Simulation and RTDS Hardware implementation of SHAF for Mitigation of Current Harmonics with p-q and I_d-I_q Control strategies using PI controller

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Abstract **: Control strategies for extracting the three-phase reference currents for shunt active power filters are compared, evaluating their performance under different source conditions in MATLAB/Simulink environment and also with Real Time Digital Simulator (RTDS) hardware. When the supply voltages are balanced and sinusoidal, the two control strategies are converging to the same compensation characteristics but when the supply voltages are distorted and/or un-balanced sinusoidal, these control strategies result in different degrees of compensation in harmonics. The p-q control strategy is unable to yield an adequate solution when source voltages are not ideal. Extensive simulations are carried out with PI controller for both p-q and Id-Iq control strategies for different voltage conditions and adequate results were presented. The 3-ph 4-wire SHAF system is also implemented on RTDS Hardware to further verify its effectiveness. The detailed simulation and RTDS Hardware results are included.**

Keywords- ***harmonic compensation, SHAF, p-q control strategy, Id-Iq control strategy, PI controller, RTDS hardware***.

I. INTRODUCTION

Harmonics surfaced as a buzz word from 1980's which always threaten the normal operation of power system and user equipment. Highly automatic electric equipments, in particular, cause enormous economic loss every year. Owing both power suppliers and power consumers are concerned about the power quality problems and compensation techniques. Sinusoidal voltage is a conceptual quantity produced by an ideal AC generator built with finely distributed stator and field windings that operate in a uniform magnetic field. Since neither the winding distribution nor the magnetic field are uniform in a working AC machine, voltage waveform distortions are created, and the voltage-time relationship deviates from the pure sine function. The distortion at the point of generation is very small (about 1% to 2%), but nonetheless it exists. since this is a deviation from a pure sine wave, the deviation is in the form of an episodic function, and by definition, the voltage distortion contains harmonics [1].

It is noted that non-sinusoidal current results in many problems for the utility power supply company, such as: low power factor, low energy efficiency, electromagnetic interference (EMI), distortion of line voltage etc. and it is noted that, in three-phase four-wire system, zero line may be overheated or causes fire disaster as a result of excessive harmonic current going through the zero line three times or times that of three. Thus a perfect compensator is necessary to avoid the consequences due to harmonics [2]. Though several control strategies have been developed but still two control theories, instantaneous active and reactive currents (i_d–i_q) method and instantaneous active and reactive power (p-q) methods [3-4] are always dominant. The present paper is mainly focused on two control strategies (p-q and I_d-I_q) with PI controller. To validate current observations, Extensive simulations are carried out with PI controller for both p-q and I_d-I_q methods for different voltage conditions like sinusoidal, non-sinusoidal, and un-balanced conditions and adequate results were presented. The 3-ph 4-wire SHAF system is also implemented on a Real Time Digital Simulator (RTDS Hardware) [5] to further verify its effectiveness.

II. CONTROL STRATEGY

In this section two control strategies are discussed in detail. Ideal analysis has done in steady state conditions of the active power filter. Steady state analysis, using Fast Fourier Transform (FFT) for the two control methods that are presented, is briefly enlightened below. Figure 1 shows a basic architecture of three-phase - four wire shunt active filter.

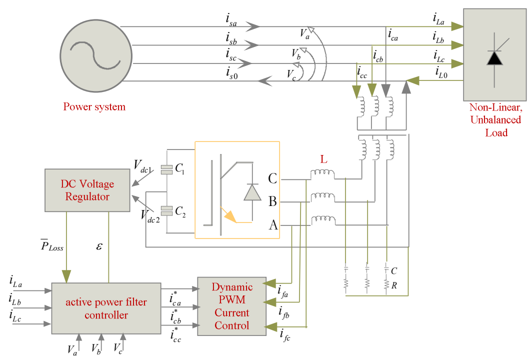


Fig. 1. Three-phase - four wire shunt active filter.

A. Instantaneous real and reactive power method

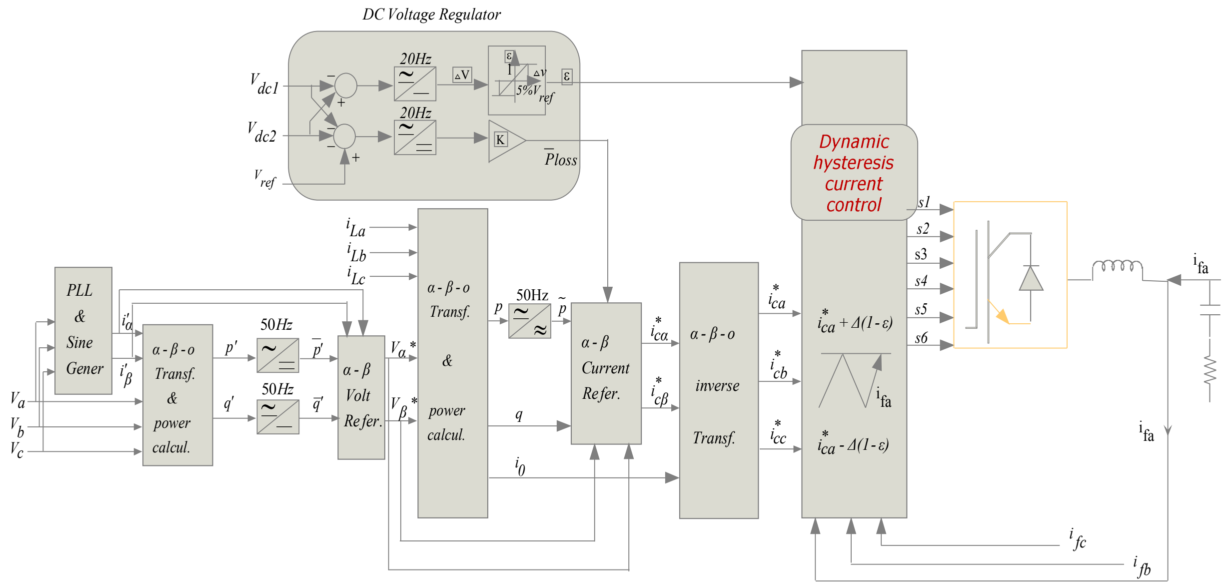


Fig. 2. Control block diagram of shunt active power filter.

Transformation of the phase voltages v_a, v_b, and v_c and the load currents i_{La}, i_{Lb}, and i_{Lc} into the α - β orthogonal coordinates are given in equation (1-2). The compensation objectives of active power filters are the harmonics present in the input currents. Present architecture represents three phase four wire and it is realized with constant power controls strategy [6]. Figure 2 illustrates control block diagram and Inputs to the system are phase voltages and line currents of the load. It was recognized that resonance at relatively high frequency might appear between the source impedance. So a small high pass filter is incorporated in the system. The power calculation is given in detail form in equation (3).

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

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

From Figure 2 we can observe a high pass filter with cut off frequency 50 Hz separates the powers $-\tilde{p}$ from p and a low-Pass filter separates $\overline{p}_0$ from p_0. The powers $\tilde{p}$ and p_0 of the load, together with q, should be compensated to provide optimal power flow to the source. It is Important to note that system used is three phase four wire, so additional neutral currents has to be supplied by the shunt active power filter thus P_{loss} is incorporated to correct compensation error due to feed forward network unable to suppress the zero sequence power. Since active filter compensates the whole neutral current of the load in the presence of zero-sequence voltages, the shunt active filter eventually supplies p_o. Consequently if active filter supplies p_o to the load, this make changes in dc voltage regulator, hence additional amount of active power is added automatically to P_{loss} which mainly provide energy to cover all the losses in the power circuit in the active filter [7]. Thus, with this control strategy shunt active filter gains additional capability to reduce neutral currents and there-by supply necessary compensation when it is most required in the system. Thus the $\alpha\beta$ reference currents can be found with following equation.

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \Delta\overline{p} \\ -q \end{bmatrix} \tag{4}$$

$$\Delta\overline{p} = \overline{p}_0 + \overline{p}_{Loss}$$

Where $\tilde{p}$ is the ac component / oscillating value of p,

$\overline{p_0}$ is the dc component of p_0,

P_{loss} is the losses in the active filter,

$\overline{P_{loss}}$ is the average value of P_{loss} ,

$\Delta\bar{p}$ Provides energy balance inside the active power filter and using equation (5) inverse transformation can be done.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} -i_0 \\ i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (5)$$

where i_{ca}*, i_{cb}*, i_{cc}* are the instantaneous three phase current references

In addition PLL (Phase locked loop) employed in shunt filter tracks automatically, the system frequency and fundamental positive–sequence component of three phase generic input signal. Appropriate design of PLL allows proper operation under distorted and unbalanced voltage conditions. Controller includes small changes in positive sequence detector as harmonic compensation is mainly concentrated on three phase four wire [8]. As we know in three- phase three wire, v_a', v_b', v_c' are used in transformations which resemble absence of zero sequence component and it is given in equation (6). Thus in three phase four wire it was modified as v_α', v_β' and it is given in equation (7).

$$\begin{bmatrix} v_a' \\ v_b' \\ v_c' \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha' \\ v_\beta' \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} v_\alpha' \\ v_\beta' \end{bmatrix} = \frac{1}{i_\alpha'^2 + i_\beta'^2} \begin{bmatrix} i_\alpha' & -i_\beta' \\ i_\beta' & i_\alpha' \end{bmatrix} \begin{bmatrix} \bar{p}' \\ \bar{q}' \end{bmatrix} \quad (7)$$

The dc capacitor voltages Vdc1 and Vdc2 may be controlled by a dc voltage regulator. A low-pass filter with cut-off frequency 20Hz is used to render it insensitive to the fundamental frequency (50Hz) voltage variations. The filtered voltage difference $\Delta V = V_{dc2} - V_{dc1}$ produces voltage regulation ε according to the following limit function generator:

$$\varepsilon = -1; \qquad \Delta V < -0.05V_{ref}$$

$$\varepsilon = \frac{\Delta V}{-0.05V_{ref}}; \quad -0.05V_{ref} \le \Delta V \le 0.05V_{ref}$$

$$\varepsilon = 1; \qquad \Delta V > 0.05V_{ref}$$

Where V_{ref} is a pre-defined dc voltage reference and $0.05V_{ref}$ was arbitrarily chosen as an acceptable tolerance margin for voltage variations.

If $(V_{dc1} + V_{dc2}) < V_{ref}$, the PWM inverter should absorb energy from the ac network to charge the dc capacitor. The inverse occur if $(V_{dc1} + V_{dc2}) > V_{ref}$.

The signal $\overline{P_{loss}}$ generated in the dc voltage regulator is useful for correcting voltage variations due to compensation errors that may occur during the transient response of shunt active filter.

B. Instantaneous active and reactive current method ($i_d - i_q$)

In this method reference currents are obtained through instantaneous active and reactive currents i_d and i_q of the non linear load [9-10]. Calculations follows Similar to the instantaneous power theory, however *dq* load currents can be obtained from equation (8). Two stage transformations give away relation between the stationary and rotating reference frame with active and reactive current method. Figure 4 shows voltage and current vectors in stationary and rotating reference frames. The transformation angle 'θ' is sensible to all voltage harmonics and unbalanced voltages; as a result $d\theta/dt$ may not be constant. Arithmetical relations are given in equation (8) and (9); finally reference currents can be obtained from equation (10).

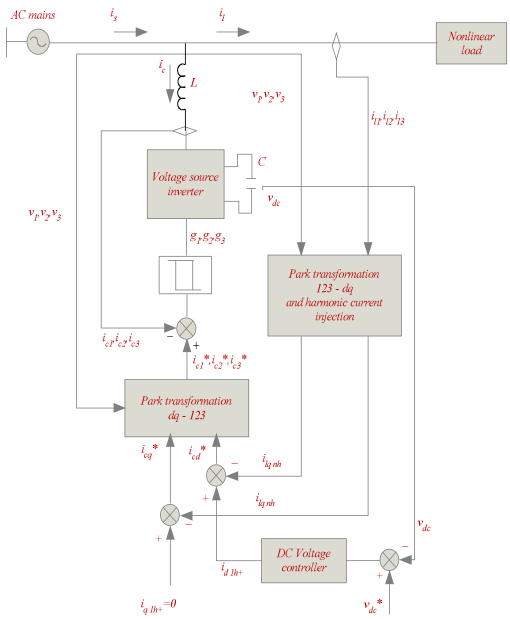


Fig. 3. Active powers filter control circuit.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

Where i_α , i_β are the instantaneous α-β axis current references

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} ic_d \\ ic_q \end{bmatrix} \quad (10)$$

where i_{cd} ,i_{cq} are compensation currents .

One of the advantages of this method is that angle θ is calculated directly from main voltages and thus makes this method frequency independent by avoiding the PLL in the control circuit. Consequently synchronizing problems with unbalanced and distorted conditions of main voltages are also evaded. Thus $i_d - i_q$ achieves large frequency operating limit essentially by the cut-off frequency of voltage source inverter (VSI) [11]. Figures 3 and 5 show the control diagram for shunt active filter and harmonic injection circuit. On owing load currents i_d and i_q are obtained from park transformation then they are allowed to pass through the high pass filter to eliminate dc components in the nonlinear load currents. Filters used in the circuit are Butterworth type and to reduce the influence of high pass filter an alternative high pass filter (AHPF) can be used in the circuit. It can be obtained through the low pass filter (LPF) of same order and cut-off frequency simply difference between the input signal and the filtered one, which is clearly shown in Figure 5. Butterworth filters used in harmonic injecting circuit have cut-off frequency equal to one half of the main frequency ($f_c=f/2$), with this a small phase shift in harmonics and sufficiently high transient response can be obtained.

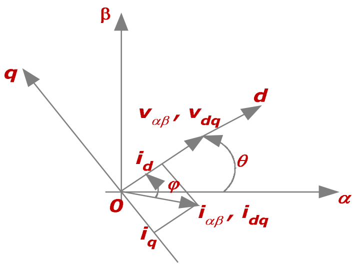


Fig. 4. Instantaneous voltage and current vectors.

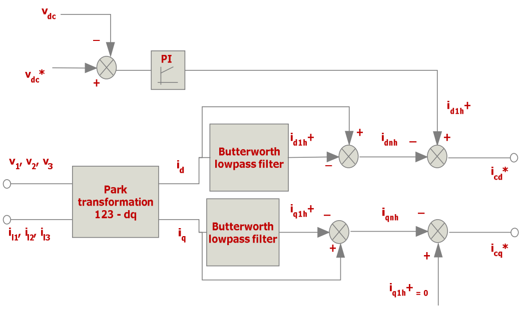


Fig. 5. Park transformation and harmonic current injection circuit.

The function of voltage regulator on dc side is performed by proportional – integral (PI) controller, inputs to the PI controller are, change in dc link voltage (V_{dc}) and reference voltage (V_{dc}*), on regulation of first harmonic active current of positive sequence $i_{d1h}{}^{+}$ it is possible to control the active power flow in the VSI and thus the capacitor voltage V_{dc}. In similar fashion reactive power flow is controlled by first harmonic reactive current of positive sequence $i_{q1h}{}^{+}$. On the contrary the primary end of the active power filters is just the exclusion of the harmonics caused by nonlinear loads hence the current $i_{q1h}{}^{+}$ is always set to zero.

III. CONSTRUCTION OF PI CONTROLLER

Figure 6 shows the internal structure of the control circuit. The control scheme consists of PI controller [12], limiter, and three phase sine wave generator for reference current generation and generation of switching signals.

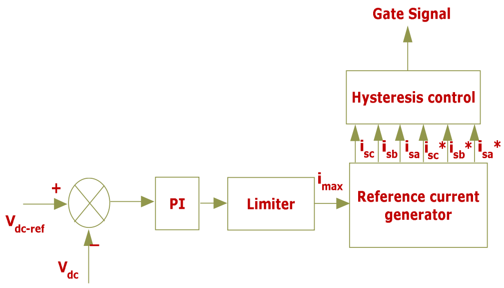


Fig. 6. Conventional PI Controller

The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components: (a) fundamental active power component of load current, and (b) loss component of APF; to maintain the average capacitor voltage to a constant value. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents (I_{sa}*, I_{sb}*, I_{sc}*) and sensed actual currents (Isa, Isb, Isc) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents I_{sabc} are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band. The width of hysteresis window determines the source current pattern, its harmonic spectrum and the switching frequency of the devices. The DC link capacitor voltage is kept constant throughout the operating range of the converter. In this scheme, each phase of the converter is controlled independently. To increase the current of a particular phase, the lower switch of the converter associated with that particular phase is turned on while to decrease the current the upper switch of the respective converter phase is turned on. With this one can realize, potential and feasibility of PI controller.

The actual source currents are monitored instantaneously, and then compared to the reference currents [13] generated by the proposed algorithm. In order to get accurate instantaneously control, switching of IGBT device should be such that the error signal should approaches to zero, thus provides quick response. For this reason, hysteresis current controller with fixed band which derives the switching signals of three phase IGBT based VSI bridge is used. The upper device and the lower device in one phase leg of VSI are switched in complementary manner else a dead short circuit will be take place. The APF reference currents isa, isb, isc compared with sensed source currents isa, isb, isc and the error signals are operated by the hysteresis current controller to generate the firing pulses which activate the inverter power switches in a manner that reduces the current error.

IV. RTDS HARDWARE

The Real Time Digital Simulator (RTDS) allows developers to accurately and efficiently simulate electrical power systems and their ideas to improve them The RTDS Simulator operates in real time, therefore not only allowing the simulation of the power system, but also making it possible to test physical protection and control equipment. This gives developers the means to prove their ideas, prototypes and final products in a realistic environment.

The RTDS is a fully digital power system simulator capable of continuous real time operation. It performs electromagnetic transient power system simulations with a typical time step of 50 microseconds utilizing a combination of custom software and hardware. The proprietary operating system used by the RTDS guarantees "hard real time" during all simulations. It is an ideal tool for the design, development and testing of power system protection and control schemes. With a large capacity for both digital and analogue signal exchange (through numerous dedicated, high speed I/O ports) physical protection and control devices are connected to the simulator to interact with the simulated power system.

V. SIMULATOR HARDWARE

The real time digital simulation hardware used in the implementation of the RTDS is modular, hence making it possible to size the processing power to the simulation tasks at hand. Figure 7 illustrates typical hardware configurations for real time digital simulation equipment. As can be seen, the simulator can take on several forms including a new portable version which can easily be transported to a power-plant or substation for on-site pre-commissioning tests. Each rack of simulation hardware contains both processing and communication modules. The mathematical computations for individual power system components and for network equations are performed using one of two different processor modules. An important aspect in the design and implementation of any real time simulation [14] tool is its ability to adapt to future developments. Since the power system industry itself continues to advance with the introduction new innovative devices, both the hardware and software of the simulator must be able to follow such changes. Great care has been taken to ensure such upward compatibility in all aspects of the real time simulator. Adhering to this approach provides significant benefit to all simulator users since they are able to introduce new features to already existing simulator installations.

VI. SYSTEM PERFORMANCE

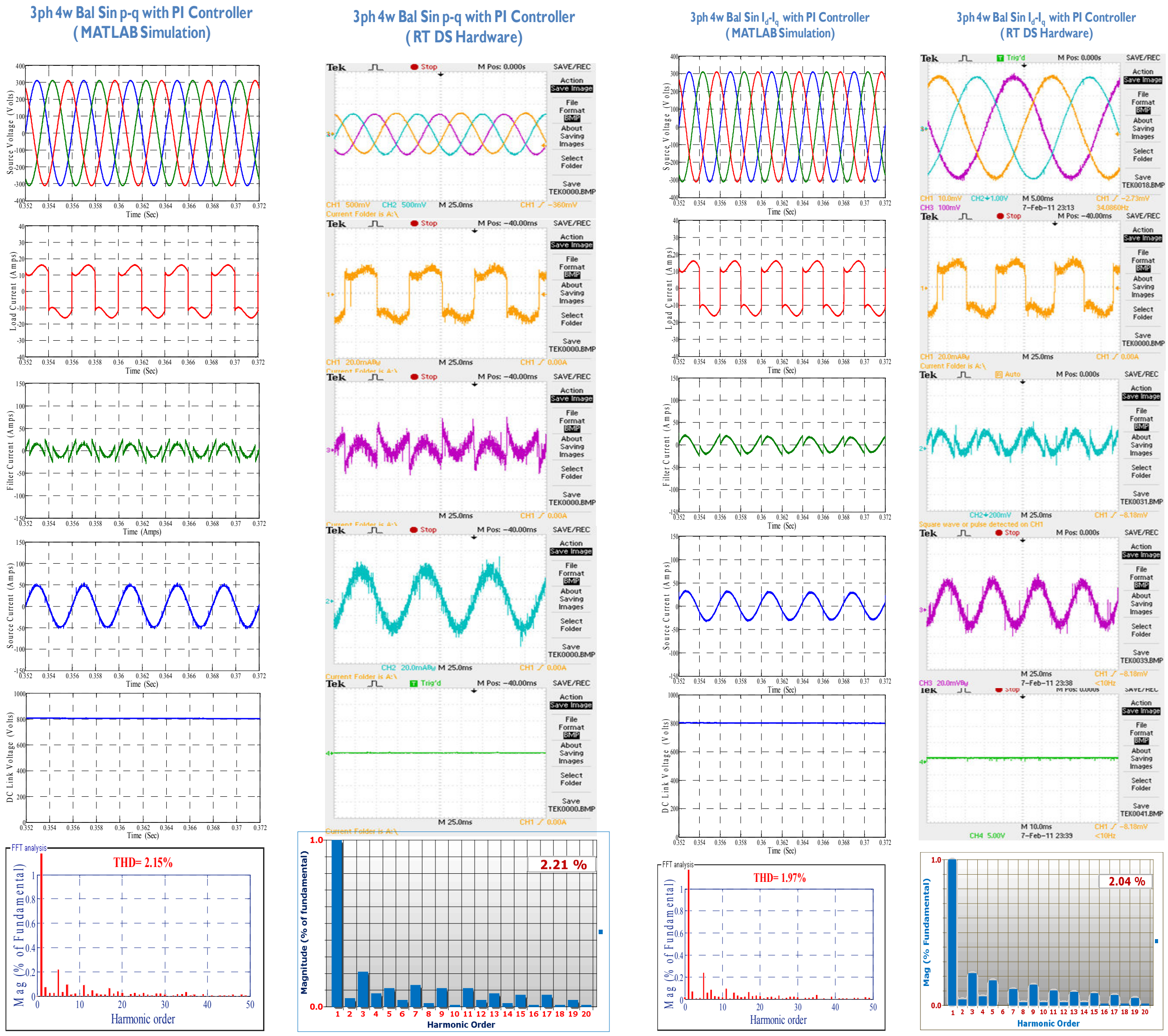
In this section 3 phase 4 wire shunt active power filter responses are presented in transient and steady state conditions. In the present simulation AHPF (alternative high pass filter) were used in Butterworth filter with cut-off frequency f_c=f/2. Simulation shown here are for different voltage conditions like sinusoidal, non-sinusoidal, and unbalanced conditions. Simulation is carried out with PI controller for both instantaneous real active and reactive power control strategy (p-q) and active and reactive current control strategy (i_d-i_q).

Figure 8, Figure 9 and Figure 10 illustrates the performance of shunt active power filter under different main voltages, as load is highly inductive, current draw by load is integrated with rich harmonics. Figure 8 illustrates the performance of Shunt active power filter under balanced sinusoidal voltage condition, THD for *p-q* method with PI Controller using matlab simulation is 2.15% and using RTDS Hard ware is 2.21; THD for i_d-i_q method with PI Controller using matlab simulation is 1.97% and using RTDS Hard ware is 2.04% . Figure 9 illustrates the performance of Shunt active power filter under un-balanced sinusoidal voltage condition, THD for *p-q* method with PI Controller using matlab simulation is 4.16% and using RTDS Hard ware is 4.23; THD for i_d-i_q method with PI Controller using matlab simulation is 3.11% and using RTDS Hard ware is 3.26%.

Fig. 7. RTDS Hardware

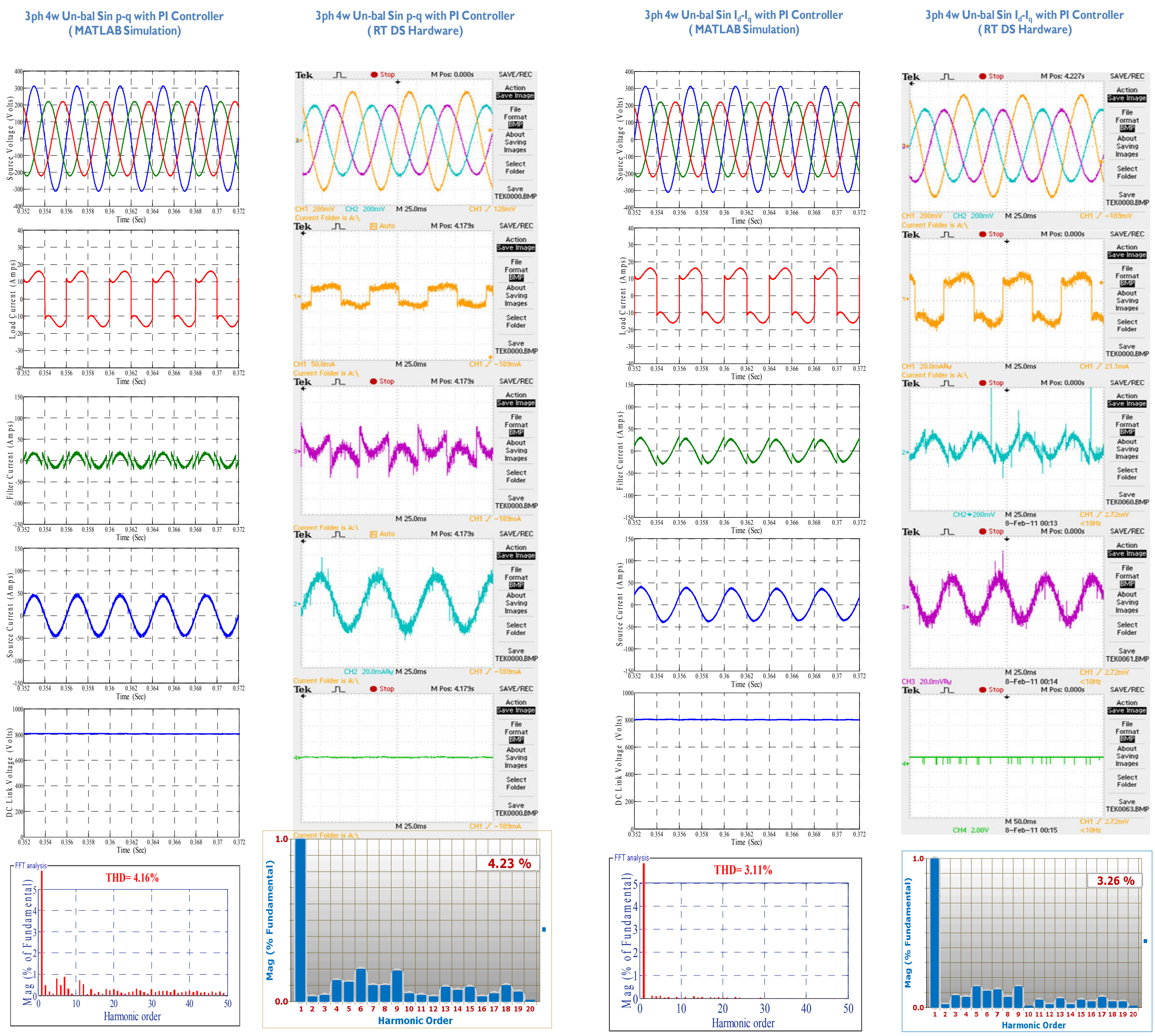
Figure 10 illustrates the performance of Shunt active power filter under balanced non-sinusoidal voltage condition, THD for p-q method with PI Controller using matlab simulation is 5.32% and using RTDS Hard ware is 5.41; THD for id-iq method with PI Controller using matlab simulation is 4.92% and using RTDS Hard ware is 5.05%.

Fig 11 gives the comparison between p-q and Id-Iq control strategies with PI Controller Using Matlab/Simulink and RTDS Hardware. It is shown that Total Harmonic Distortion (THD) of Id-Iq control strategy with PI controller is better than THD of p-q control strategy with PI controller in both Matlab/Simulink environment and also when using RTDS Hardware.



(a) (b) (c) (d)

Fig. 8. 3ph 4wire Shunt ative filter response with PI controller Under balanced Sinusoidal using (a) p-q with Matlab (b) p-q with RTDS Hardware (c) i_d-i_q with Matlab (d) i_d-i_q with RTDS Hardware



(a) (b) (c) (d)

Fig. 9. 3ph 4wire Shunt ative filter response with PI controller Under Un-balanced Sinusoidal using (a) p-q with Matlab (b) p-q with RTDS Hardware (c) i_d-i_q with Matlab (d) i_d-i_q with RTDS Hardware

VII. CONCLUSION

In the present paper two control strategies are developed and verified with three phase four wire system. Though the two strategies are capable to compensate current harmonics in the 3 phase 4-wire system, but it is observed that instantaneous active and reactive current (i_d-i_q) control strategy with PI controller leads to better result under un-balanced and non-sinusoidal voltage conditions compared to the instantaneous active and reactive power (*p-q)* control strategy. Further, *p-q* theory needs additional PLL circuit for synchronization, since it is a frequency variant method, whereas in i_d-i_q method angle 'θ' is calculated directly from main voltages. This enables the (i_d-i_q) method to be frequency independent. Thus large numbers of synchronization problems with un-balanced and non-sinusoidal voltages are avoided. Over all, it is shown that the performance of i_d-i_q control strategy with PI controller is superior to *p-q* control strategy with PI controller.

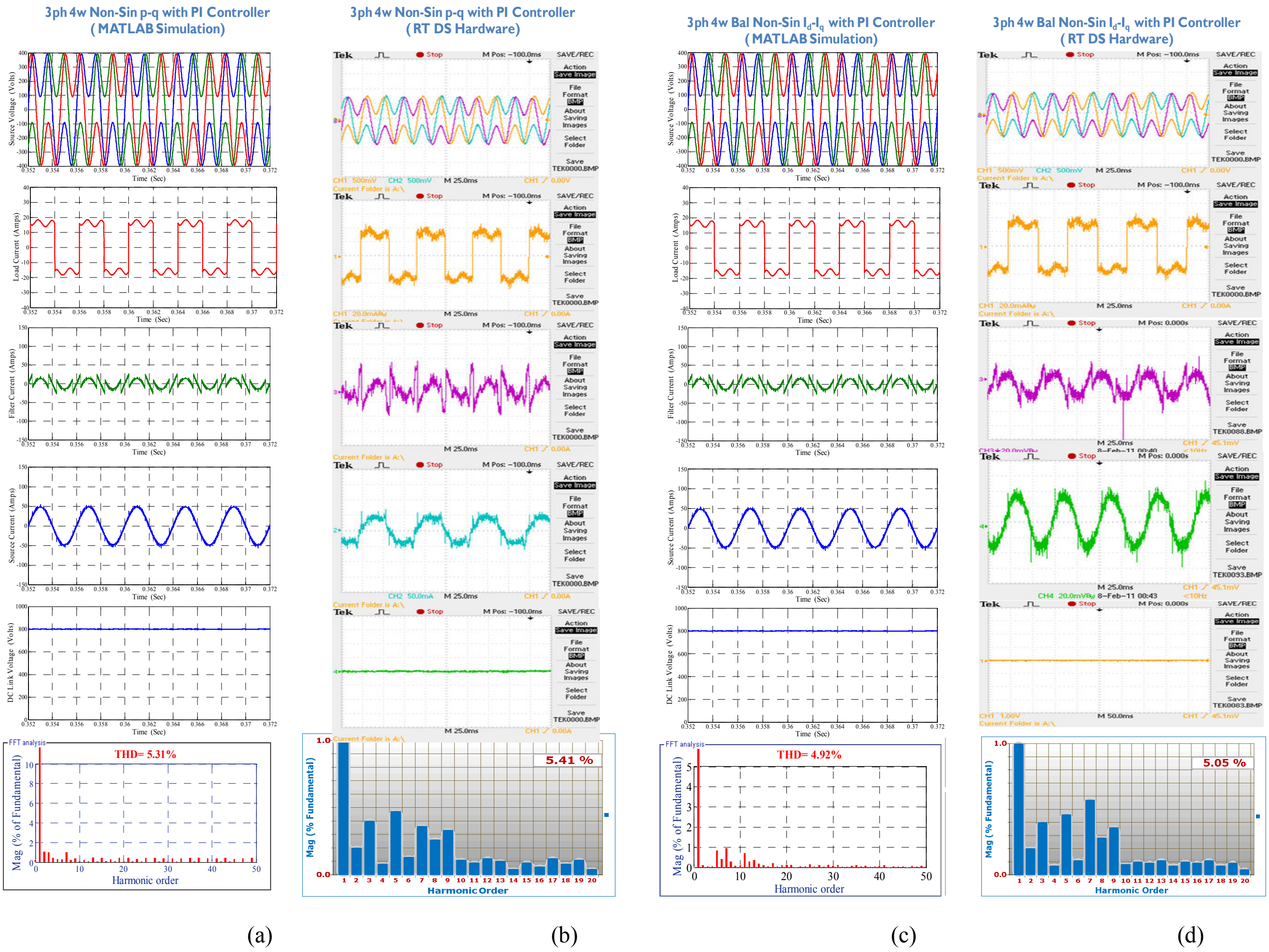


Fig. 10. 3ph 4wire Shunt ative filter response with PI controller Under balanced Non-Sinusoidal using (a) p-q with Matlab (b) p-q with RTDS Hardware (c) i_d-i_q with Matlab (d) i_d-i_q with RTDS Hardware

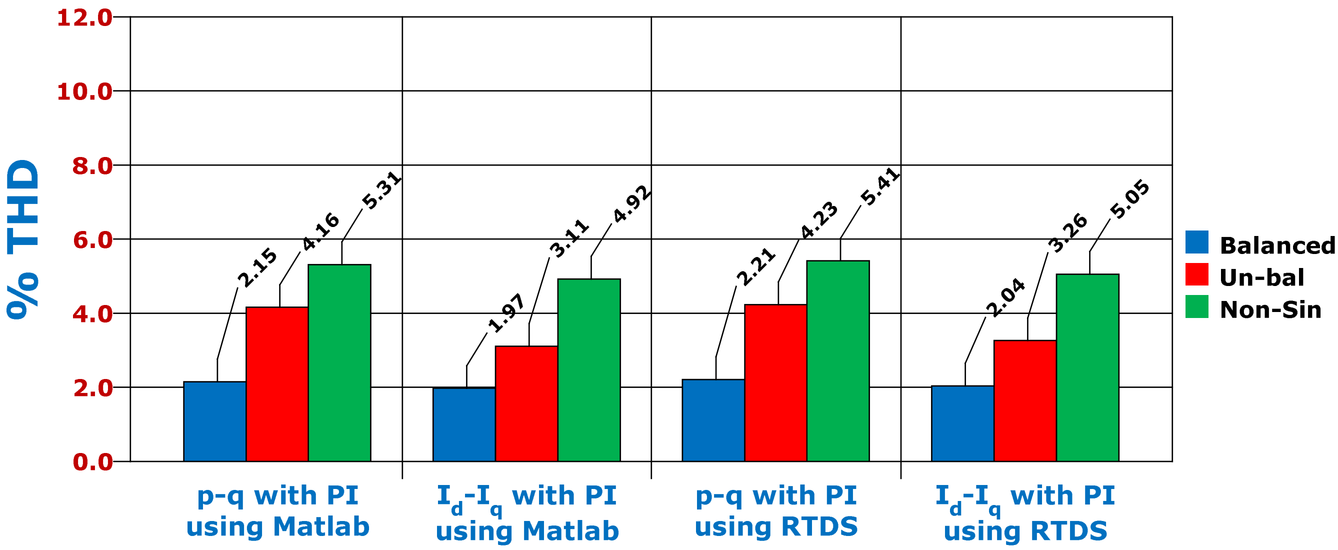


Fig. 11. THD for p-q and i_d-i_q control strategies with PI Controller Using Matlab and RTDS Hardware

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His research interest include analysis and design of high frequency power conversion circuits, power factor correction circuits, power quality improvement in power system and electric drives.