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RTDS Hardware Implementation and Simulation of 3-ph 4-wire SHAF for Mitigation of Current Harmonics using p-q Control strategy With Fuzzy Controller

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ABSTRACT

The main objective of this paper is to develop Fuzzy controller 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. 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. With PI controller the p-q control strategy unable to yield an adequate solution when source voltages are not ideal. Extensive simulations are carried out with Fuzzy controller for p–q control strategy under different main voltages. The 3-ph 4-wire SHAF system is also implemented on a Real Time Digital Simulator (RT DS Hardware) to further verify its effectiveness. The detailed simulation and RT DS Hardware results are included.

Keywords: *Harmonic compensation, SHAF, p–q control strategy, Fuzzy Controller and RT DS Hardware*

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INTRODUCTION

In recent years 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.

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 of the fundamental frequency. Examples of nonlinear loads are battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies [3]. 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 [4] 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 had developed but still performance of filter in contradictions, these became primarily motivation for the current paper.

Present paper mainly focused on Fuzzy controller [5] 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. Even though two controllers are capable to compensate current harmonics in the 3 phase 4-wire system, but it is observed that Fuzzy Logic controller shows some dynamic performance over Conventional PI controller. PWM pattern generation based on carrier less hysteresis based current control is used for quick response. It is also observed that DC voltage regulation system valid to be a stable and steady-state error free system was obtained. Thus with fuzzy logic and *p*-*q* approaches a novel shunt active filter can be developed.

SHUNT ACTIVE FILTER

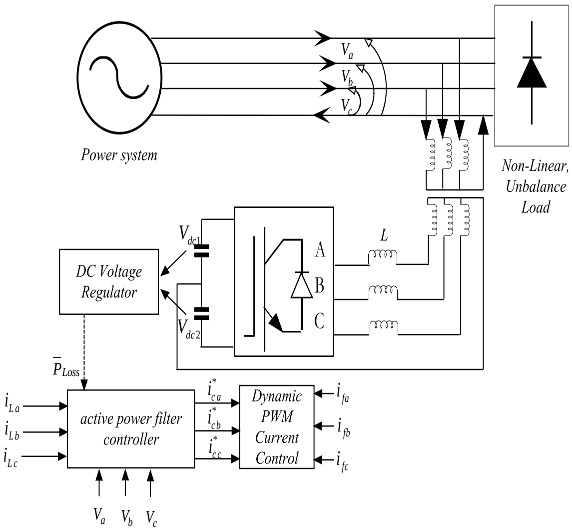


Fig.1 A Basic Architecture of Three-Phase Four -Wire Shunt Active Filter.

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

The active power filter is controlled to draw/supply the a compensating current if 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.

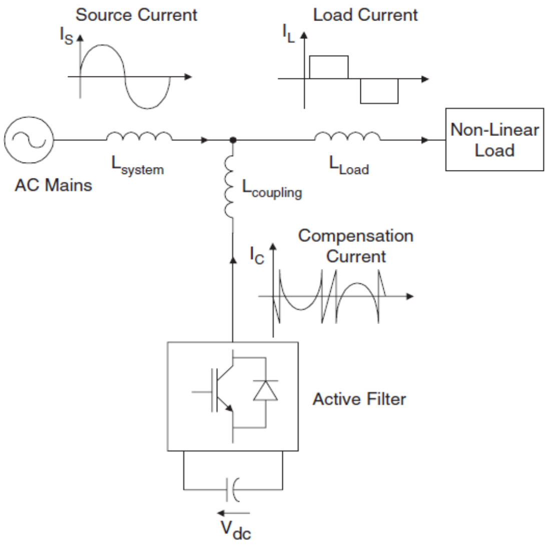


Fig. 2 Compensation Characteristics of a Shunt Active Power Filter.

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. Figure.1 shows the block diagram to attain reference currents from 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 α - β orthogonal coordinates are given in equation (1–2). The compensation objectives of active power filters [4–5] 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].

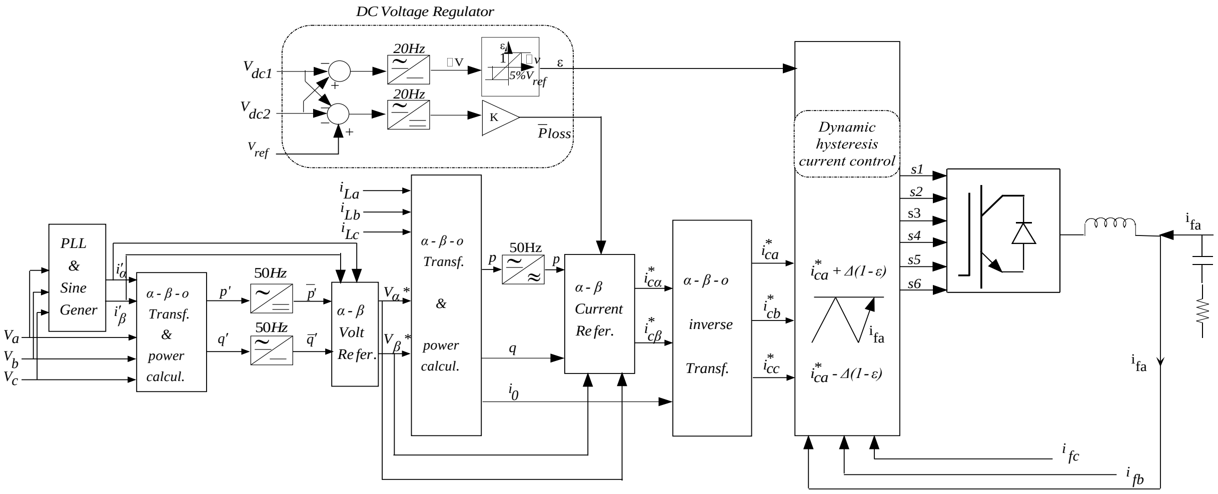


Fig. 3 Control Block Diagram of Shunt Active Power Filter.

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

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

Figure3 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).

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

From Figure 3 we can observe a high pass filter with cut off frequency 50 Hz separates the powers $-p$ from p and a low-Pass filter separates $\overline{p}_0$ from p_0. The powers 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. 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 [7].

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

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

Where 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}

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

Where i_{ca}*, i_{cb}*, i_{cc}* are the instantaneous three-phase current references $\Delta\overline{p}$ Provides energy balance inside the active power filter and using equation (5) inverse transformation can be done.

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 [8]. 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. 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).

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

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

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:

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

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.

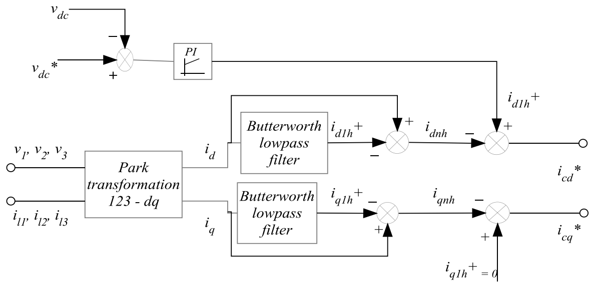


Fig. 4 Park Transformation and Harmoniccurrent Injection Circuit.

CONSTRUCTION OF FUZZY CONTROLLER

The concept of Fuzzy Logic (FL) was proposed by Professor Lotfi Zadeh in 1965, at first as a way of processing data by allowing partial set membership rather than crisp membership. Soon after, it was proven to be an excellent choice for many control system applications since it mimics human control logic.

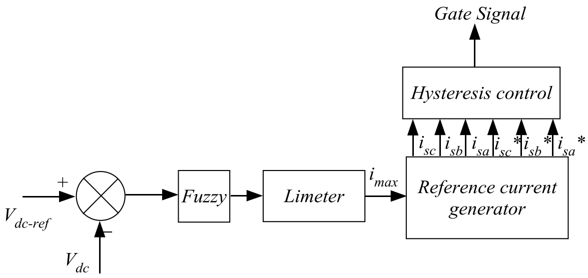


Fig. 5 Conventional Fuzzy Controller.

Figure 5 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller [12], 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. The error signal is then processed through a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal.

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage V_{dc} and the input reference voltage $V_{dc\text{-}ref}$ have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current I_{max}. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Figure 6.

The fuzzy controller is characterized as follows:

(i) Seven fuzzy sets for each input and output.

(ii)Fuzzification using continuous universe of discourse.

(iii) Implication using Mamdani's 'min' operator.

(iv) De-fuzzification using the 'centroid' method.

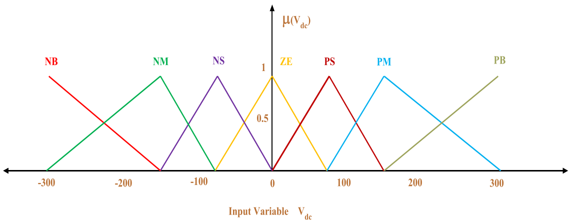


Fig. 6 (a) Input V_{dc} Normalized Membership Function.

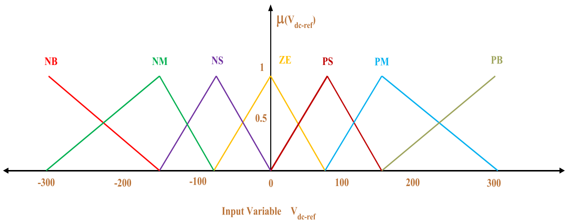


Fig. 6 (b) Input $V_{dc\text{-}ref}$ Normalized Membership Function.

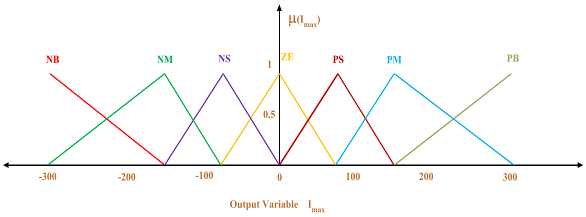


Fig.6 (c) Output I_{max} Normalized Membership Function.

Fuzzification: The process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

De-fuzzification: The rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number).

Database: The Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table.I, with'V_{dc}' and '$V_{dc\text{-}ref}$' as inputs.

TABLE I. RULE BASE

$V_{dc\text{-}ref}$ / V_{dc}	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Hysteresis Current Controller

The actual source currents are monitored instantaneously, and then compared to the reference currents 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 is_a,is_b ,is_c compared with sensed source currents is_a ,is_b ,is_c and the error signals are operated by the hysteresis current controller to generate the firing pulses which activate he inverter power switches in a manner that reduces the current error.

RT DS HARDWARE

Fig.7 RT DS 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 [14] 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.

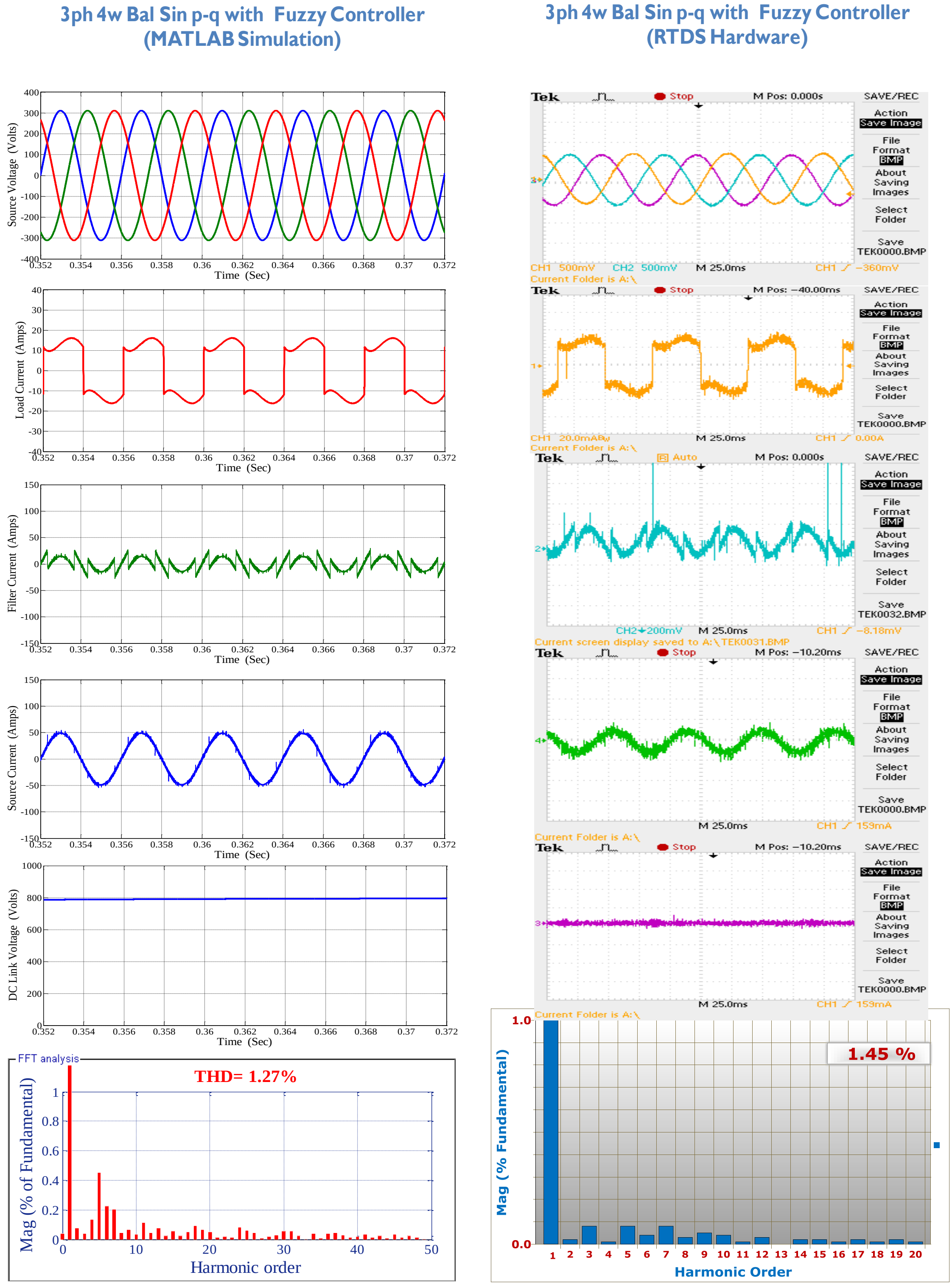
The RTDS is a fully digital power system simulator capable of continuous real time operation. It performs electromagnetic transient power system simulations with a typical time step of 50 microseconds utilizing a combination of custom software and hardware. The proprietary operating system used by the 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.

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.

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 Fuzzy Controller using matlab simulation is 1.27% and using RT DS Hard ware is 1.45%. Figure 9 illustrates the performance of Shunt active power filter under un-balanced sinusoidal voltage condition, THD for *p-q* method with Fuzzy Controller using matlab simulation is 2.98% and using RT DS Hard ware is 3.27%. Figure 10 illustrates the performance of Shunt active power filter under balanced non-sinusoidal voltage condition, THD for *p-q* method with Fuzzy Controller using matlab simulation is 3.85% and using RT DS Hard ware is 4.15%.

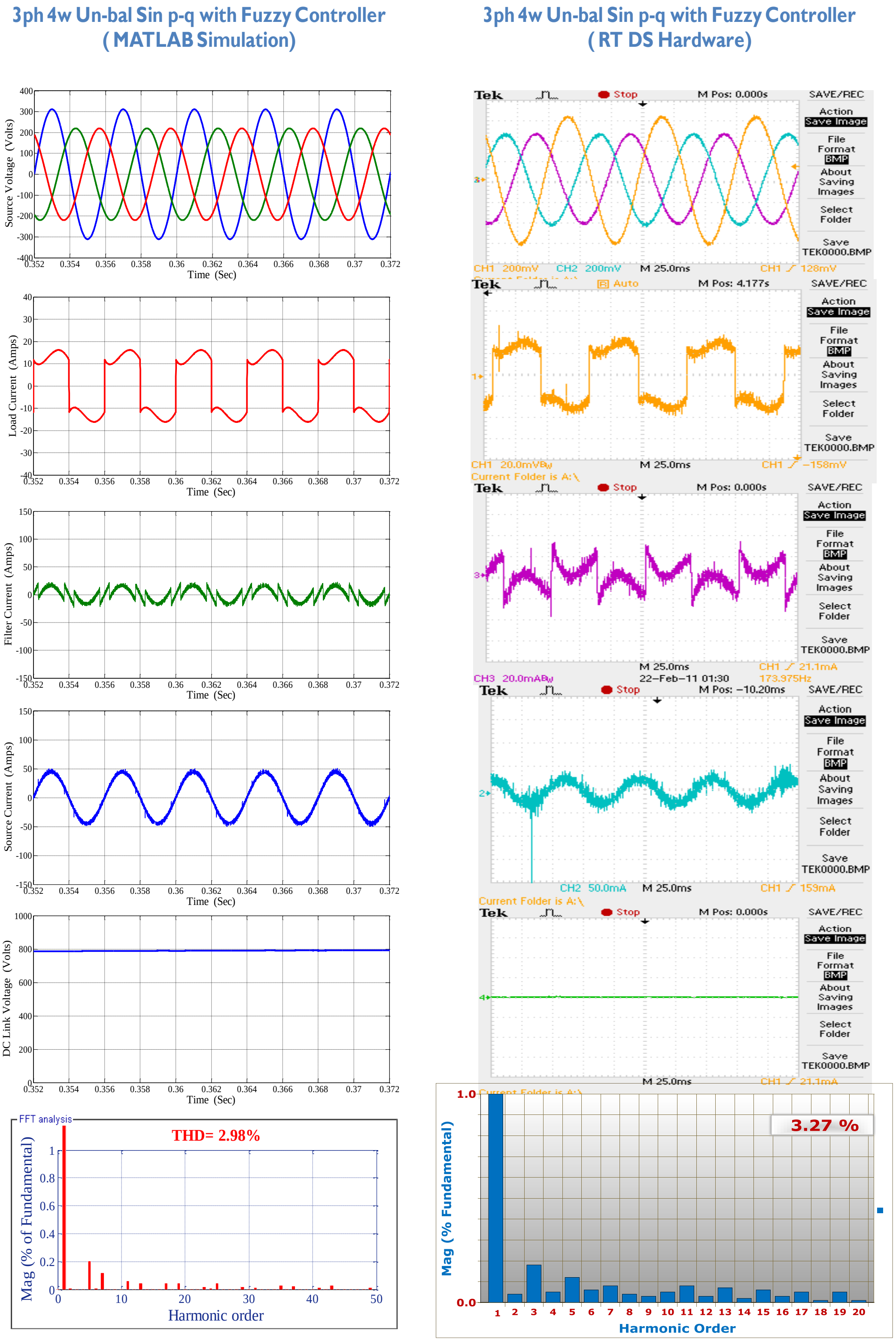
SIMULATION AND RTDS RESULTS


3ph 4w Bal Sin p-q with Fuzzy Controller (MATLAB Simulation)

3ph 4w Bal Sin p-q with Fuzzy Controller (RTDS Hardware)

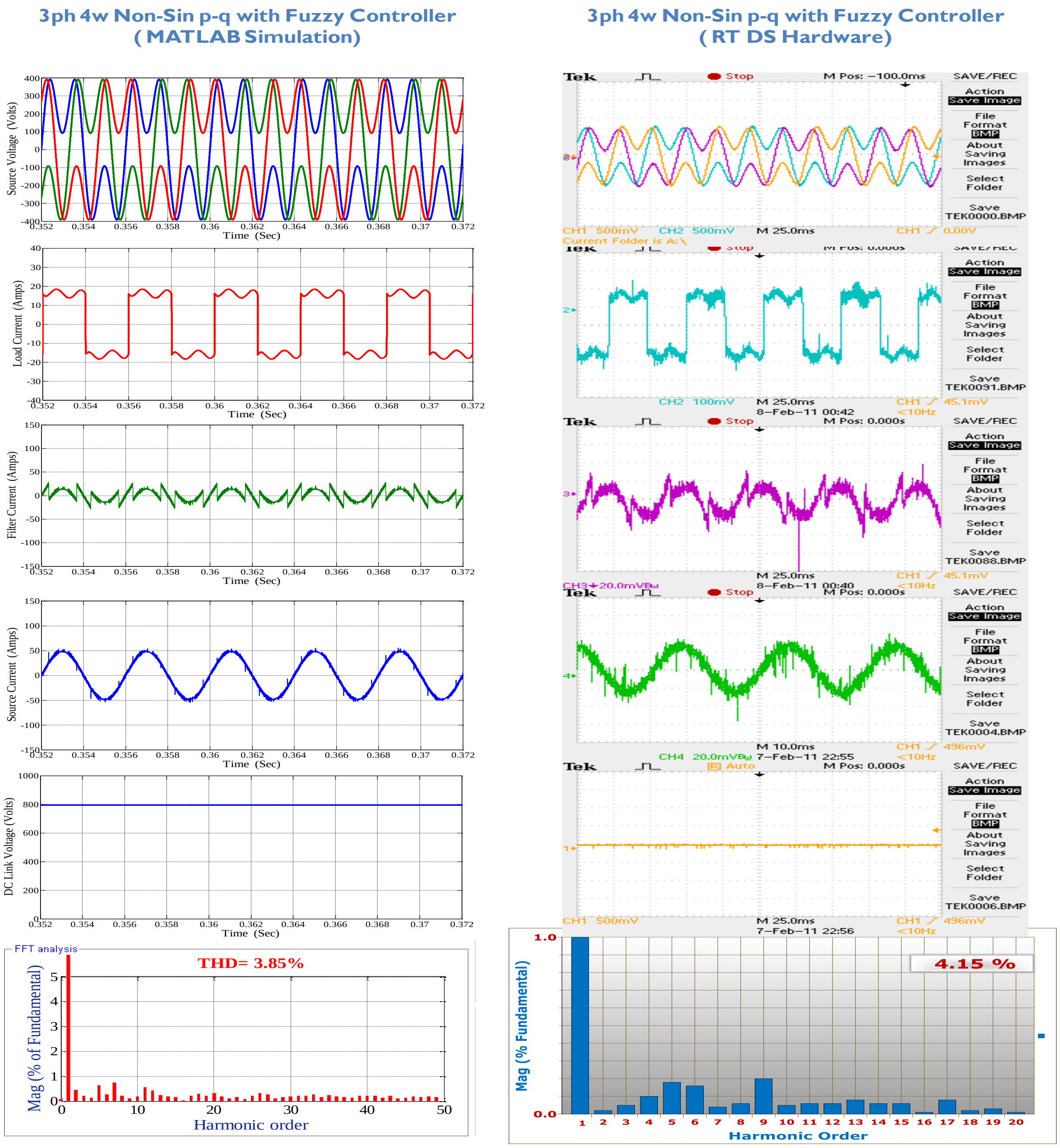
(a) (b)

Fig. 8 3ph 4wire Shunt ative Filter Response Using p-q Control Strategy Fuzzy controller Under Balanced Sinusoidal (a) Matlab Simulation (b) RT DS Hardware.



(a) (b)

Fig. 9 3ph 4wire Shunt ative Filter Response Using p-q Control Strategy Fuzzy ControllerUnder Un-balanced Sinusoidal Matlab Simulation (b) RT DS Hardware.



(a) (b)

Fig. 10 3ph 4wire Shunt Ative Filter Response Using p-q Control Strategy Fuzzy controller Under Balanced Non-Sinusoidal Matlab Simulation (b) RT DS Hardware.

CONCLUSION

With PI controller the p-q control strategy is unable to yield an adequate solution when source voltages are not ideal. Thus Fuzzy controller based p-q control strategy developed to suppress the current harmonics in the system under distorted main voltages using matlab/simulink environment and it verified with Real Time Digital Simulator. Fuzzy Logic controller shows some dynamic performance over Conventional PI controller.

PWM pattern generation based on carrier less hysteresis based current control is used for quick response. It is also observed that DC voltage regulation system valid to be a stable and steady-state error free system was obtained. 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 Fuzzy controller.

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