Power Quality Enhancement Using Distributed Static Compensator in Direct Coupled Mode

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Abstract- Power quality (PQ) enhancement is an important area of research in which all the stake holders like residential and industrial sectors are responsible to manage the power effectively and efficiently at an optimistic level. This paper suggests an improvement of PQ using Distributed static compensator (DSTATCOM) for compensating the concerns of PQ in direct coupled mode. This requires a proper design and implementation of direct filtering with and without LC Filter. This is achieved using DSTATCOM in order to compensate reactive power and proper establishing its voltage magnitude and its phase angle. An important strategy of *icos* ϕ control has also been implemented. This *icos* ϕ control used as an optimal current harmonic extractor to generate the appropriate firing pulses. This algorithm has been carried out using MATLAB Simulink model. An important realistic approach using the suggested system of direct coupled distributed Static Compensator (DC-DSTATCOM) has been implemented in the power system utility (PSU) to achieve high accuracy, compatibility and flexibility as compared to other conventional approach. The comparison study is analyzed with the DC-DSTATCOM without LC connected filter and DC-DSTATCOM with LC connected filter. It is observed that the suggested system of DC-DSTATCOM with LC connected filter mode happens to be more effective in improving DC voltage regulation across the self-supported capacitor, voltage balancing at the side of PCC (point of common coupling) and decrease in harmonics at source side. This shows an enhancement of PQ attributes under different loading conditions.

Keywords PQ, DSTATCOM, DC-DSTATCOM, PSU, PCC.

1. Introduction

The vigorously budding solicitation due to increase in loads of non-linear characteristics, sources presents significant harmonics problem in power distribution networks [1]-[2]. One of the preferred devices for harmonic compensation is DSTATCOM [3]-[4]. Usually, harmonics initiated by non-linear loads are compensated through DSTATCOM [5]-[6].

The different models of inverter and different control approach has been recommended since a couple of years in order to enhance the current quality [7]-[8]. After careful review of the DC-DSTATCOM or DSTATCOM, the interference is made to additional filter with the existing filter [9]-[10]. Hence, the adverse effect observed from the existing filter can be eradicated [11]-[12]. So that better PQ can be provided to the consumers which will be right option nowadays [13]-[14]. Before to this date, different filters like notch, low pass, high pass, band pass, band stop filter are used in the PSU. But, the problem found in these controllers are used of more number of sensors, detectors, multipliers, poor tracking performance and inefficient filtering performance, etc [15]-[16].

Later on, remarkable design is made to improve the inverter performance by the suitable combination of the passive elements [17]. Hence, this control technique proposes the suitability of LC filter for the DC-DSTATCOM. The LC filter is required to counter balanced the both higher order and lower order components present in the inverter [18]. The selection of LC filter is made in the following ways

- The inductor is chosen to smoothen the ripples by reducing the lower order components.
- The capacitor is selected to improve the fundamental magnitude by decreasing higher order components.

In this way the value of inductor and capacitor is selected to equip with VSI [19]-[20].

The original contribution of this technique is five folded which are mentioned below

1. It offers very fast dynamic response compared to others.
2. It proves shunt compensation features for source current harmonic reduction, voltage balancing and voltage regulation.
3. It also provides the better power supply by showing improved power factor in source side
4. It improves the disturbance rejection capabilities for a wide range of frequencies.
5. It reduces the heating stresses due to the involvement of LC filter so that the switching stress of control devices of the unbalanced loading conditions will be less.

Thus, the strategies that can alleviate the PQ glitches and provide reliable PSU operation are of great significance [21]-[22].

The respite of the research work is designed into six sections. Subsequent to introduction, the power flow control and compensation capability of the DC-DSTATCOM with LC connected filter is presented. The basic topology configuration, system operation is arranged in the section 2. Derivation of control methodology and the activation process are inspected in section 3. Section 4 explores the operation of DC-DSTATCOM inverter using MATLAB/Simulink software. Also, it presents the experimental results which specify good performance of the designed control method. The conclusion part has been presented in last part of the article, section 5.

2. Basic Topology Configuration

The conventional PSU comprises of a 3 - ϕ balanced supply delivering a power to 3 - ϕ non-linear load. Consisting of a DC-link capacitor (C_{dc}) and six insulated type of gate bipolar-transistors (IGBTs), the DSTATCOM is directly coupled at PCC by means of an interfacing impedance (Z_c) is depicts in Fig. 1 whereas Fig. 2 depicts the circuit arrangement of suggested system model when DSTATCOM is connected in conventional PSU through LC filter. In the proposed topology, DC-DSTATCOM (with and without LC filter interface) is utilized as a shunt compensator for advancement in the issues of PQ such as source and load current harmonic reduction. Selecting a specific topology by using *icos* ϕ algorithm is the purpose of this paper.

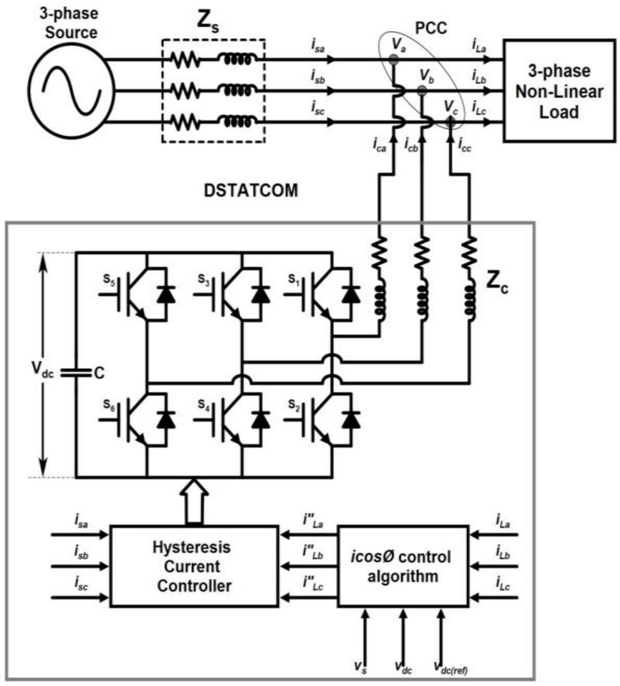


Fig. 1. Schematic diagram of DC- DSTATCOM in PSU.

IGBT switching pulses due to VSC are produced by means of *icos* ϕ algorithm and its mathematical modeling is explicated in following section.

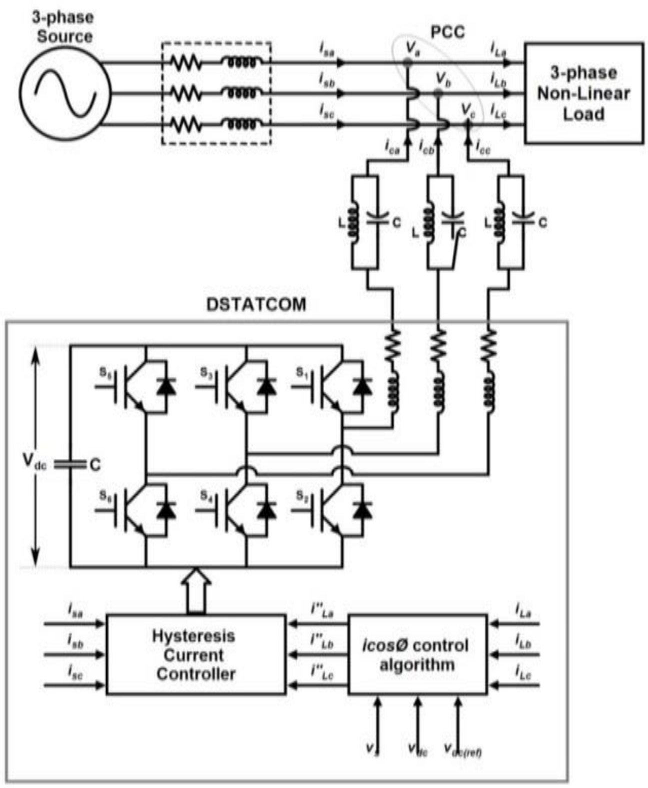


Fig. 2. Schematic diagram of DC- DSTATCOM through LC filter in PSU.

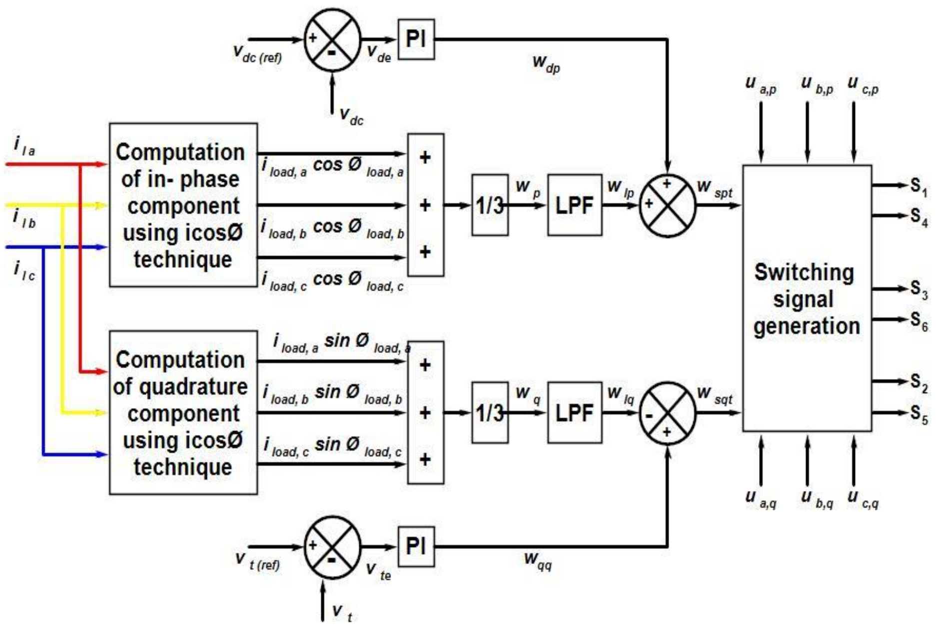


Fig. 3. Schematic diagram of VSC for generation of switching signals with the help of *icos* ϕ control algorithm.

3. Mathematical Modelling of *icos* ϕ Topology Using PI Controller

For fundamental load currents, real power component magnitudes are shown as

$$\left.\begin{aligned} i_{l\,a\,p} &= i_{load,a}\ \cos\phi_{load,a} \\ i_{l\,b\,p} &= i_{load,b}\ \cos\phi_{load,b} \\ i_{l\,c\,p} &= i_{load,c}\ \cos\phi_{load,c} \end{aligned}\right\} \quad (1)$$

The average value of weighted real component (w_p) can be given as

$$w_p = \frac{1}{3}\left(i_{load,a}\ \cos\phi_{load,a} + i_{load,b}\ \cos\phi_{load,b} + i_{load,c}\ \cos\phi_{load,c} \right) \quad (2)$$

With selected value of cut off frequency (i.e. 20 Hz), 1st order LPF (low pass filter) is used for extracting low order frequency components as presented in Fig. 3.

For fundamental load currents, imaginary power component magnitudes are given as

$$\left.\begin{aligned} i_{l\,a\,p} &= i_{load,a}\ \sin\phi_{load,a} \\ i_{l\,b\,p} &= i_{load,b}\ \sin\phi_{load,b} \\ i_{l\,c\,p} &= i_{load,c}\ \sin\phi_{load,c} \end{aligned}\right\} \quad (3)$$

Also, the average value of weighted imaginary component (w_q) can be given as

$$w_q = \frac{1}{3}\left(i_{load,a}\ \sin\phi_{load,a} + i_{load,b}\ \sin\phi_{load,b} + i_{load,c}\ \sin\phi_{load,c} \right) \quad (4)$$

3.1. Reference Real & Imaginary Source Current Components Estimation

Here, $v_{dc\,(ref)}$ & v_{dc} represents reference and sensed DC voltages respectively. Subtraction of ref. DC voltage and DC voltage, sensed provides an error of DC voltage (v_{de}) and for maintaining constant bus voltage of DC value, the estimated error of DC voltage (v_{de}) has been supplied to a PI-type (Proportional-Integral) controller.

Hence, PI controller output of is presented as

$$w_{dp} = k_{p\,dp} v_{de} + k_{i\,dp} \int v_{de} dt \quad (5)$$

Here, $k_{p\,dp}$ represents DC Proportional-type controller and $k_{i\,dp}$ represents DC Integral-type controller.

Total real components of ref. source current is calculated by addition of a PI-type controller output and magnitude of average real load current component as in the following equation

$$w_{spt} = w_{dp} + w_{lp} \quad (6)$$

Where, w_{lp} represents average magnitude of real load current components.

Here, $v_{t\,(ref)}$ & v_t represents reference and sensed AC voltages respectively. Similarly, Subtraction of reference and sensed AC voltage gives error AC voltage (v_{te}) and keeping constant AC value of bus voltage. The measured error AC voltage (v_{te}) has been supplied to PI-type controller.

Hence, PI-type controller output of is presented as

$$w_{qq} = k_{p\,qq} v_{te} + k_{i\,qq} \int v_{te} dt \quad (7)$$

Here, $k_{p\,qq}$ represents AC Proportional-type controller and $k_{i\,qq}$ represents AC Integral-type controller.

Total imaginary components of ref. source current is achieved by subtraction of PI-type controller output and magnitude of average imaginary, load current component as in the following equation

$$w_{sqt} = w_{qq} - w_{lq} \quad (8)$$

Where, w_{lq} represents average magnitude of imaginary load current components.

3.2. Switching Signal Generation

The real components of instantaneous 3 - ϕ reference source are calculated as below. The in-phase unit voltages multiplication with a current component of real power given as follows

$$\left.\begin{aligned} i_{s,ap} &= w_{spt}\, u_{a,p} \\ i_{s,bp} &= w_{spt}\, u_{b,p} \\ i_{s,cp} &= w_{spt}\, u_{c,p} \end{aligned}\right\} \quad (9)$$

Where, $i_{s,ap}$, $i_{s,bp}$, $i_{s,cp}$ are real power current component of three phases.

Also, $u_{a,p}$ $u_{b,p}$, $u_{cp,}$ are unit amplitudes of in-phase, voltages are as follows

$$\left.\begin{aligned} u_{a,p} &= \frac{v_{s,a}}{v_t} \\ u_{b,p} &= \frac{v_{s,b}}{v_t} \\ u_{c,q} &= \frac{v_{s,c}}{v_t} \end{aligned}\right\} \quad (10)$$

Here, v_t represents the peak voltage value at PCC and can be expressed as

$$v_t = \sqrt{\frac{2\,(v_{s,a}^2 + v_{s,b}^2 + v_{s,c}^2)}{3}} \quad (11)$$

Similarly, the imaginary components of 3 - ϕ instantaneous reference source are calculated as below

$$\left.\begin{aligned} i_{s,aq} &= w_{sqt}\, u_{a,q} \\ i_{s,bq} &= w_{sqt}\, u_{b,q} \\ i_{s,cq} &= w_{sqt}\, u_{c,q} \end{aligned}\right\} \quad (12)$$

Where, $i_{s,aq}$, $i_{s,bq}$, $i_{s,cq}$ are imaginary power current component of three phases.

Also, $u_{a,q}$, $u_{b,q}$, $u_{cq,}$ are unit amplitude of quadrature voltages and are expressed as

$$\left.\begin{aligned} u_{a,q} &= \frac{u_{b,p} + u_{c,p}}{\sqrt{3}} \\ u_{b,q} &= \frac{3\,u_{a,p} + u_{b,p} - u_{c,p}}{2\sqrt{3}} \\ u_{c,q} &= \frac{-3\,u_{a,p} + u_{b,p} - u_{c,p}}{2\sqrt{3}} \end{aligned}\right\} \quad (13)$$

The reference source currents are determined by summation real and imaginary components of current and are presented as

$$\left.\begin{aligned} i_{s,a}^* &= i_{s,ap} + i_{s,aq} \\ i_{s,b}^* &= i_{s,bp} + i_{s,bq} \\ i_{s,c}^* &= i_{s,cp} + i_{s,cq} \end{aligned}\right\} \quad (14)$$

Relating to both the source currents in actual (i_{sa}, i_{sb}, i_{sc}), source currents in reference ($i_{s,a}^*$, $i_{s,b}^*$, $i_{s,c}^*$) of all the phases a, b, c respectively. The evaluated error signals are provided to the Hysteresis current controllers (HCC).

The implementation of HCC is due to the flexible use of implementation, less burdened of hardware complications over the conventional type of modulation controller. The condition of operation is expressed as below

Case-1: $i_{sc} < i_{s,c}^*$, s_3 (ON) and s_6 (OFF)

Similarly, Case-2: $i_{s,c} > i_{s,c}^*$, s_3 (OFF) and s_6 (ON)

Their outputs are used to generate the switching signal of proposed DC-DSTATCOM.

4. MATLAB/Simulink Outcomes & Discussion

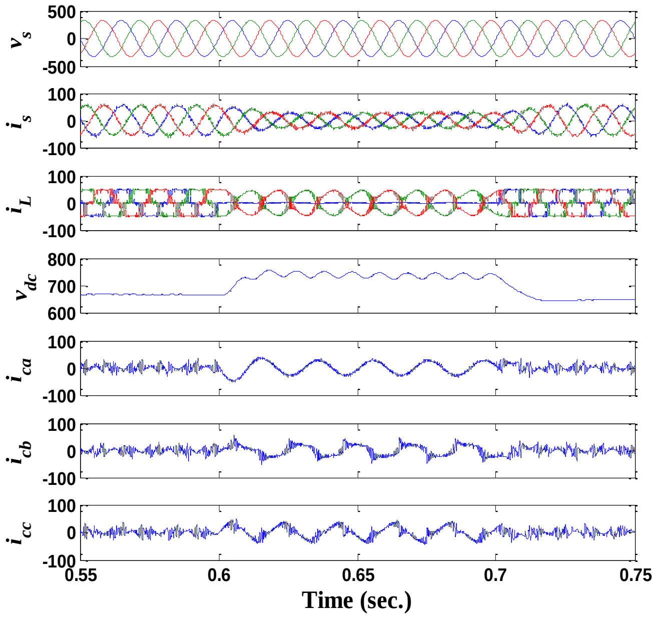
The PSU comprising of a balanced 3 - ϕ supply system delivering a power to 3 - ϕ non-linear load is modeled in MATLAB/Simulink environment. DSTATCOM is coupled in direct mode at PCC with the help interfacing impedance. Also, circuit arrangements have done according to suggested topology in MATLAB/Simulnk model by connecting LC filter.The basic design parameter specification is depicted in Table 3.

The PSU network presented in Fig. 1 and Fig. 2 has been implemented and simulated using MATLAB/Simulink software with SimPowerSystems toolboxes in Simulink to investigate the effectiveness of proposed topology in PUS.

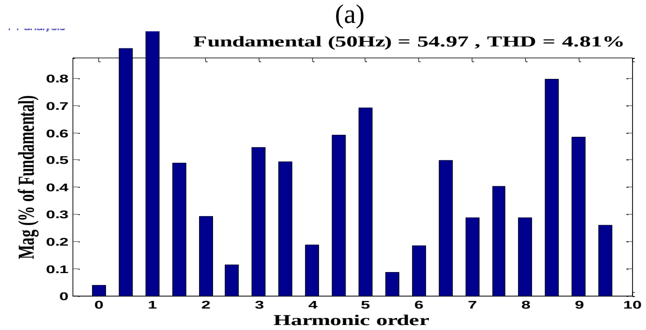
Here, to verify this *icos* ϕ control technique under unbalanced conditions for both DC-DSTATCOM with and without LC filter, phase a load is removed by disconnecting the circuit breaker at a time of 0.6 Sec. and reconnected at a time of 0.7 Sec. Although both these conditions are executed for about 1.0 sec, the simulation results are presented in the time span from 0.55 sec. to 0.75 sec for accuracy. Without using DSTATCOM, conventional PSU source current amplitude (A) and (%) THD of 51.18 and 20.66 respectively. Afterwards DSTATCOM is connected to conventional PSU directly and through LC filter, then simulation is performed for both the conditions and the simulation results of *icos*ϕ control techniques when DSTATCOM is connected to conventional PSU directly and through LC filter are compared, respectively.

4.1. DSTATCOM Connected Directly in Conventional PSU

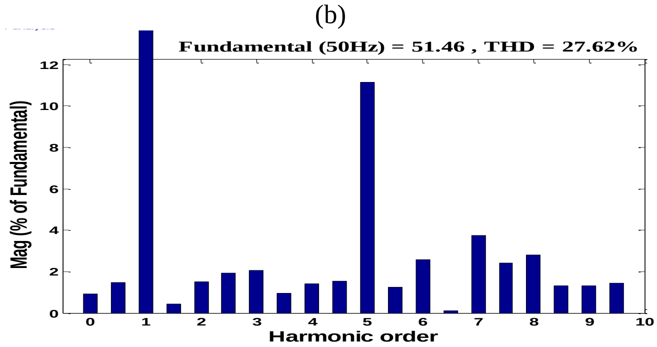
The simulation results of distribution system containing DC-DSTATCOM without LC filter using *i*cos ϕ control technique with a condition of unbalanced loading are depicted in Fig. 4 (a)–(d). The subplots of Fig. 4 (a) are organized starting from source voltage (v_s), source current (i_s), load current (i_L), load capacitor voltage (v_{dc}), compensating currents (i_{ca}, i_{cb} , i_{cc}) respectively. The total harmonic distortion for source current is 4.81% whereas for load current, it is 27.62 % and are depicted in the Fig. 4(b)–(c) respectively. The source voltage waveform and current waveform of a-phase are presenting the PF correction in Fig. 4 (d). Also, the value of v_{dc} (DC-link voltage) is regulated at 723–756 V by DC- DSTATCOM without LC Filter in the interval of 0.6–0.7 sec. As per IEEE standards, the simulation results validated that presented technique (DC-DSTATCOM without LC) achieves elimination of source harmonics, balancing of load and voltage regulation. part was not up to the mark. All the voltage and currents magnitudes are presented in volts (V) & ampere (A) respectively.



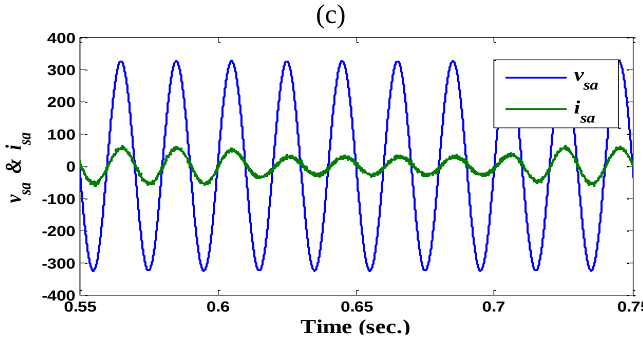
(a)



(b)



(c)

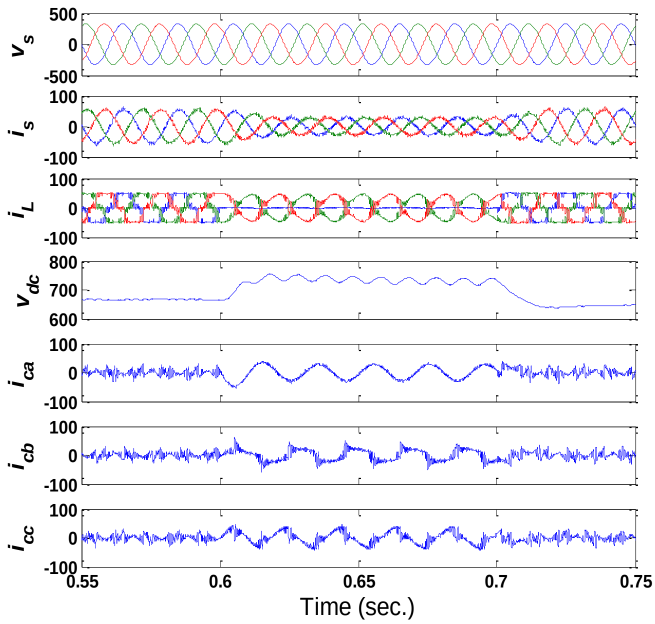


(d)

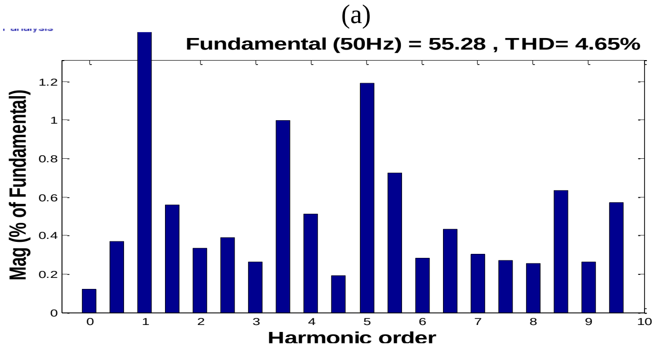
Fig. 4. For Directly coupled DSTATCOM without LC filter (a) Performance Parameters, (b) Source current THD spectrum, (c) Load current THD spectrum (d) Relation between source voltage and current waveform of a-phase.

4.2. DSTATCOM Connected Directly with LC Filter In Conventional PSU

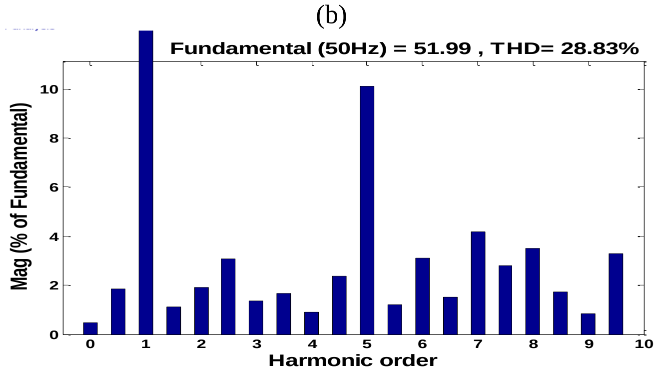
The simulation results of distribution system including DC-DSTATCOM with LC connected filter using $i\cos\phi$ control are shown in the Fig. 5(a)–(d). The subplots of Fig. 5(a) are organized starting from source voltage (v_s), source current (i_s), load current (i_L), load capacitor voltage (v_{dc}), compensating currents (i_{ca}, i_{cb}, i_{cc}) respectively. The total harmonic distortion for source current is 4.65% whereas for load current, it is 28.83 % and are depicted in the Fig. 5(b)–(c) respectively. The source voltage waveform and current waveform of a-phase are presenting the PF correction in Fig. 5 (d). Also, the value of v_{dc} (DC-link voltage) is regulated at 722–754 V by DSTATCOM with LC Filter in the interval of 0.6–0.7 sec.



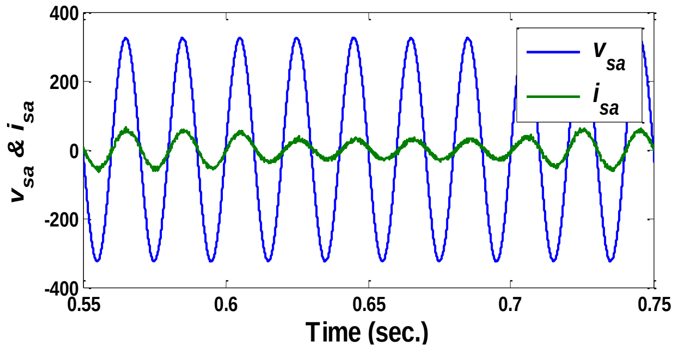
(a)



(b)



(c)



(d)

Fig. 5. For DC-DSTATCOM coupled through LC Filter (a) Performance Parameters, (b) Source current THD spectrum, (c) Load current THD spectrum and (iv) Relation between source voltage and current waveform of a-phase.

As per IEEE standards, the simulation results validated that presented technique (DC- DSTATCOM with LC filter) achieves elimination of source harmonics, balancing of load and its voltage regulation part in comparison with DC-DSTATCOM without LC Filters. All the voltage and currents magnitudes are presented in volts (V) & ampere (A) respectively.

The switching states of VSC of DSTATCOM is described as: It consisting of 6 IGBT switches where required gating signal is provided by pulse generator. With a phase difference of 120^0, each phase has two switches, one for ON and other for OFF. The switching table for VSC of DSTATCOM is shown in Table 1.

Table 1. The switching performance for the VSC of DSTATCOM

State No.	Switching States					
	S_1	S_2	S_3	S_4	S_5	S_6
1	ON	ON	OFF	OFF	OFF	ON
2	ON	ON	ON	OFF	OFF	OFF
3	OFF	ON	ON	ON	OFF	OFF
4	OFF	OFF	ON	ON	ON	OFF
5	OFF	OFF	OFF	ON	ON	ON
6	ON	OFF	OFF	OFF	ON	ON

The summary for simulation results for designed PSU is depicted in Table 2.

Table 2. Comparison of DC-DSTATCOM without and with LC filter.

Operating Condition for DC-DSTATCOM	Performance Parameter			
	Source Side		Load side	
	Current	THD	Current	THD
without LC connected Filter	54.97 A	4.81 %	51.46 A	27.62 %
with LC connected Filter	55.28 A	4.65 %	51.99 A	28.83 %

The basic parameters of designed PSU are represented in Table 3 as below

Table 3. Basic parameters of designed PSU

Basic parameters	
Source Voltage (v_S)	400 V (line-to-line)
Source Frequency (f_S)	50 Hz
Resistance of Source (R_S)	0.5 Ω,
Inductance of Source (L_S)	2 Mh
Resistance of Source (R_l)	10 Ω
Inductance of Source (L_l)	20 mH
Compensator Resisance (R_C)	0.25 Ω
Compensator Inductance (L_C)	1.5 Mh
Capacitance of DC link (C_{dc})	2000 μF
Reference DC link Voltage ($V_{dc\ (ref)}$)	560 V
LC Connected Filter with R,L,C	0.25 Ω, 1.5 mH, 1 μF
AC Integral Controller ($K_{i\ qq}$)	1.1
DC Integral Controller ($K_{i\ dp}$)	0.01
AC Proportional Controller ($K_{p\ qq}$)	0.2
DC Proportional Controller ($K_{p\ dp}$)	0.005

5. Conclusion

In this research work, PQ enhancement using DSTATCOM in direct coupled mode has been suggested. Here, two cases are considered for PQ improvement such as with and without LC filter. From the simulation result, it is observed that better PQ improvement has been performed in case of an LC connected filter. The detailed comparison study has been discussed in Table No.2. The Source current THD percentage is less that 5% (as per the IEEE standard limit). In addition to these, it can diminish additional losses, noise and vibration of the transformer. Finally, the performance obtained from the above study can be considered for the industry requirement to meet the consumer's satisfaction.

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