

RTDS Hardware implementation and Simulation of 3ph 4wire SHAF for mitigation of Current harmonics with p-q Control strategy using PI controller

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Abstract: - This paper presents a control strategy for a three phase four-wire shunt active filter. The shunt active filter is a custom-power device capable to compensate, in real time, harmonics and unbalances in an electrical system. The main objective of this paper is to analyse the performance of instantaneous real active and reactive power ($p-q$) control strategy for extracting reference currents of shunt active filters under balanced, un-balanced and balanced non-sinusoidal conditions with **PI controller** in MATLAB/Simulink environment and also with Real Time Digital Simulator (RTDS) Hardware. When the supply voltages are balanced and sinusoidal, the all control strategies are converge to the same compensation characteristics; However, the supply voltages are distorted and/or un-balanced sinusoidal, these control strategies result in different degrees of compensation in harmonics. Extensive simulations are carried out with PI controller for $p-q$ control strategy under different main voltages. The 3-ph 4-wire SHAF system is also implemented on a RTDS Hardware to further verify its effectiveness. The detailed simulation and RTDS Hardware results are included.

Index Terms— Harmonic compensation, SHAF, $p-q$ control strategy, PI Controller and RTDS Hardware.

1. INTRODUCTION

ELECTRICAL power quality has been an important and growing problem because of the proliferation of nonlinear loads such as power electronic converters in typical power distribution systems. Particularly, voltage harmonics and power distribution equipment problems result from current harmonics [1-2] produced by nonlinear loads. 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. When a pure sinusoidal voltage is

applied to a certain type of load, the current drawn by the load is proportional to the voltage and impedance and follows the envelope of the voltage waveform. These loads are referred to as linear loads (loads where the voltage and current follow one another without any distortion to their pure sine waves). Examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction and synchronous motors. In contrast, some loads cause the current to vary disproportionately with the voltage during each half cycle, These loads are defined as nonlinear loads, and the current and voltage have waveforms that are no sinusoidal, containing distortions, whereby the 50-Hz waveform has numerous additional waveforms superimposed upon it, creating multiple frequencies within the normal 50-Hz sine wave. The multiple frequencies are harmonics [3] of the fundamental frequency. Examples of nonlinear loads are battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies. As nonlinear currents flow through a facility's electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed, and utilized, voltage and current waveform distortions are produced. 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. Eminent issues always arises in three-phase four-wire system, it is well-known that 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.

Though several control techniques and strategies [4] had developed but still performance of filter in contradictions, these became primarily motivation for the current paper. Present paper mainly focused on instantaneous active and reactive power ($p-q$) control strategy, which is prominent one with this we analysed the performance of filter under

different main voltages with PI controller. To validate current observations, Extensive simulations were performed and adequate results were presented. The 3-ph 4-wire SHAF system is also implemented on a Real Time Digital Simulator (RTDS Hardware) to further verify its effectiveness.

2. SHUNT ACTIVE FILTER

The active filter currents are achieved from the instantaneous active and reactive powers p and q of the non-linear load [5-6]. Fig.1 shows a basic architecture of three-phase - four wire shunt active filter.

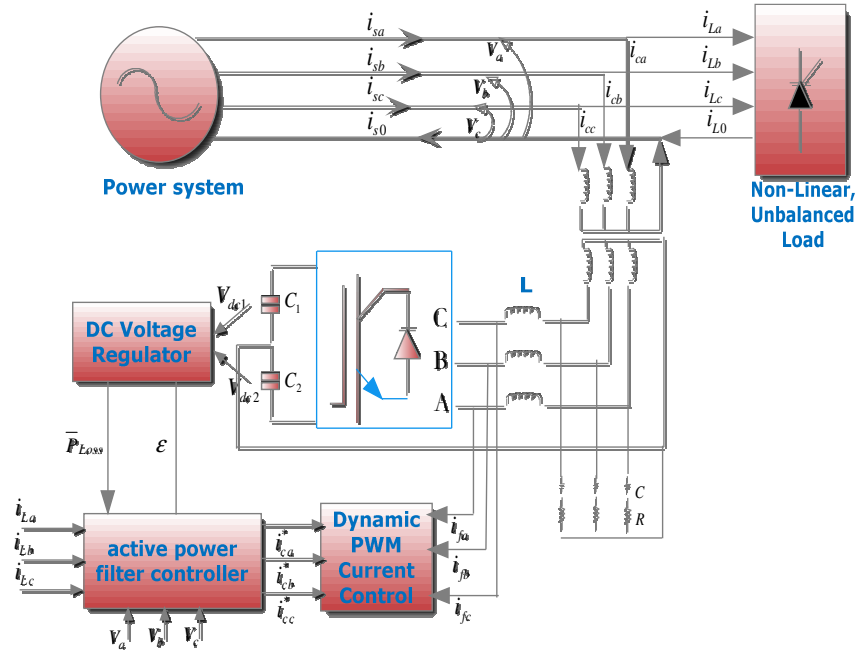


Fig.1. Basic architecture of three-phase - four wire shunt active filter.

2.1 Compensation principle: -

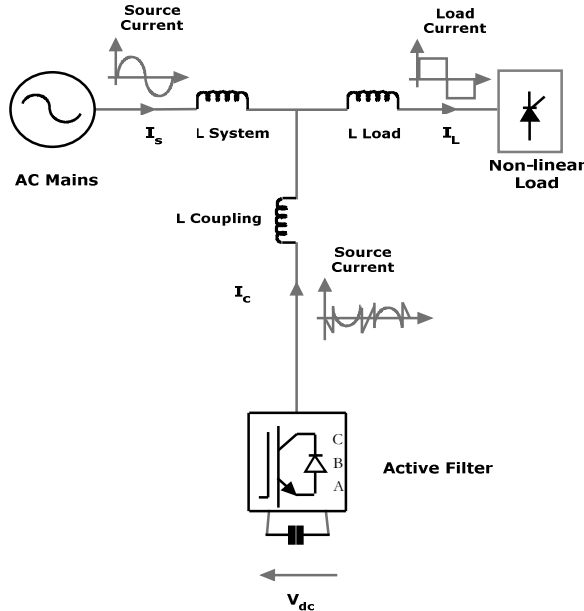


Fig 2. Compensation Characteristics of a SHAF

The active power filter is controlled to draw/supply the a compensating current i_f from/to the load to cancel out the current harmonics on AC

side and reactive power flow from/to the source there by making the source current in phase with source voltage. Figure 2 shows the basic compensation principle of the active power filter.

2.2 Instantaneous real and reactive power method ($p - q$):

The active filter currents are achieved from the instantaneous active and reactive powers p and q of the non-linear load. 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 $\alpha - \beta$ 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. Fig.3 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).

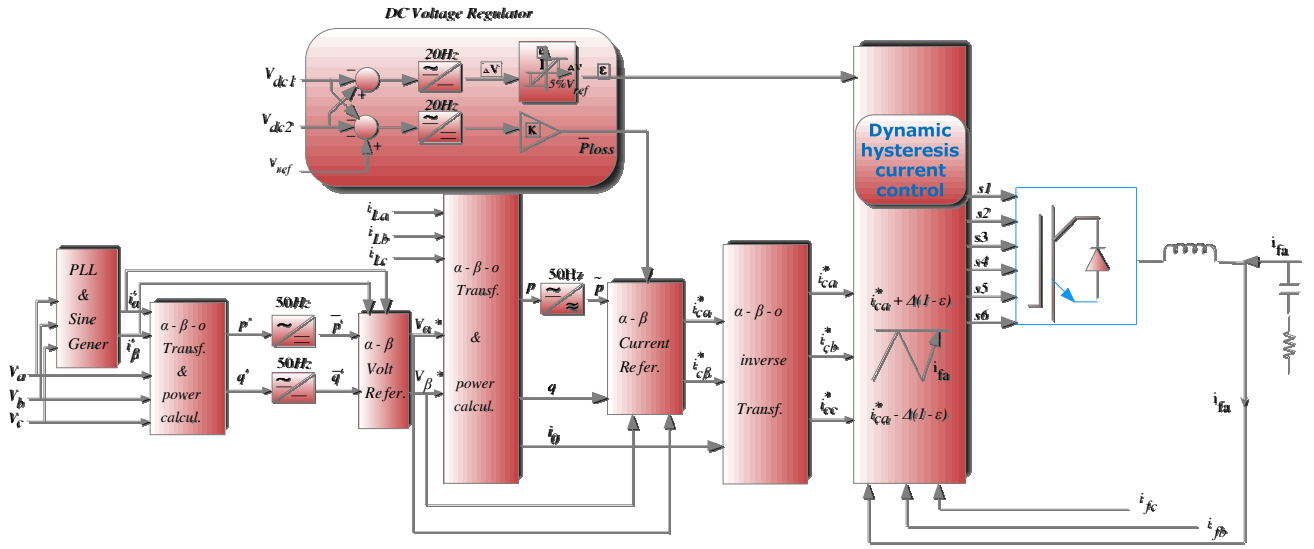


Fig.3. control block diagram of shunt active power filter.

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

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

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

From Fig.3 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 \bar{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 [7-8]. 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_0 . Consequently if active filter supplies p_0 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. 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.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \Delta p \\ -q \end{bmatrix} \quad (4)$$

$$\Delta \bar{p} = \bar{p}_0 + \bar{P}_{Loss}$$

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

p

\bar{p}_0 is the dc component of p_0

P_{loss} is the losses in the active filter

\bar{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 [9]. 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 [10]. 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_a' , v_b' and it is given in equation (7).

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

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

DC voltage regulator (p-q):-

The dc capacitor voltages V_{dc1} and V_{dc2} 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:

$$\begin{aligned} \varepsilon &= -1; & \Delta V &< -0.05V_{ref} \\ \varepsilon &= \frac{\Delta V}{-0.05V_{ref}}; & -0.05V_{ref} &\leq \Delta V \leq 0.05V_{ref} \\ \varepsilon &= 1; & \Delta V &> 0.05V_{ref} \end{aligned}$$

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.

3. CONSTRUCTION OF PI CONTROLLER

Fig.4 shows the internal structure of the control circuit. The control scheme consists of PI controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. 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 [11].

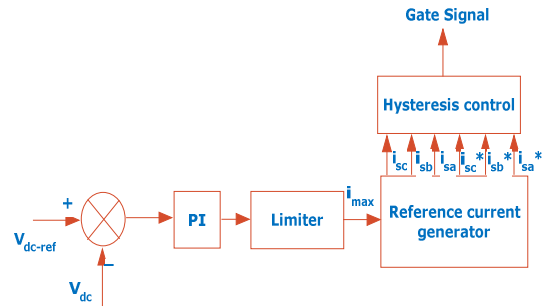


Fig.4 Conventional PI Controller

The error signal is then processed through a PI controller [12-13], 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 (I_{sa} , I_{sb} , I_{sc}) 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.

4 RTDS HARDWARE

This simulator was developed with the aim of meeting the transient simulation needs of electromechanical drives and electric systems while solving the limitations of traditional real-time simulators. It is based on a central principle: the use of widely available, user-friendly, highly competitive commercial products (PC platform, Simulink™). The real-time simulator [14] consists of two main tools: a real-time distributed simulation package (RT-LAB) for the execution of Simulink block diagrams on a PC-cluster, and algorithmic toolboxes designed for the fixed-time-step simulation of stiff electric circuits and their controllers. Real-time simulation and Hardware-In-the-Loop (HIL) applications are increasingly recognized as essential tools for engineering design and especially in power electronics and electrical systems.

Simulator Architecture

A. Block Diagram and Schematic Interface

The present real-time electric simulator is based on RT LAB real-time, distributed simulation

platform; it is optimized to run Simulink in real-time, with efficient fixed-step solvers, on PC Cluster. Based on COTS non-proprietary PC components, RT LAB is a modular real-time simulation platform, for the automatic implementation of system-level, block diagram models, on standard PC's. It uses the popular MATLAB/Simulink as a front-end for editing and viewing graphic models in block-diagram format. The block diagram models become the source from which code can be automatically generated, manipulated and downloaded onto target processors (Pentium and Pentium-compatible) for real-time or distributed simulation.

B. Inputs and Outputs (I/O)

A requirement for real-time HIL applications is interfacing with real world hardware devices, controller or physical plant alike. In the RT-LAB real-time simulator, I/O interfaces are configured through custom blocks, supplied as a Simulink toolbox. The engineer merely needs to drag and drop the blocks to the graphic model and connect the inputs and outputs to these blocks, without worrying about low-level driver programming. RT-LAB manages the automatic generation of I/O drivers and models code so to direct the model's data flow onto the physical I/O cards.

C. Simulator Configuration

In a typical configuration (Figure.5), the RT-LAB simulator consists of

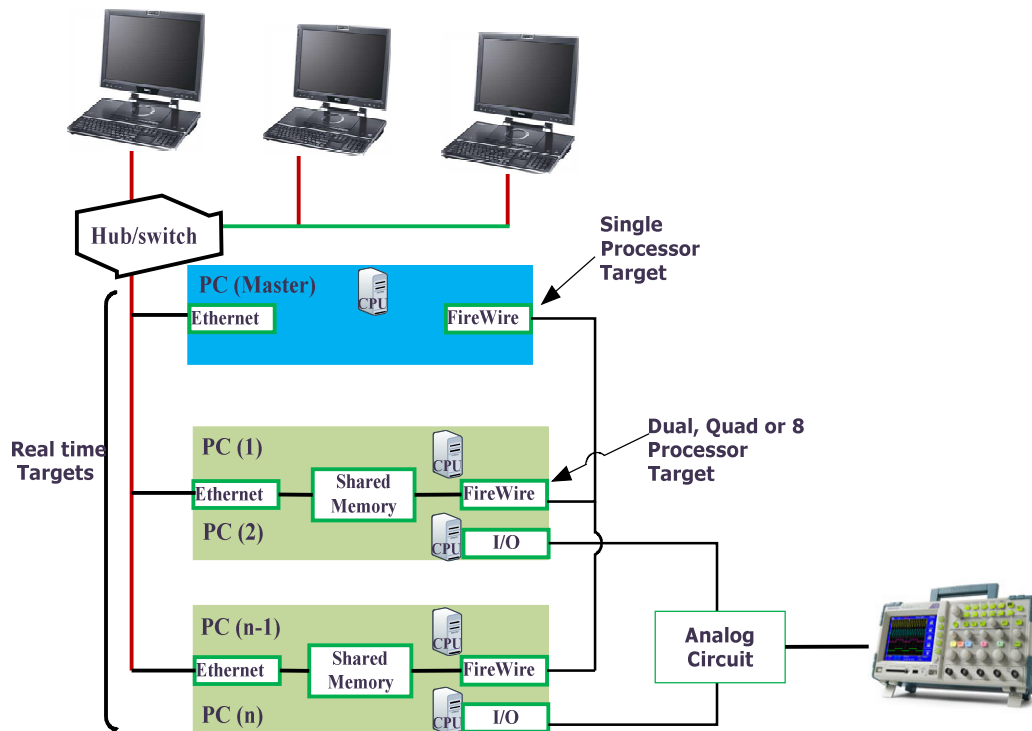


Fig 5. RT-LAB Simulator Architecture

- One or more target PC's (computation nodes); one of the PCs (Master) manages the communication between the hosts and the targets and the communication between all other target PC's. The targets use the REDHAT real-time operating system.
- One or more host PC's allowing multiple users to access the targets; one of the hosts has the full control of the simulator, while other hosts, in read-only mode, can receive and display signals from the real-time simulator.
- I/O's of various types (analog in and out, digital in and out, PWM in and out, timers, encoders, etc). I/O's can be managed by dedicated processors distributed over several nodes.
- Ethernet connection (100 Mb/s) between the hosts and target PC's.
- Ethernet connection between target nodes allowing parallel computation of models with low and medium step size (in the millisecond range), or for free-running, on real-time simulation.
- Fast IEEE 1394 (FireWire) communication links (400 Mb/s) between target PC's for parallel simulation of models with small step sizes (down to 20 μ s) and tight communication constraints (power systems, electric drive control, etc).
- Fast shared-memory communication between processors on the same motherboard (dual, quad or 8 processors)

The simulator uses the following communication links



Fig.6 RTDS Hardware

D. Simulator solvers

The RT-LAB electrical simulator [15] uses advanced fixed time-step solvers and computational techniques designed for the strict constraints of real-time simulation of stiff systems. They are implemented as a Simulink toolbox called ARTEMIS, which is used with the sim Power Systems (PSB). PSB is a Simulink toolbox that enables the simulation of electric circuits and drives within the Simulink environment. While PSB now supports a fixed-time-step solver based on the Tustin method, PSB alone is not suitable for real-time simulation due to many serious

limitations, including iterative calculations to solve algebraic loops, dynamic computation of circuit matrices, un-damped switching oscillations, and the need for a very small step size which greatly slows down the simulation. The ARTEMIS solver uses a high-order fixed-time-step integration algorithm that is not prone to numerical oscillations, and advanced computational techniques necessary for the real-time simulation of power electronic systems and drives such as:

- Exploitation of system topology to reduce matrices' size and number by splitting the equations of separated systems

- Support for parallel processing suitable for distributed simulation of large systems
- Implementation of advanced techniques for constant computation time
- Strictly-non-iterative integration
- Real-time compensation of switching events occurring anywhere inside the time step, enabling the use of realistic simulation step sizes

while ensuring a good precision of circuits with switches (GTO, IGBT, etc).

5. SIMULATION AND RTDS RESULTS

Fig.7, Fig.8 and Fig.9 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.

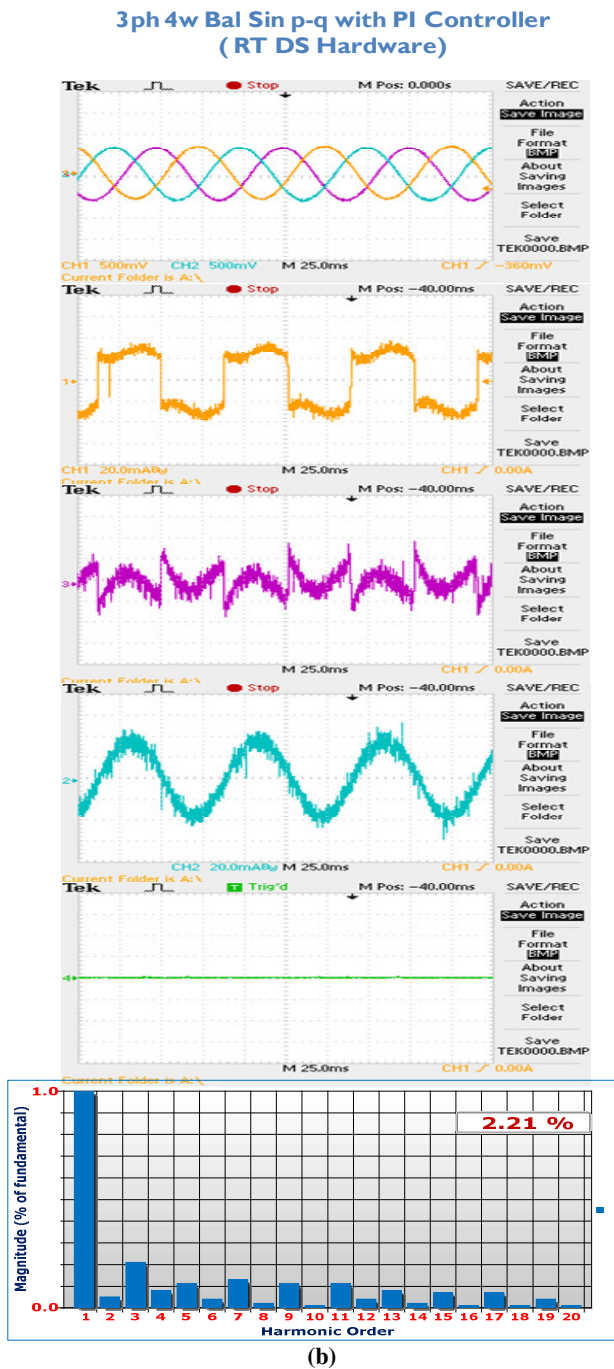
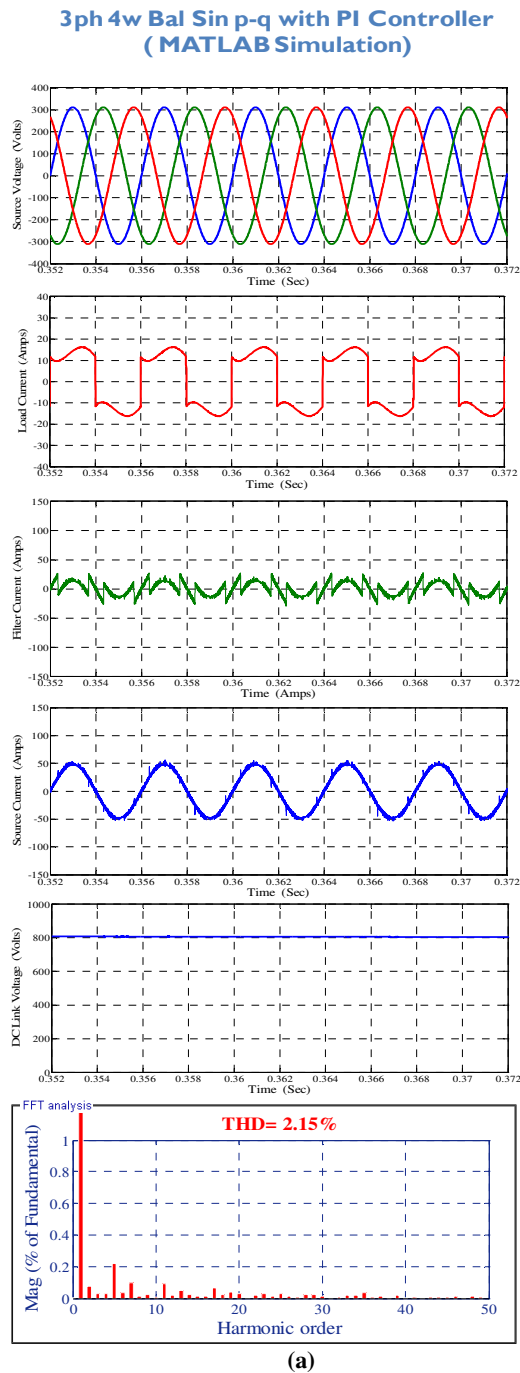
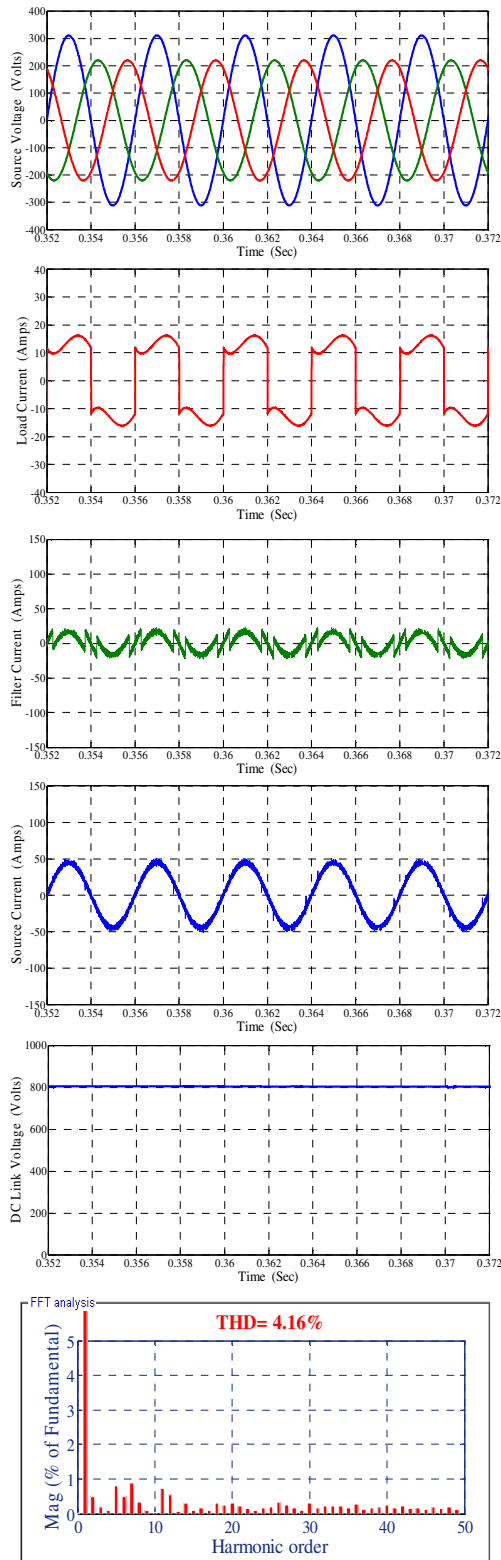


Fig 7. p-q method with PI controller Under Bal Sin

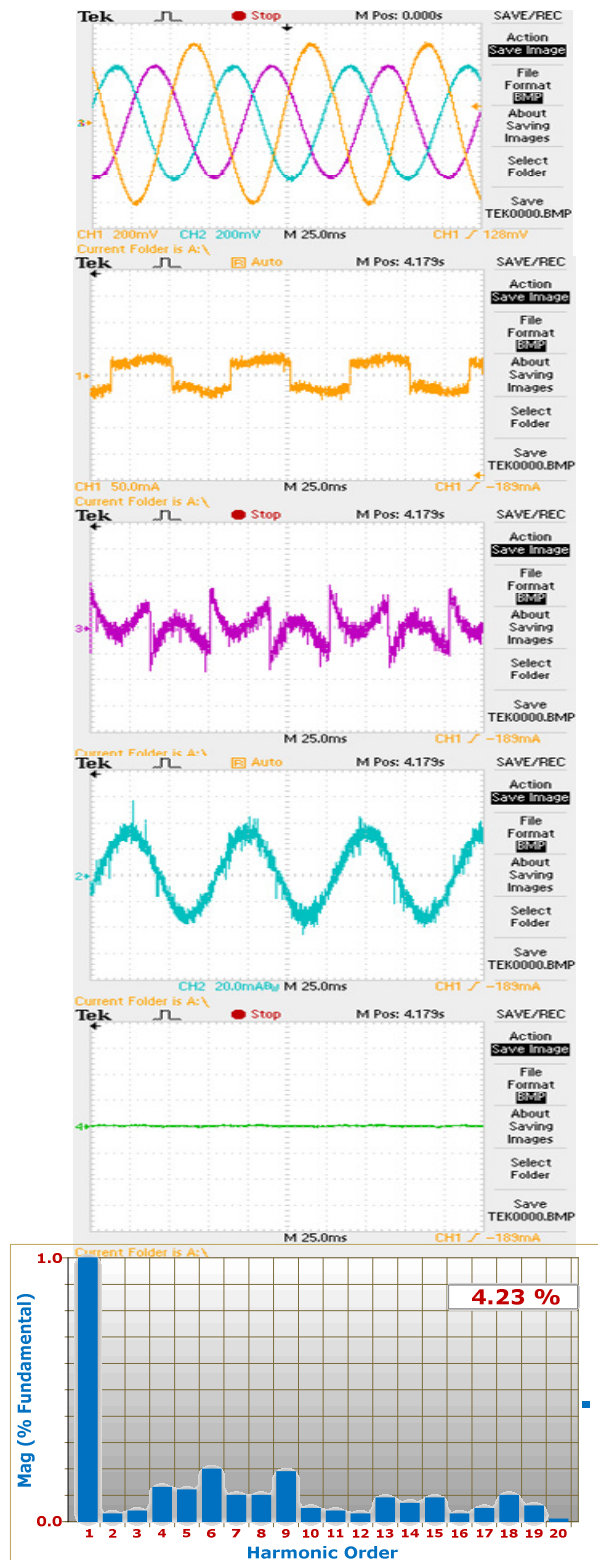
(a) Matlab Simulation (b) RTDS Hardware

3ph 4w Un-bal Sin p-q with PI Controller (MATLAB Simulation)



(a)

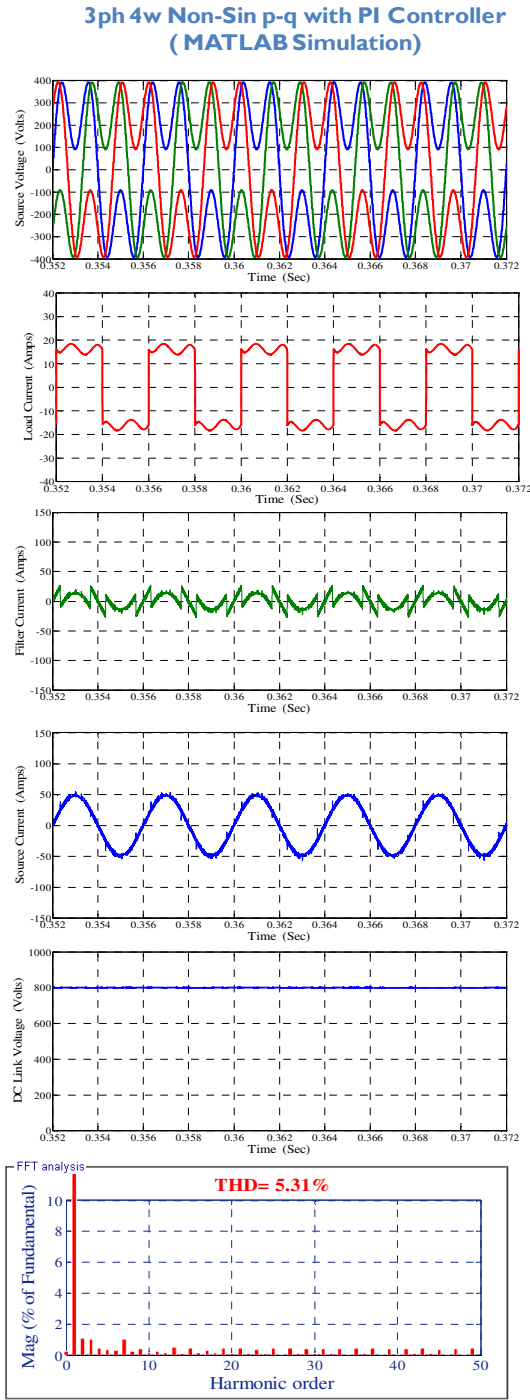
3ph 4w Un-bal Sin p-q with PI Controller (RT DS Hardware)



(b)

Fig 8. p-q method with PI controller Under Un-bal Sin

(a) Matlab Simulation (b) RTDS Hardware



(a)



(b)

Fig 9. p-q method with PI controller Under Bal Non-Sin

(a) Matlab Simulation (b) RTDS Hardware

Fig.7 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% . Fig.8 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%. Fig.9 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 5.31% and using RTDS Hard ware is 5.41%.

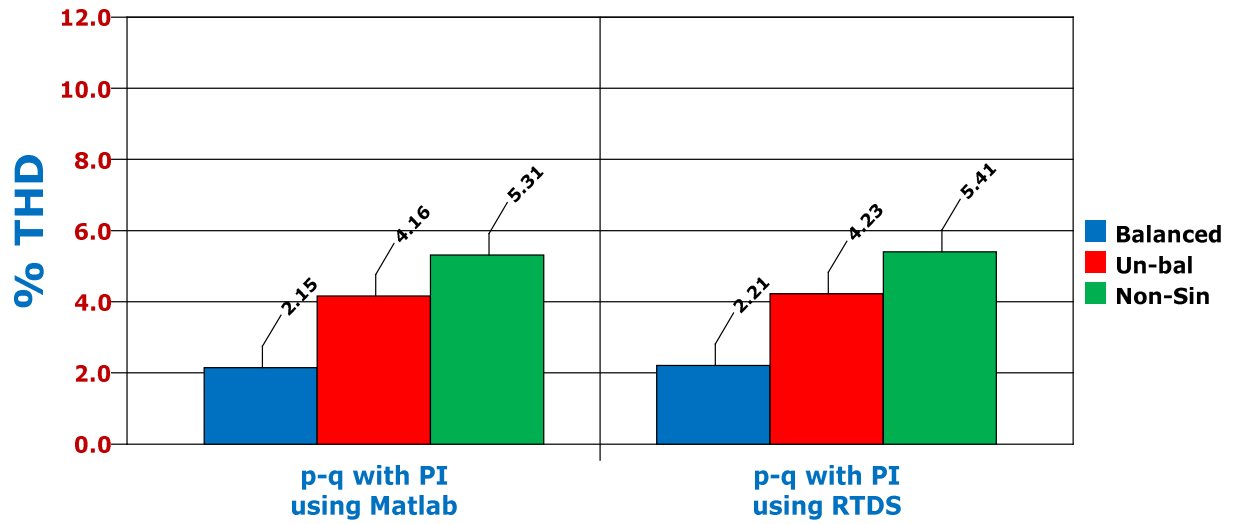


Fig 10. THD for p-q control strategy with PI controller using Matlab and RTDS Hardware

Table 1. System parameters

Parameter	Value
Supply Voltage	$V_s = 311.12 \text{ V}$
Source Resistance	$R_s = 0.1 \Omega$
Source Inductance	$L_s = 1 \text{ mH}$
Filter Phase-branch Resistance	$R_f = 0.01 \Omega$
Filter Phase-branch Inductance	$L_f = 0.1 \text{ mH}$
DC Link Capacitance	$C_{dc} = 3000 \mu\text{f}$
DC Link Voltage	$V_{dc} = 800 \text{ V}$
Hysterisis band	$\pm 0.2 \text{ A}$
Load	Diode rectifier Snubber Resistance $R_{sn} = 500 \Omega$ Snubber Capacitance $L_{sn} = 250 \text{ e-9 f}$
Load Resistance	$R_L = 15 \Omega$
Load Inductance	$L_L = 60 \text{ mH}$

6. CONCLUSION

In the present paper instantaneous active and Reactive power control strategy with PI controller is developed and verified with three phase four wire system in matlab/simulink environment and also using Real Time Digital Simulator. This control strategy is capable to suppress the harmonics in the system during balanced sinusoidal, un-balanced sinusoidal and balanced non-sinusoidal conditions. Overall the system performance is quite good not only under balanced condition but also under un-balanced and non-sinusoidal condition using p-q control strategy with PI controller.

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AUTHOR'S BIOGRAPHIES



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