



A CRITICAL EVALUATION OF POWER QUALITY FEATURES USING UNIQUE FUNDAMENTAL REFERENCE CURRENT BASED BATTERY INTEGRATED DSTATCOM

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ABSTRACT

The incredible demand for power quality enhancement has been advancing in present situation. Generally, because of large-sized non-linear loads are integrated at electric power distribution system provoking of imperative distortions at point of common coupling. An effective harmonic compensation scheme is furnished at common coupling for acquiring the power quality features in a three phase electric power distribution system. Over the, several compensation schemes a Distributed Static Compensation (D-STATCOM) scheme creates a significant role in distribution systems for power quality enhancement with attractive control strategy. Classical control strategies are greatly adversed with high switching loss due to extreme harmonic frequencies in a reference current component. This paper, proposes the attractive reference current extraction control strategy for optimum functioning of battery energy storage system (BESS) integrated D-STATCOM with fruitful advantages. The validation of the proposed BESS integrated DSTATCOM with proposed control objective under several case studies, is evaluated by Matlab/Simulink tool and simulation results are illustrated with respect to proper comparative analysis.

Keywords: battery energy system, DSTATCOM, fundamental reference current Id-Iq theory power quality enhancement.

INTRODUCTION

Several efforts for acquiring quality power or power quality improvement are raised gradually in power distribution system [1]. It is predefined end-user related issue which is accompanied by evading the mis-functioning of power-semi-conductor devices. Due to this, current harmonics or voltage harmonics are attained at common point level, which influences the distortions of proper power quality standards in a distribution system. An efficient active compensator is required for improving the power quality features; out of several compensators a DSTATCOM is very popular for reactive power and harmonic problems [2]-[4]. The performance of the DSTATCOM is limited by its control theory as well as various control strategies are evaluated in the literature survey, out of those Id-Iq control theory is effectively used due to its simple conversions and low complex. In this theory load current is sensed and divided into fundamental and harmonic currents from these fundamental current has to be supplied from DSTATCOM [5]. Battery energy storage system is used in the distribution system to overcome power cut problem [6].

Conventional Id-Iq theory generates harmonized reference currents for DSTATCOM with high switching frequency eventually causing high switching losses, low efficiency. This leads to find a novel control strategy is required for generation of fundamental current reference for DSTATCOM operating with fundamental switching frequency [7]-[9]. This reduces the switching losses and improving the efficiency of the DSTATCOM and entire compensation scheme. For integrating battery energy storage system requires voltage source inverter (VSI), a VSI in DSTATCOM is utilized instead of using separate

voltage source converter for battery energy interfacing [10]. The battery charging and discharging depends on load condition which is regulated by proposed novel control strategy and such that battery current is controlled [11]. The proposed strategy with battery current control is discussed in detail, the simulation results are evaluated for various test cases such as without battery, with battery charging, with battery discharging.

DSTATCOM INTERFACING TO DISTRIBUTION SYSTEM

Conventional DSTATCOM

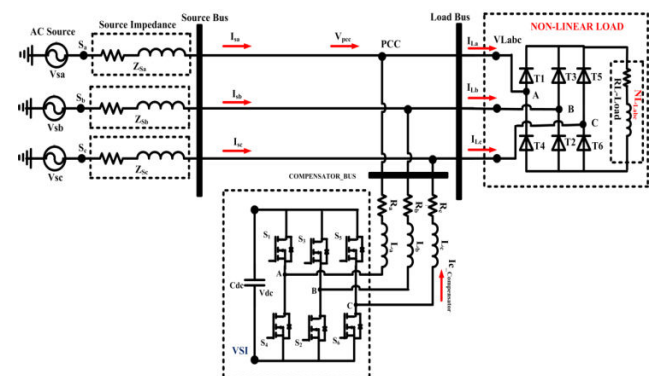


Figure-1. Conventional DSTATCOM.

This work presents a new control scheme in distribution system with integration of battery to DSTATCOM for improving the power quality features. The battery system will get charge and discharge based on load requirement. The proposed control strategy again



modified to control the battery current which is evaluated by simulation tool, simulation results are presented for various test cases. Figure-1 shows the conventional DSTATCOM connected in distribution system. The DSTATCOM consists of voltage source converter and capacitor. DSTATCOM supplies the reactive power and harmonics required by the load.

Battery integrated DSTATCOM

Figure-2 shows the battery integrated DSTATCOM for compensation of harmonics, reactive power and part of active power based on the load condition battery will charge or discharge, this type of system has advantage of power reliability and continuity [12].

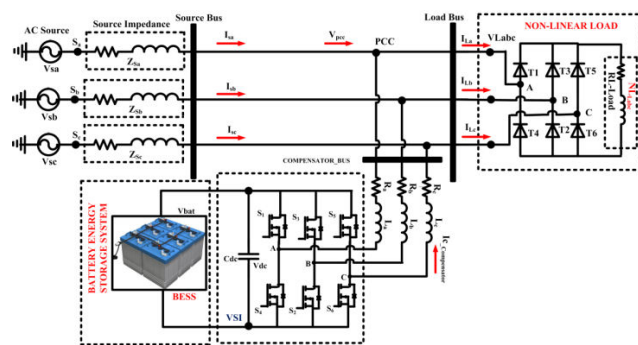


Figure-2. Battery integrated DSTATCOM with distribution system.

DSTATCOM CONTROL SCHEMES

Conventional Id-Iq control theory

The fundamental current reference I_d - I_q theory is illustrated in Figure-3. In this theory, instantaneous active and reactive current component (i_d - i_q) method is evaluated with active currents i_{abc} . It can be obtained from the instantaneous active and reactive current components i_d and i_q of the nonlinear load [13]. This method is by using Park transformation on two phase α - β (by Clarke transformation) we will get (d-q) components. In Park transformation two phase α - β are fed to vector rotation block where it will be rotated over an angle θ to follow the frame d-q. The definitions apply in either the $\alpha\beta 0$ - or $dq0$ -domains and for balanced sinusoidal three-phase systems would yield constant. The PLL generates $\sin\omega t$ and $\cos\omega t$ components are given to conversion blocks (abc-dq0). PI controller have an input from the difference between actual and reference dc voltages. Finally I_{dc} actual is generated is given to PWM generator which develops gate pulses for converter.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (2)$$

Similarly, the instantaneous source current i_{sa}, i_{sb}, i_{sc} also transformed into the $\alpha \beta$ coordinate's current i_α, i_β by Clarke transformation that is given as;

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (3)$$

Inverse Clarke transformation:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} \quad (4)$$

v_0, v_α, v_β are zero sequence voltage, α axis, and β axis voltages respectively.

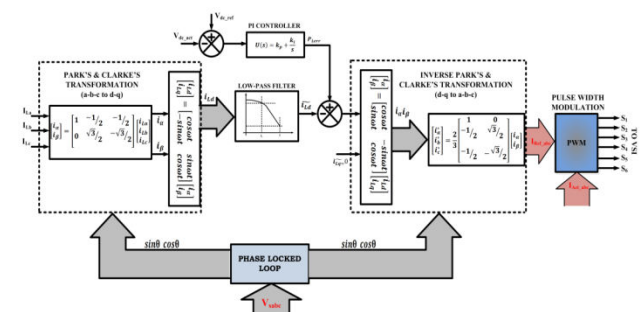


Figure-3. Proposed control fundamental current reference I_d - I_q theory.

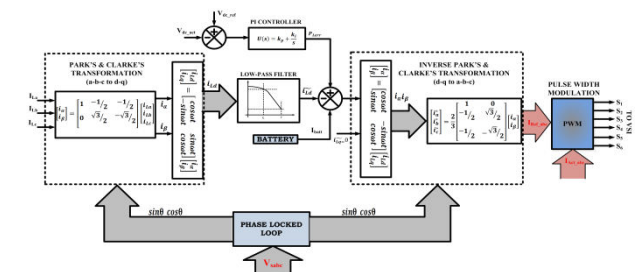


Figure-4. Proposed control fundamental current reference I_d - I_q theory with battery integrated scheme.

Proposed fundamental reference based I_d - I_q theory

Figure-4 shows the proposed fundamental current reference based I_d - I_q theory. The main difference between proposed and conventional theory, in conventional theory reference current is generated for DSTATCOM. Since the DSTATCOM current consists of harmonics, so its switching frequency is high. Where as in proposed theory reference current is generated for source, it consists of on fundamental current, so switching frequency is less. In proposed theory load current is sensed and converted to



abc to dq frame the d component has fundamental and harmonics, the fundamental current is separated with low pass filter and loss component of current is added to this to get total I_d - I_q reference. Since source should not supply the reactive power so I_q reference is zero the I_d currents are converted into abc frame and compare with actual source I_{abc} currents.

Modified proposed fundamental current reference I_d - I_q theory with battery integration

During battery integration the proposed strategy is modified is shown in Figure-5 when battery is supplying

the load the source reference should decrease and when battery is drawing the current source current reference increases based on this the battery current has opposite polarity with source based on the reference value set for the battery it will draw or inject the current [14]-[18]. Figure-6 shows that complete block diagram of Battery integrated D-STATCOM with proposed control strategy is shown in Figure-6 based on the current setting of the battery, battery will charge or discharge. Here the loss component of current is taken from source because when there is no battery D-STATCOM should work.

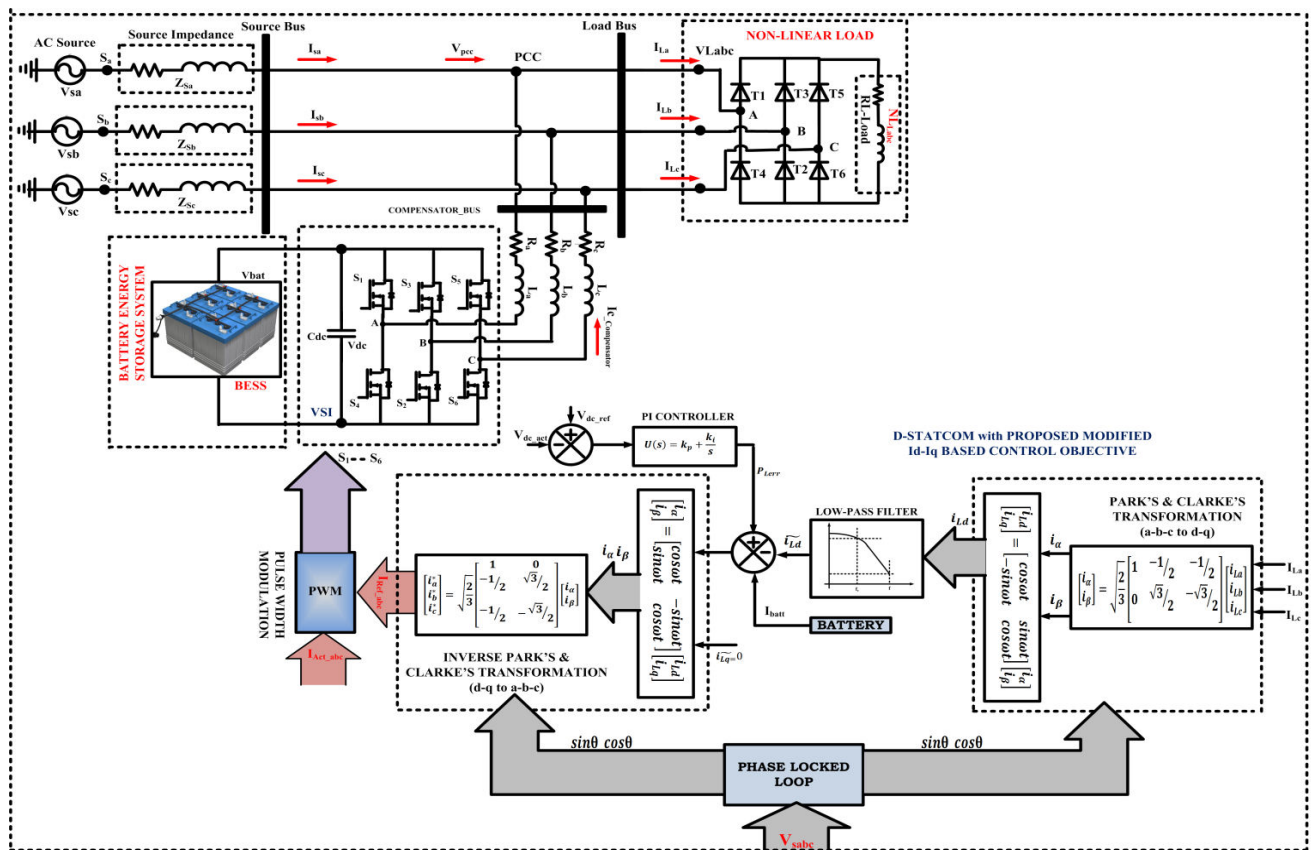


Figure-5. Complete block diagram of battery integrated D-STATCOM with proposed control strategy.

MATLAB/SIMULINK RESULTS

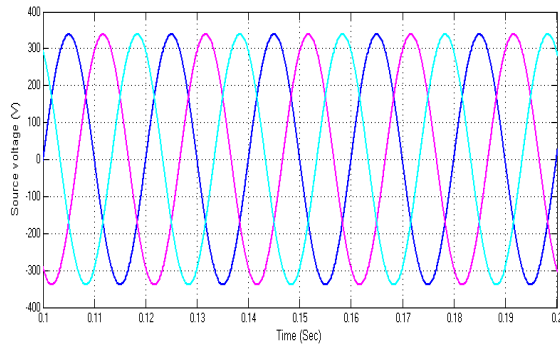
Simulation models were built for the system without battery integrated D-STATCOM and with battery charging, discharging and no charging discharging modes with D-STATCOM. Results for the source voltage, load current containing non-linearity, source currents with disturbances, power factor and DC link voltage of VSI converter are shown for all cases. Table-1 shows the system parameters used to develop the models. As case 1, system without D-STATCOM was shown and as:

Table-1. Simulation parameters.

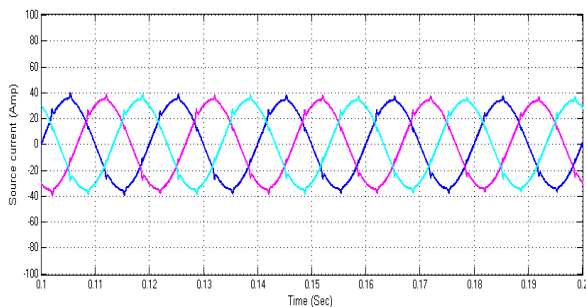
Parameter	Value
Source Voltage (Ph-Ph RMS)	440V
Source Impedance	$0.1+j0.282 \Omega$
Load Impedance	$20+j6.28 \Omega$
DC Link Capacitance	4000 μ F
Proportional Gain	0.8
Integral Gain	0.5
Battery voltage	800V



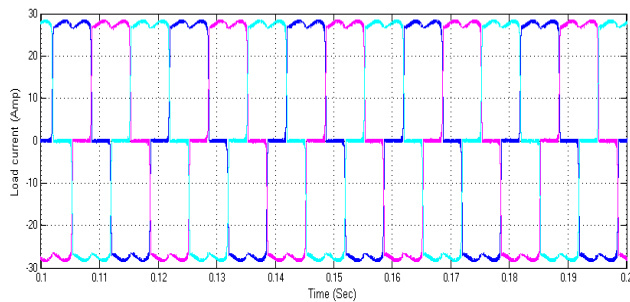
DSTATCOM with proposed theory and without battery



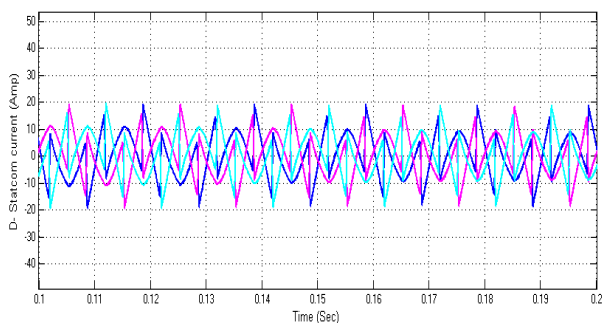
(a) Three phase source voltage.



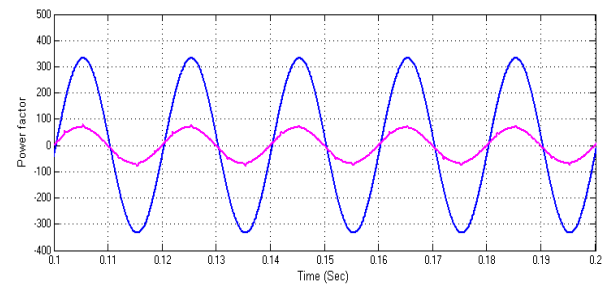
(b) Three phase source current.



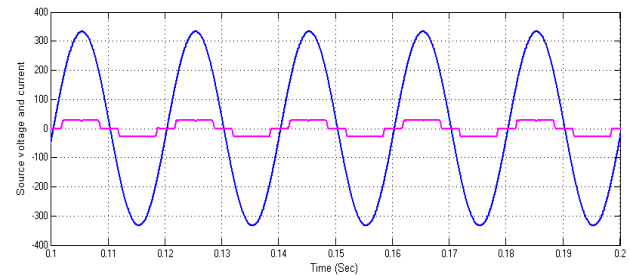
(c) Three phase load current.



(d) DSTATCOM injected current.



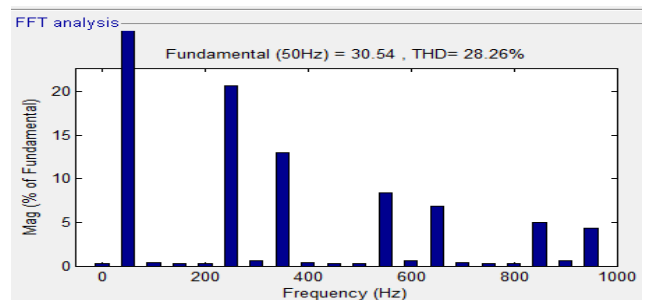
(e) Power factor angle between source voltage and current.



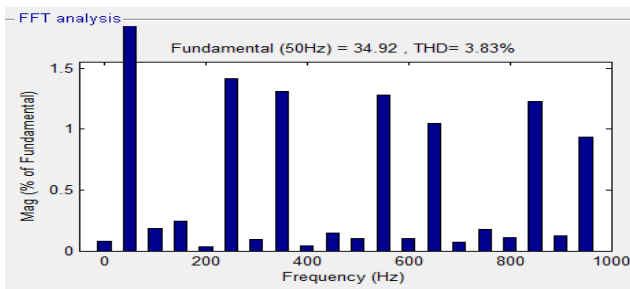
(f) Power factor angle between Load voltage and current.

Figure-6. Simulation outcomes when distribution system is integrated with non-linear load without DSTATCOM.

Figure-6(a) shows the simulation result of three phase source voltage wave form at non-linear load connected in Distribution system without DSTATCOM. The peak amplitude of source voltage is 320V. Figure-6(b) shows the source current waveforms at non linear load connected in Distribution system without Battery integrated DSTATCOM. Figure-6(c) shows the simulation results of three phase load current wave form at non-linear load connected in distribution system. Due to non linear load nature the current contains harmonics as showed and has peak current of 28A. Figure-6(d) shows DSTATCOM current without battery integration. Figure-6(e) shows the simulation results of power factor without using D-STATCOM without battery integration. Figure-6(f) shows both load voltage and load current contains no harmonics and compensation was placed.



(a) THD plot o load current.



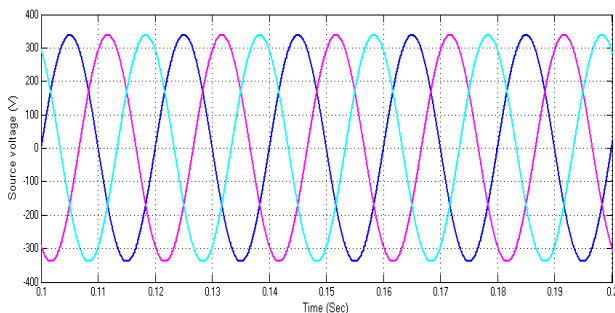
(b) THD plot of source current.

Figure-7. FFT analysis without DSTATCOM.

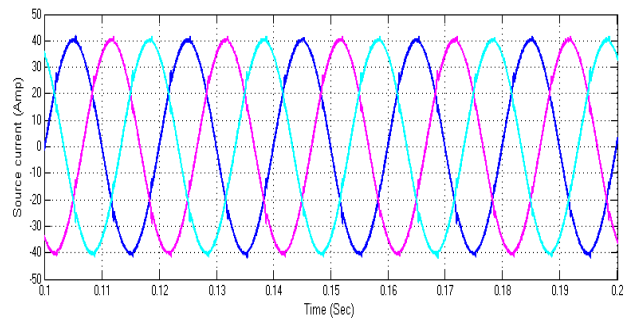
Figure-6(a) shows the THD Plot for load current. The %THD value of source current without DSTATCOM is 28.26% and Figure-6(b) shows the THD plot for source current. The % THD value of source current without DSTATCOM is 3.83%. This THD value indicates presence of harmonics in source current is mitigated.

DSTATCOM with battery integration charging mode

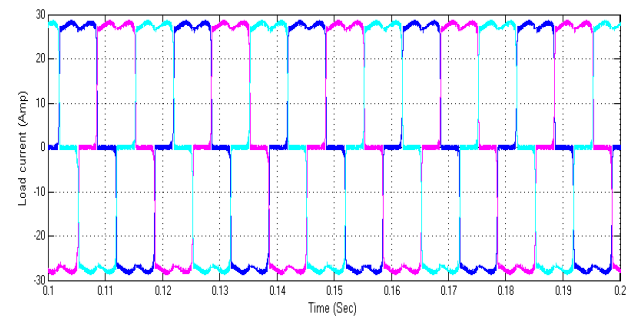
Figure-7(a) shows the simulation result of three phase source voltage wave form with non-linear load connected in distribution system with Battery integration DSTATCOM in charging mode. The peak amplitude of source voltage is 320V. Figure-7(b) shows the source current waveforms with non linear load connected in distribution system with DSTATCOM. Due to non linear load nature the source current contains distortions without DSTATCOM but here the source current is sinusoidal because the DSTATCOM compensates the harmonics and reactive component. It has peak current of 40A. Figure-7(c) shows the simulation results of three phase load current wave form with magnitude of 28amps. Figure-7(d) shows the compensating DSTATCOM current waveforms injected in to distribution system for harmonic nullification. But load current draws non-linear components as observed from the result. Figure-7(e) shows the simulation results of power factor with DSTATCOM; the power factor was maintained around unity. Figure-7(f) shows the simulation results of load voltage and current waveform. The magnitude of voltage value is 320 volts, and the magnitude of current value is 20 amps.



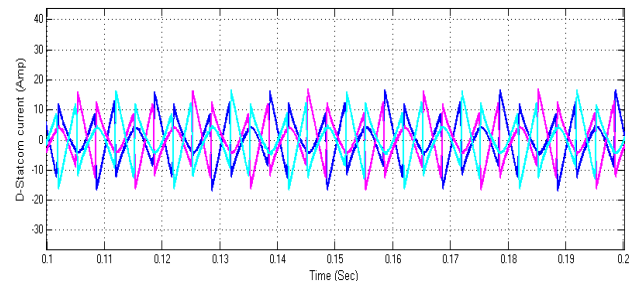
(a) Three phase source voltage.



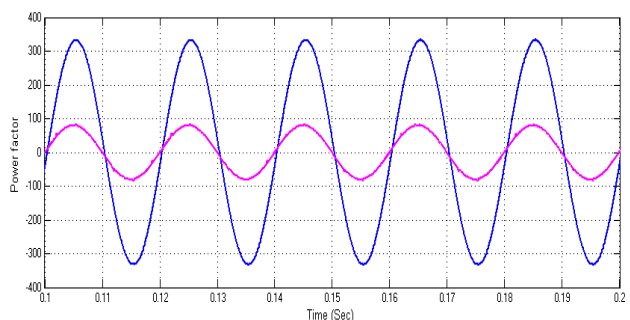
(b) Three phase source current.



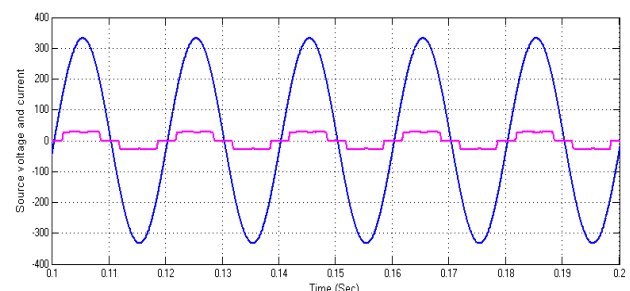
(c) Three phase load current.



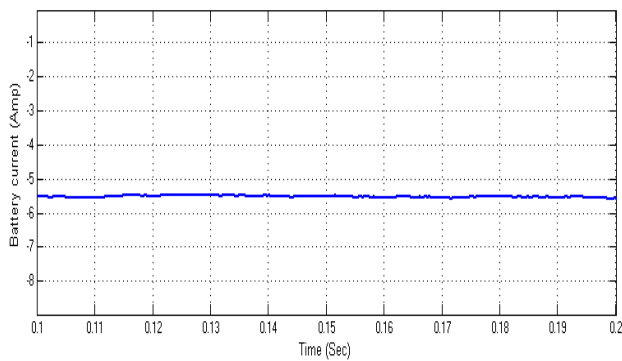
(d) DSTATCOM injected current.



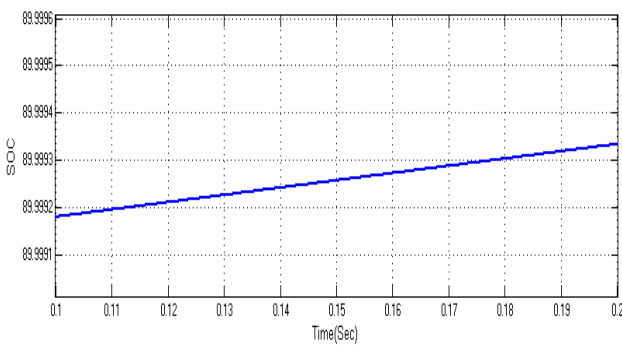
(e) Power factor angle between source voltage and current.



(f) Power factor angle between Load voltage and current.



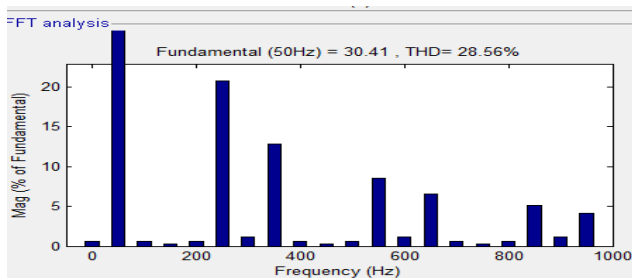
(g) Battery charging current (Amp).



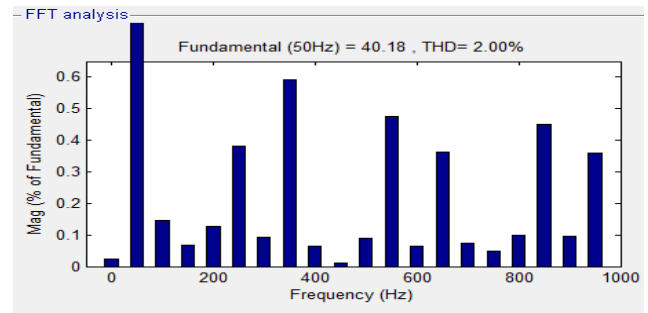
(h) State of charge (SOC).

Figure-8. Simulation outcomes when distribution system is integrated with non-linear load with battery interfaced DSTATCOM under charging mode.

Figure-8(g) shows the simulation results of battery current under charge mode condition of battery integration with DSTATCOM. The value of battery current is -5.5amps. Figure-8 (h) shows the simulation results of battery under the state of charging mode condition under charging condition the SOC of battery integration.



(a) THD plot of load current.

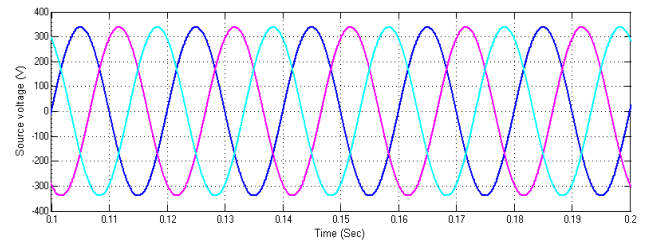


(b) THD plot of source current

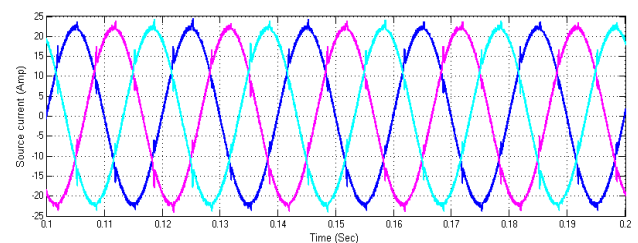
Figure-9. FFT analysis with battery DSTATCOM under charging mode.

Figure-9(a) shows THD plot for the load current. The %THD value of load current with DSTATCOM is 28.56%. Figure-9(b) shows the THD plot of source current. The %THD value of source current with DSTATCOM is 2.0%. Reduction in THD value can be clearly observed in source current since DSTATCOM is connected to compensate harmonics under battery charging mode.

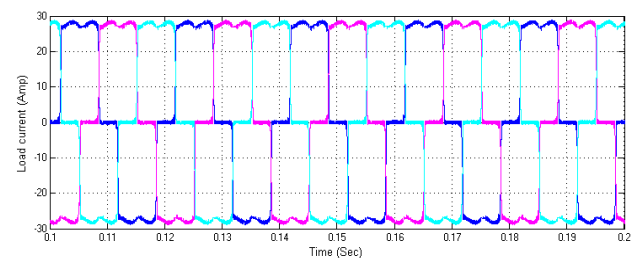
DSTATCOM with battery integration discharging mode



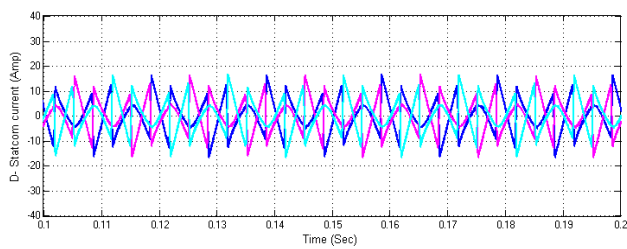
(a) Three phase source voltage.



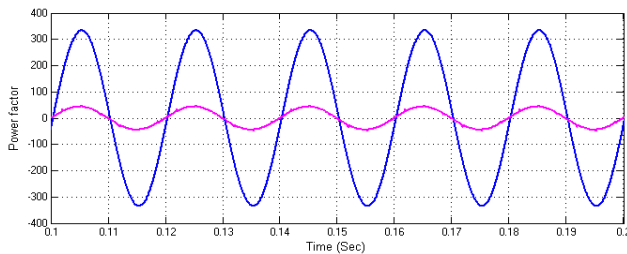
(b) Three phase source current.



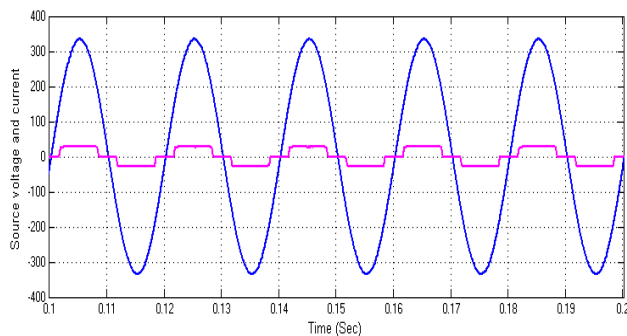
(c) Three phase load current.



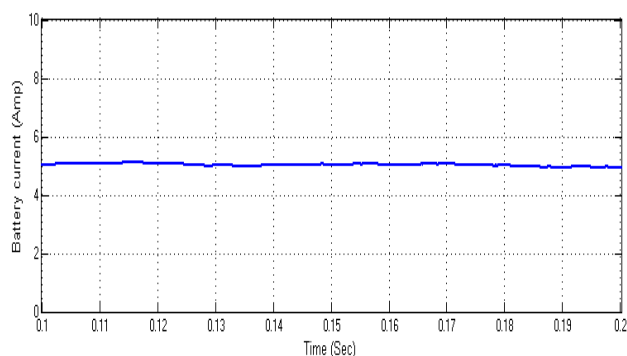
(d) DSTATCOM injected current.



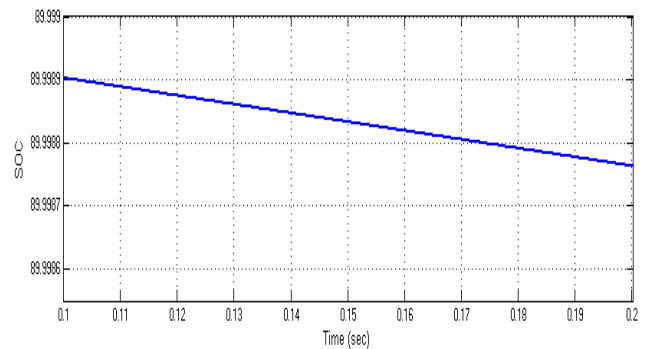
(e) Power factor angle between source voltage and current.



(f) Power factor angle between load voltage and current.



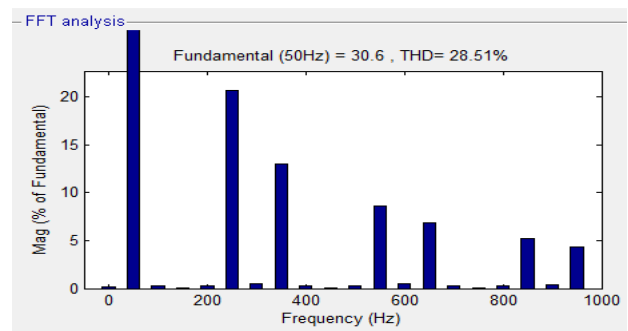
(g) Battery discharging current.



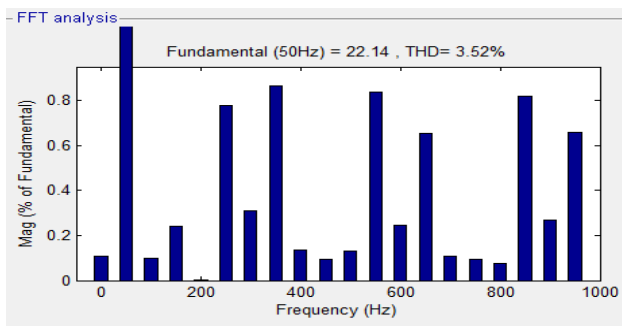
(h) State of charge (SOC)

Figure-10. Simulation outcomes when distribution system is integrated with non-linear load with battery interfaced DSTATCOM under dis-charging mode.

Figure-10(a) shows the simulation result of three phase source voltage wave form with nonlinear load connected in distribution system with Battery integration DSTATCOM in charging mode. The peak amplitude of source voltage is 320V. Figure-10(b) shows the source current waveforms with non linear load connected in distribution system with DSTATCOM. It has peak current of 23A. Figure-10(c) shows the simulation results of three phase load current wave form with magnitude of 28amps. Figure-9(d) shows the compensating DSTATCOM current waveforms injected in to distribution system for harmonic nullification. But load current draws non-linear components as observed from the result. Figure-10(e) shows the simulation results of power factor with DSTATCOM; the power factor was maintained around unity. Figure-10(f) shows the simulation results of load voltage and current waveform. The magnitude of voltage value is 320 volts, and the magnitude of current value is 20 amps. Figure-10(g) shows the simulation results of battery current under battery charging condition mode. The value of battery current is 5.5amps. Figure-10 (h) shows the simulation results of state of charge under battery discharging condition mode. During discharging SOC is decreasing.



(a) THD analysis of load current.

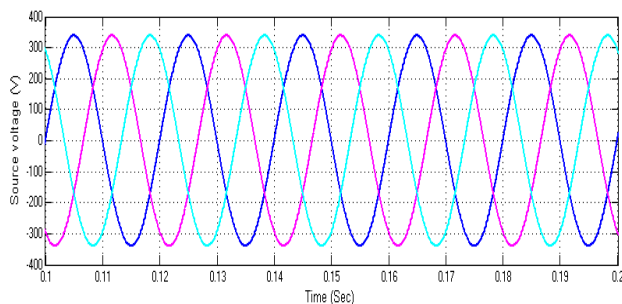


(b) THD plot of source current

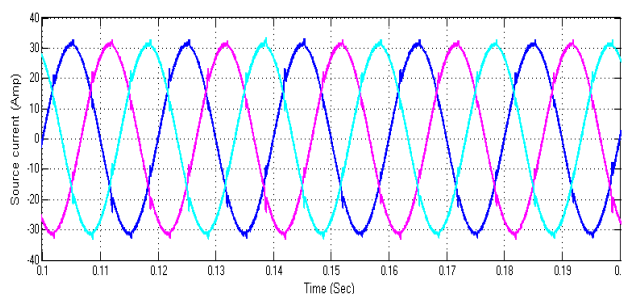
Figure-11. FFT analysis with battery DSTATCOM under dis-charging mode.

Figure-11 (a) shows THD plot for the load current. The %THD value of load current with DSTATCOM is 28.56%. Figure-11(b) shows the THD plot of source current. The %THD value of source current with DSTATCOM is 2.0%. Reduction in THD value can be clearly observed in source current since DSTATCOM is connected to compensate harmonics under battery charging mode.

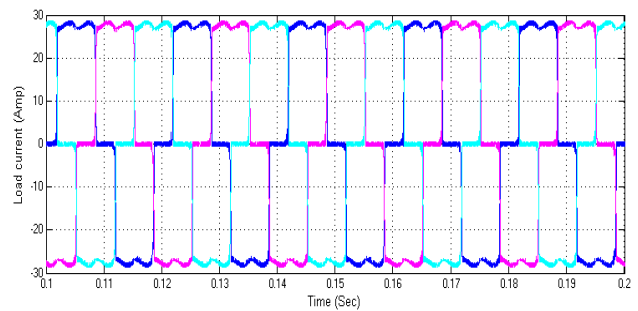
DSTATCOM with battery integration no charge and no discharging mode



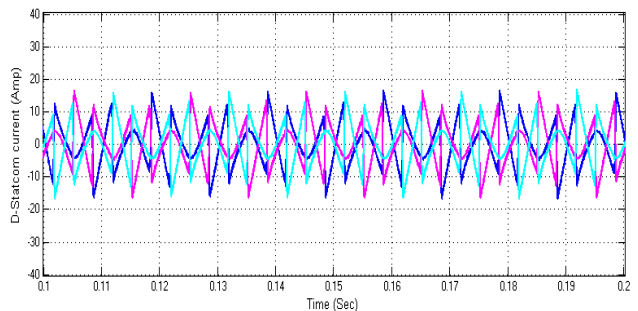
(a) Three phase source voltage.



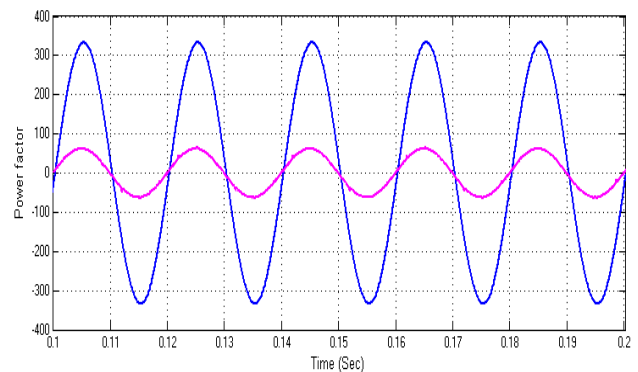
(b) Three phase source current.



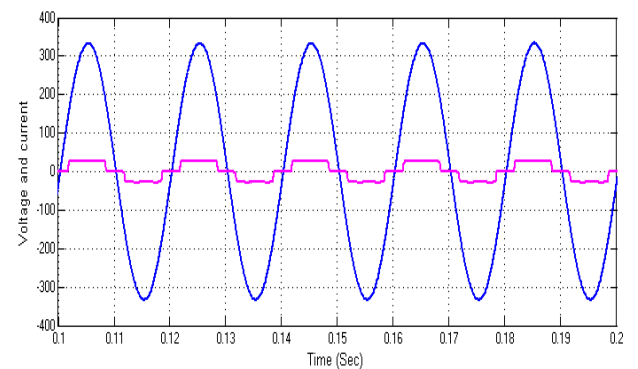
(c) Three phase load current.



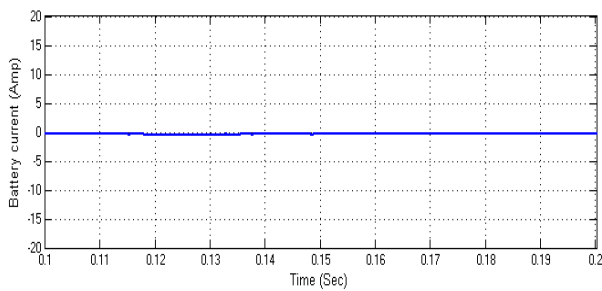
(d) DSTATCOM injected current.



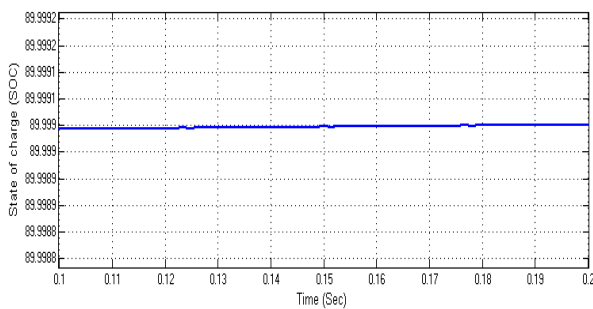
(e) Power factor angle between load voltage and current.



(f) Power factor angle between load voltage and current.

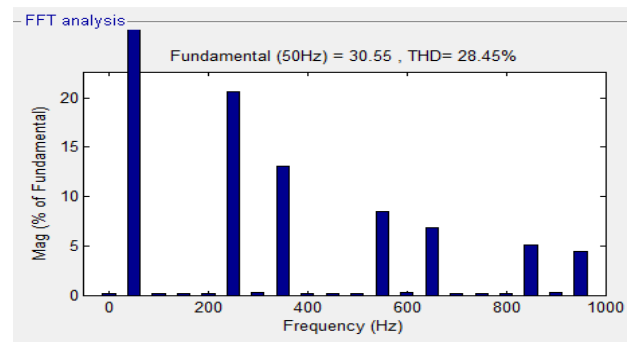


(g) Battery no charge and no discharge current.

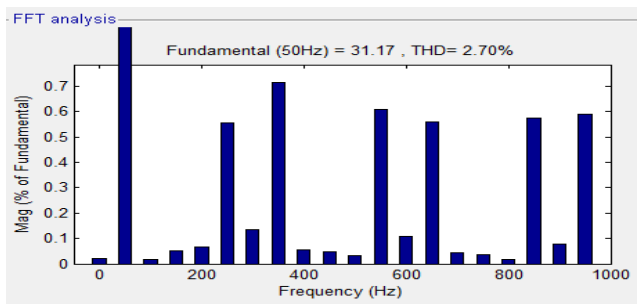


(h) State of charge.

Figure-12. (a) shows the simulation result of three phase source voltage wave form with nonlinear load connected in distribution system with Battery integration DSTATCOM in charging mode. The peak amplitude of source voltage is 320V. Figure-12 (b) shows the source current waveforms with non linear load connected in distribution system with DSTATCOM. It has peak current of 23A. Figure- 11(c) shows the simulation results of three phase load current wave form with magnitude of 30 amps. Figure-12 (d) shows the compensating DSTATCOM current waveforms injected in to distribution system for harmonic nullification. But load current draws non-linear components as observed from the result. Figure-12 (e) shows the simulation results of power factor with DSTATCOM; the power factor was maintained around unity. Figure-11 (f) shows the simulation results of load voltage and current waveform. The magnitude of voltage value is 320 volts, and the magnitude of current value is 20 amps. Figure-12 (g) shows the simulation results of batter current waveform. The value of battery current under battery no charge and no discharge condition mode is approximately zero. Figure-12 (h) shows the simulation result of state of charge (SOC) waveform. The value of state of charge under battery no charge no discharge condition is approximately constant.



(a) THD plot of load current.



(b) THD plot of source current.

Figure-13. FFT analysis with battery DSTATCOM under no charge & no dis-charging mode.

Figure-13(a) shows THD plot for the load current. The %THD value of load current with DSTATCOM is 28.45%. Figure-12 (b) shows the THD plot of source current. The %THD value of source current with DSTATCOM is 2.70%. Reduction in THD value can be clearly observed in source current since DSTATCOM is connected to compensate harmonics under battery charging mode.

Table-2. THD comparison.

PARAMETERS	% THD of source current
Without Battery integration	3.83%
Battery under charging	2.0%
Battery under discharging	3.52%
No charging and discharging	2.70%

CONCLUSIONS

The conferred simulation results enhancing the viability of DSTATCOM usage with integrated battery energy storage system (BESS) for improved power quality features. The proposed fundamental reference current extraction control objective is very effectively compensate the harmonics and maintain the voltage and frequency as a constant at PCC level by using BESS. The proposed fundamental reference based Id-Iq control strategy provides the optimal compensation current for superior enhancement of PQ features with attractive merits such as little switching loss, little switch stress, incredible efficiency. And also able to supplying the reactive power



under dynamic voltage compensation and controlled by proper phase angle and phase magnitude on PCC level. The BESS is not integrated under normal harmonic compensation scheme and mostly BESS is integrated under sudden oscillations and dynamic conditions, to regulate the stability of the three phase distribution system. The harmonic distortions at PCC level under battery charge/discharge state under DSTATCOM compensation principle acquires well under the IEEE-519 standards.

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