lq}} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \overline{i_{Ld}} + \widetilde{i_{Ld}} \\ 0 \end{bmatrix} \tag{5}$$

Where, $\overline{i_{Ld}}$ & $\widetilde{i_{Ld}}$ constitutes as DC/AC component of load current on d-q frame, the respective two-axis load current components on regular d-q frame is shown in Equation (4) and proposed d-q frame the q-component is pretended as zero (0) shown in Equation (5). The DC-link controller is recruited to maintain the DC-link voltage as constant for acquiring the proper compensation principle. For maintaining DC-link voltage a PI regulator is employed between the

reference DC-link voltage (V_{dcref}) and actual DC-link voltage (V_{dcact}) to suppress the error quantities for measuring the precise value of P_{Loss} component.

$$V_{dcerr} = V_{dcref}^* - V_{dcact} \tag{6}$$

From the Eqnuation (5), it should be represented as d-q load current sequences consisting of single term and using low pass filter to distinct the fundamental frequency of $\widetilde{i_{Ld}}$ integrant with the proper selection of cut-off frequency. Attaned fundamental refernce current on d-frame i_{Ld} with i_{Lq} as zero are re-transformed into actual three phase load current quantities ($I_{Labc}*$) by engaging inverse Park's & Clarke's transformation process as depicted in Eqn. (7) and Eqn. (8).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} cos\omega t & -sin\omega t \\ sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$

The reference current component is extracted by summation of P_{Lerr} component and active fundamental component is known as reference current for active compensation to improve the PQ features in a distribution system. These reference current signals in phase quantities ($I_{Labc}*$) are compared with actual line currents for generation of reference signal to furnish the pulse width modulation technique which is used to produce the optimum switching states at fundamental frequency to control the DSTATCOM for enhancing PQ features under several load situations. The over-all schematic diagram of fundamental reference current extraction based Id-Iq theory fed DSTATCOM is depicted in Figure 2.
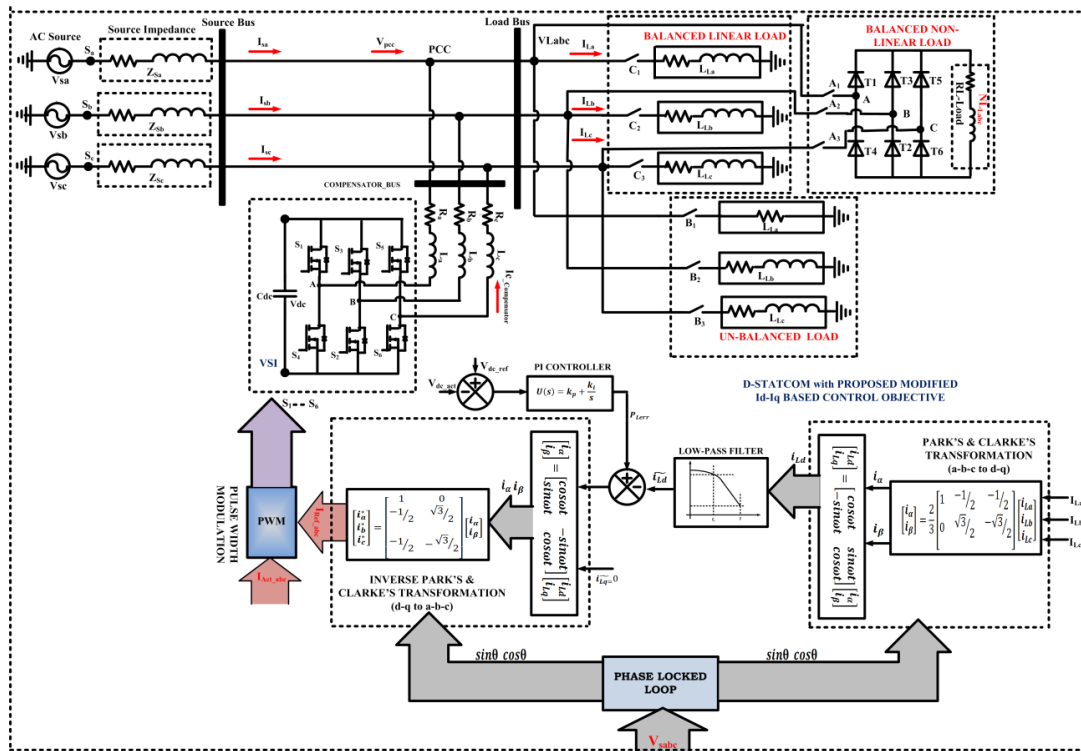

Figure 2. Over-all Schematic Diagram of Proposed Fundamental Reference Current Extraction Based Id-Iq Theory Fed DSTATCOM

3. Simulation Results

The simulation analysis is conveyed by implementation of distributed compensation (DSTATCOM) scheme in a three phase power distribution systems using proposed fundamental frequency based reference current extraction based Id-Iq theory under several load situations.

The proposed control objective is clearly evaluated with proper schematic way under several load conditions, such as linear/non-linear load with balanced & un-balanced sequence. The particular load system is alternatively conducted by proper switching sequence as A, B, C switches by additional generation as depicted in above Figure 2. The system parameters of the proposed DSTATCOM scheme with intended control objective under several load situations are clearly illustrated in above Table 1.

3.1. Three Phase Distribution System under Non-Presence of DSTATCOM

Figure 3 (a-f) illustrates the various simulation outcomes of three phase distribution system non-presence of DSTATCOM, in that (a) Source Voltage, (b) Source Current, (c) Load Current, (d) THD of Source Current, (e) Source Power Factor, (f) Load Power Factor, respectively. In this case load is treated as the balanced non-linear load, due to the NL-load device the PCC currents goes to affects as a harmonized components which is reflected the PQ concerns. Without DSTATCOM compensator load parameters is always equal to source parameters, that's why both are stared as same. The source voltage and source current are combined to form as a power factor, maintained as out-of phase as replaced as non-unity power factor.

(a) Source Voltage

(b) Source Current

(c) Load Current

(d) THD of Source Current
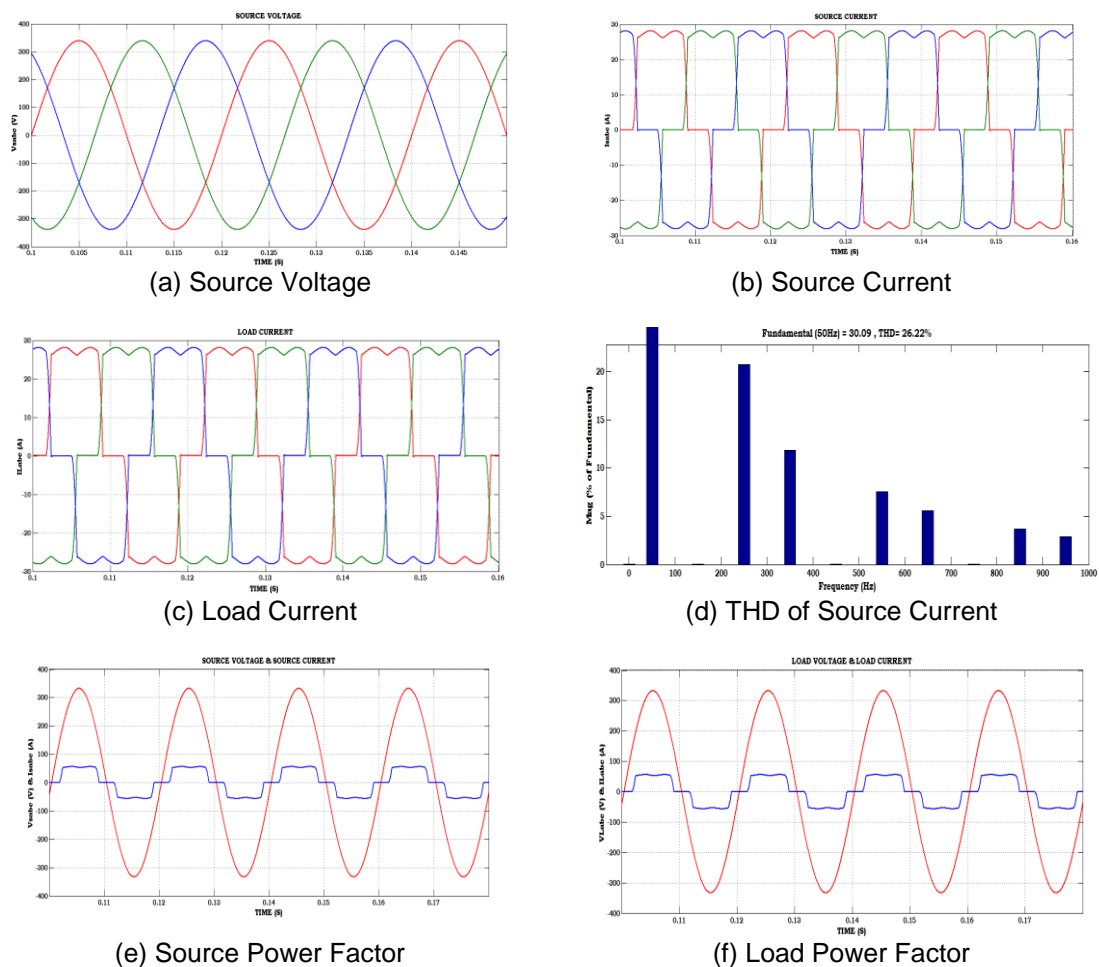
(e) Source Power Factor

(f) Load Power Factor

Figure 3. Simulation Results of Three Phase Distribution System under Non-Presence of DSTATCOM

Table 1. The System Parameters of Proposed DSTATCOM Scheme with Intended Control Objective under Several Load Situations

S.No	Parameters	Values
1	Source Voltage	11KV
2	Source Impedance	0.1+j0.282Ω
3	Load Impedance	200+j37.6Ω
4	DC-Link Capacitor	1500µF
5	VSI Filter Units	R-0.001; L-10mH
6	PI Controller Gains	Kp-0.8; Ki-0.5

3.2. Performance Analysis of DSTATCOM by using Proposed Control Strategy under Balanced Linear Load Situation

Figure 4 (a-f) illustrates the various simulation outcomes of three phase distribution system presence of DSTATCOM with proposed control strategy under balanced linear load device, in that (a) Source Voltage, (b) Source Current, (c) Load Current, (d) Compensation Current, (e) Source Power Factor, (f) Load Power Factor, respectively. In this case load is treated as the balanced linear load, due to the linear-load device the PCC currents maintains as constant and well with in standards. The source side and load side power factor maintained as unity power factor because of linear load energization.
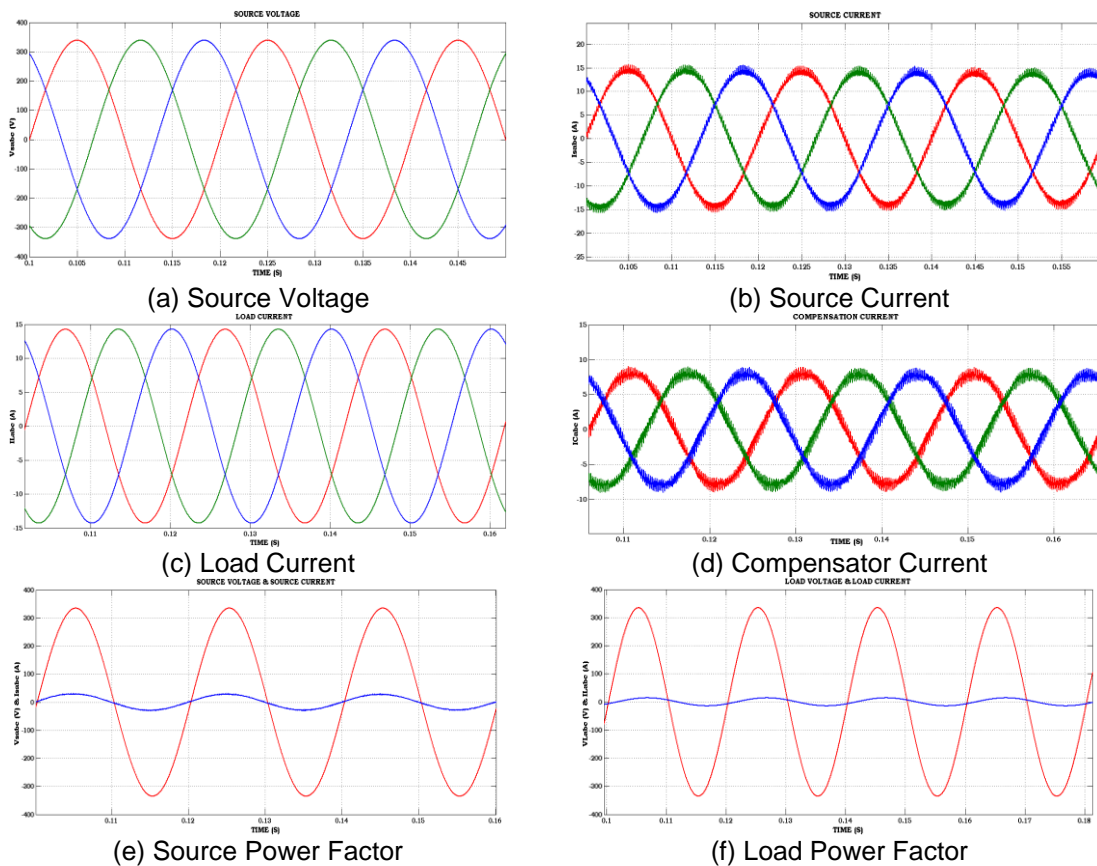

(a) Source Voltage   (b) Source Current

(c) Load Current   (d) Compensator Current

(e) Source Power Factor   (f) Load Power Factor

Figure 4. Simulation Results of DSTATCOM using Proposed Control Strategy under Balanced Linear Load Situation

3.3. Performance Analysis of DSTATCOM by using Proposed Control Strategy under Un-Balanced Linear Load Situation

Figure 5. (a-f) illustrates the various simulation outcomes of three phase distribution system presence of DSTATCOM with proposed control strategy under un-balanced linear load

device, in that (a) Source Voltage, (b) Source Current, (c) Load Current, (d) Compensation Current, (e) Source Power Factor, (f) Load Power Factor, respectively. In this case load is treated as the un-balanced linear load, due to this load device the phase components in load currents are affected in both magnitude & phase sequences. But source currents maintain as constant and well with in standards by using DSTATCOM compensator by replacing the compensation currents. The source side power factor parameters are maintained as unity power factor and the load side power factor is other than unity condition because of un-balanced linear load energization.
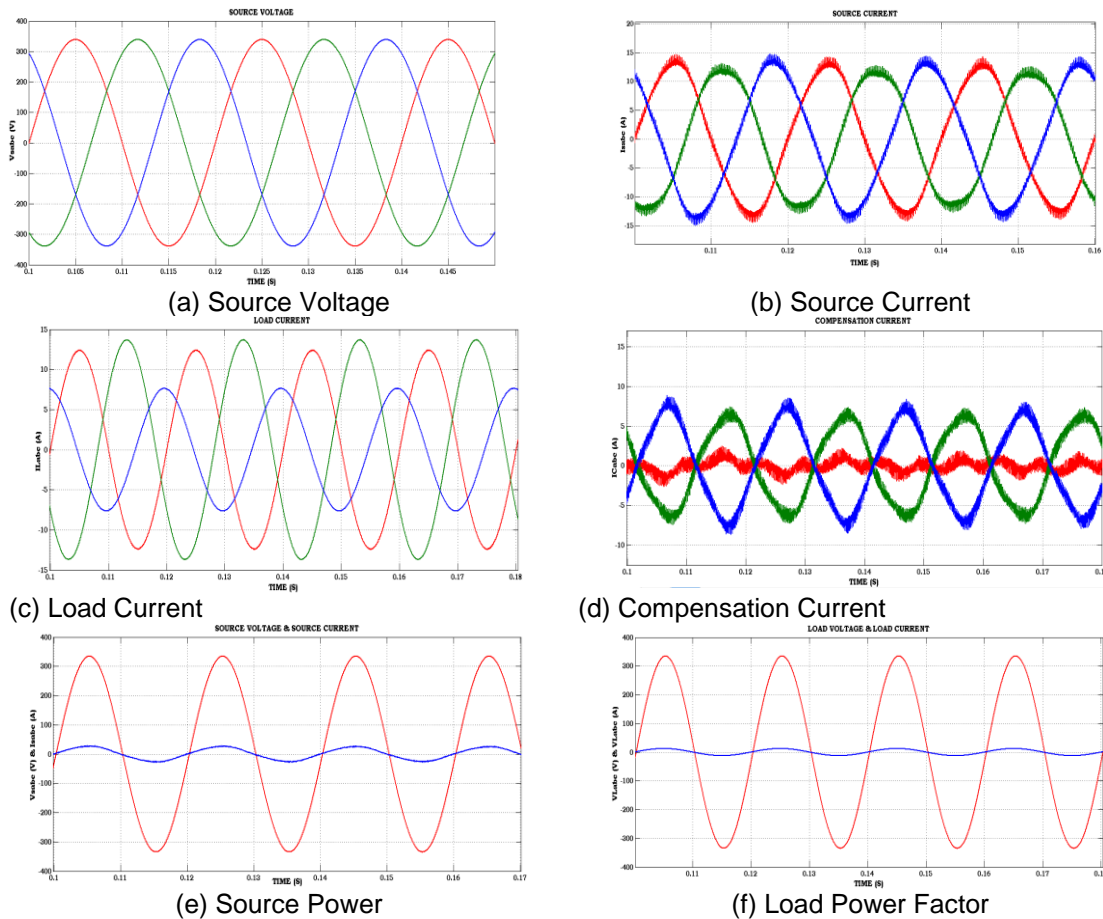

(a) Source Voltage

(b) Source Current

(c) Load Current

(d) Compensation Current

(e) Source Power

(f) Load Power Factor

Figure 5. Simulation Results of DSTATCOM using Proposed Control Strategy under Un-Balanced Linear Load Situtation

3.4. Performance Anlaysis of DSTATCOM by using Proposed Control Strategy under Balanced Non-Linear Load Situtation

Figure 6 (a-f) illustrates the various simulation outcomes of three phase distribution system presence of DSTATCOM with proposed control strategy under balanced non-linear load device, in that (a) Source Voltage, (b) Source Current, (c) Load Current, (d) Compensation Current, (e) Source Power Factor, (f) Load Power Factor, (g). THD of Source Current and (h) THD of Load Current, respectively. In this case load is treated as the balanced non-linear load, due to this load device load currents are harmonized components. But source currents maintain as harmonic-free and well with in IEEE standards by using DSTATCOM compensator by using attractive fundamental frequency based compensation currents. The source side power factor parameters are maintained as unity power factor and the load side power factor is other than unity condition because of balanced non-linear load energization. The THD of load current is

28.54% have more harmonic values and THD of source current is 3.63% have low harmonics well compensated by DSTATCOM and within a IEEE-519 standard's.
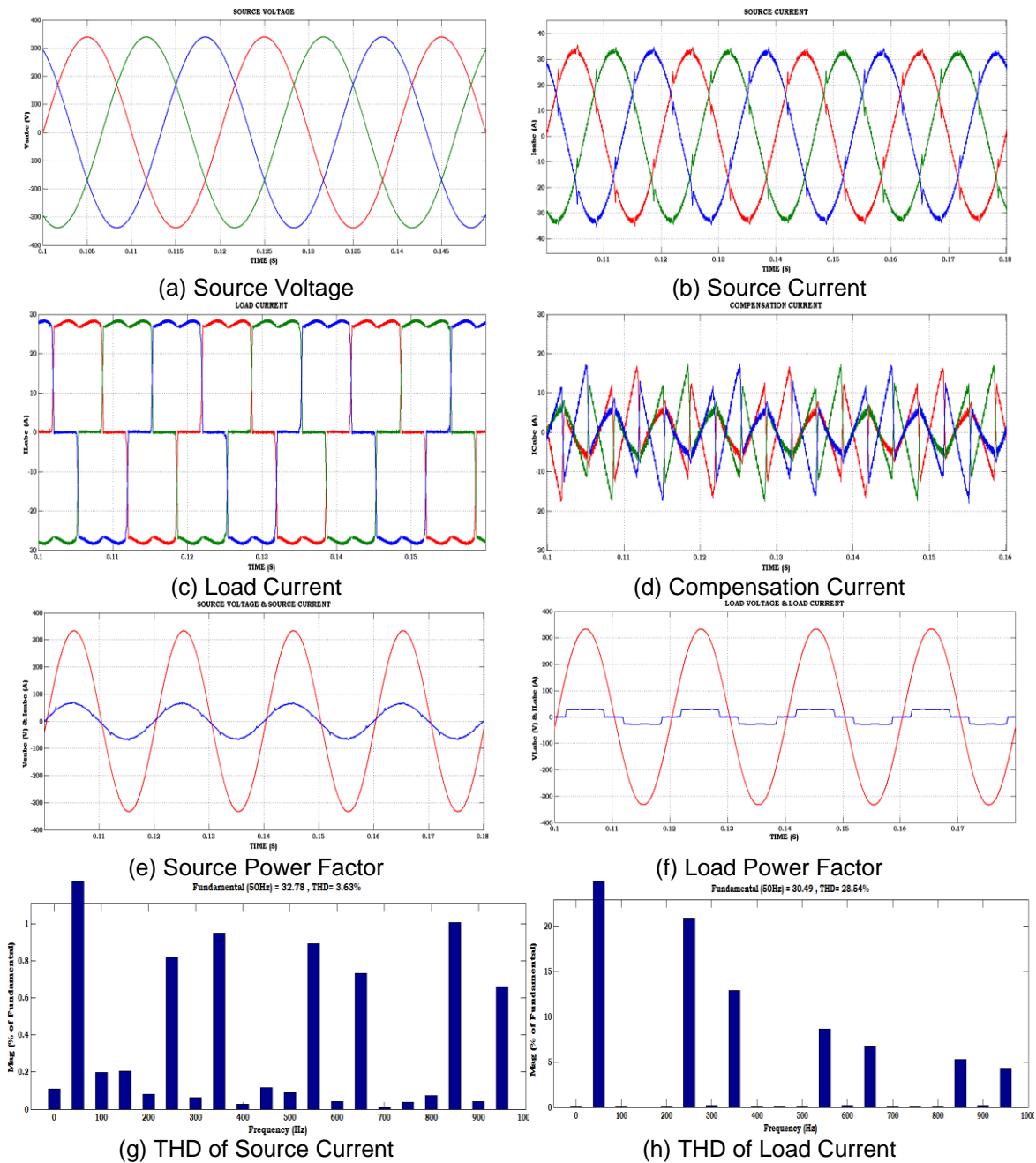

(a) Source Voltage

(b) Source Current

(c) Load Current

(d) Compensation Current

(e) Source Power Factor

(f) Load Power Factor

(g) THD of Source Current

(h) THD of Load Current

Figure 6. Simulation Results of DSTATCOM using Proposed Control Strategy under Balanced Non-Linear Load Situation

3.5. Performance Anlaysis of DSTATCOM by using Proposed Control Strategy under Un-Balanced Non-Linear Load Situtation

Figure 7 (a-f) illustrates the various simulation outcomes of three phase distribution system presence of DSTATCOM with proposed control strategy under un-balanced non-linear load device, in that (a) Source Voltage, (b) Source Current, (c) Load Current, (d) Compensation Current, (e) Source Power Factor, (f) Load Power Factor, (g). THD of Source Current and (h)

THD of Load Current, respectively. In this case load is treated as the un-balanced non-linear load, due to this load device load currents are harmonized components as well un-balanced affected in both magnitude & phase sequences . But source currents maintain as harmonic-free and balanced well with in IEEE standards by using DSTATCOM compensator by using attractive fundamental frequency based compensation currents. The source side power factor parameters are maintained as unity power factor and the load side power factor is other than unity condition because of un-balanced non-linear load energization. The THD of load current is 22.28% have more harmonic values and THD of source current is 3.14% have low harmonics well compensated by DSTATCOM and within a IEEE-519 standard's. Several THD comparisons based on the presence of DSTATCOM with proposed control objective under balanced and un-balanced non-linear load devices are clearly illustrated in below Table 2.

(a) Source Voltage

(b) Source Current

(c) Load Current

(d) Compensation Current

(e) Source Power Factor

(f) Load Power Factor

(g) THD of Source Current
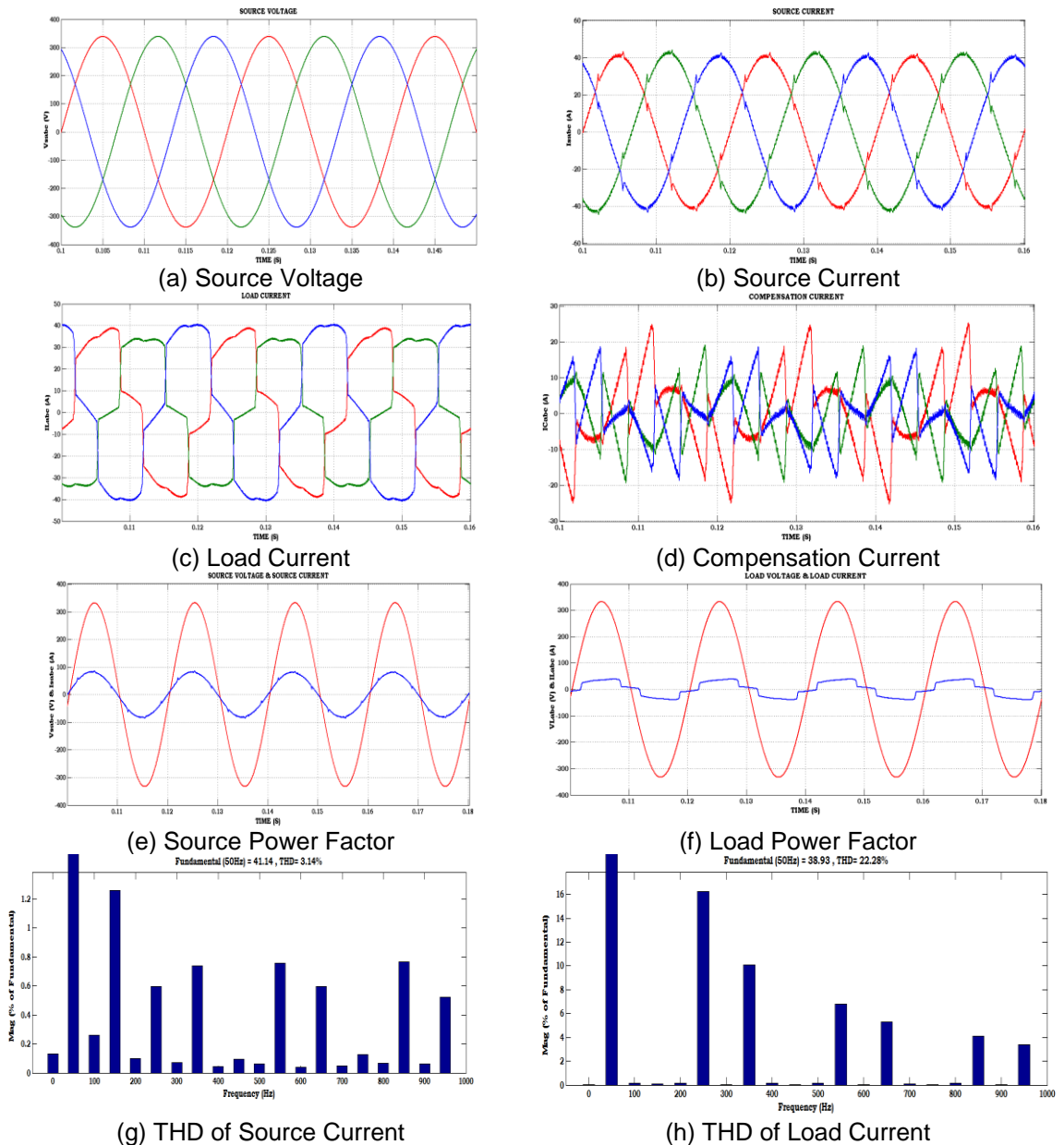
(h) THD of Load Current

Figure 7. Simulation Results of DSTATCOM using Proposed Control Strategy under Un-Balanced Non-Linear Load Situation

Table 2. THD Comparisons under Presence of DSTATCOM with Proposed Control Objective

Parameter (THD %)	Balanced Non-Linear Load	Un-Balanced Non-Linear Load
Source Current	3.63%	3.14%
Load Current	28.54%	22.28%

4. Conclusion

The proposed fundamental frequency based Id-Iq control theory is validated for generation of optimal compensation principle to mitigate the PQ features. It has been developed and simulated under several load conditions like balanced/un-balanced as a linear/non-linear load devices. The proposed control theory generates the reference current signal to DSTATCOM at fundamental frequency from the regular Id-Iq frame theory. The performance evaluation of proposed control objective to fed DSTATCOM in a three phase power distribution system under several load situations are implemented by using Matlab/Simulink tool. The intended fundamental reference based Id-Iq control theory provides the optimal compensation current for superior enhancement of PQ features with attractive merits such as little switching loss, little switch stress, incredible efficiency. The harmonic distortions at source current under balanced/un-balanced load devices under the compensation principle attains well with in IEEE-519 standards. The sources voltages/currents are balancing under the un-balanced loading condition keeping the both are in-phase to achieve the unity power factor as illustrated in simulation results. The harmonic compensation in source current under balanced as well un-balanced non-linear DBR load is 3.63% and 3.14%, the THD of load current under balanced as well un-balanced non-linear load is 28.54% and 22.28% as illustrated in above Table 2.

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