Fuzzy Logic Controller based 3-ph 4-wire SHAF for Current Harmonics Compensation with i_d-i_q Control strategy Using Simulation and RTDS Hardware

A.K. Panda and Suresh. Mikkili
Department of Electrical Engineering, N.I.T Rourkela
akpanda.ee@gmail.com and msuresh.ee@gmail.

Abstract: - *The main objective of this paper is to develop Fuzzy controller to analyse the performance of instantaneous real active and reactive current (i_d-i_q) control strategy for extracting reference currents of shunt active filters under balanced and un-balanced voltage conditions. When the supply voltages are balanced and sinusoidal, then all control strategies converge to the same compensation characteristics. However, 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 unable to yield an adequate solution when source voltages are not ideal. Extensive simulations are carried out with Fuzzy controller for I_d-Iq control strategy under different main voltages. The 3-ph 4-wire shunt active filter (SHAF) system is also implemented on a Real Time Digital Simulator (RTDS Hardware) to further verify its effectiveness. The detailed simulation and RTDS Hardware results are included.*

Index Terms— *Harmonic compensation, SHAF, i_d-i_q control strategy, Fuzzy Controller and RTDS Hardware.*

I. 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.

As nonlinear currents [3] 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 arise 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]. 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 the primarily motivation for the current paper.

Present paper mainly focused on Fuzzy controller [5] to analyse the performance of instantaneous real active and reactive current (i_d-i_q) control strategy [6] 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. Additionally, on contrast of different control strategies; i_d-i_q method is used for obtaining reference currents in the system, because in this strategy, angle 'θ' is calculated directly from main voltages and enables operation to be frequency independent their by technique avoids large numbers of synchronization problems. It is also observed that DC voltage [7] regulation system valid to be a stable and steady-state error free system was obtained. Thus with fuzzy logic and *(id-iq)* approaches a novel shunt active filter can be developed.

II. Instantaneous Active and Reactive Current Theory

This method is also known as synchronous reference frame (SRF) [8]. Here, the reference frame d-q (d direct axis, q-quadrature axis) is determined by the angle θ with respect to the α-β frame used in the p-q theory. The transformation from α – β – 0 frame to d–q –0 frame is given by

$$\begin{bmatrix} i_0 \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_0 \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (1)$$

In this method, only the currents magnitudes are transformed and p-q formulation is only performed on the instantaneous active i_d and instantaneous reactive i_q components.

If the *d* axis has the same direction as the voltage space vector $\bar{v}$, then the zero-sequence component of current remains invariant. Therefore, the i_d - i_q method may be expressed as follows:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_0 \end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_{\alpha\beta} \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_0 \end{bmatrix} \tag{2}$$

In this strategy, the source must deliver the constant term of the direct-axis component of load (for harmonic compensation and power factor correction). The reference source current will be calculated as follows:

$$i_{cd} = \overline{i_{Ld}} \;;\; i_{cq} = 0 \text{ and } i_0 = 0 \tag{3}$$

$$i_{Ld} = \frac{v_\alpha i_{L\alpha} + v_\beta i_{L\beta}}{v_{\alpha\beta}} = \frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \tag{4}$$

The dc component of the above equation will be

$$\overline{i_{Ld}} = \left(\frac{P_{L\alpha\beta}}{v_{\alpha\beta}} \right)_{dc} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \right)_{dc} \tag{5}$$

Where the subscript "dc" means the average value of the expression within the parentheses.

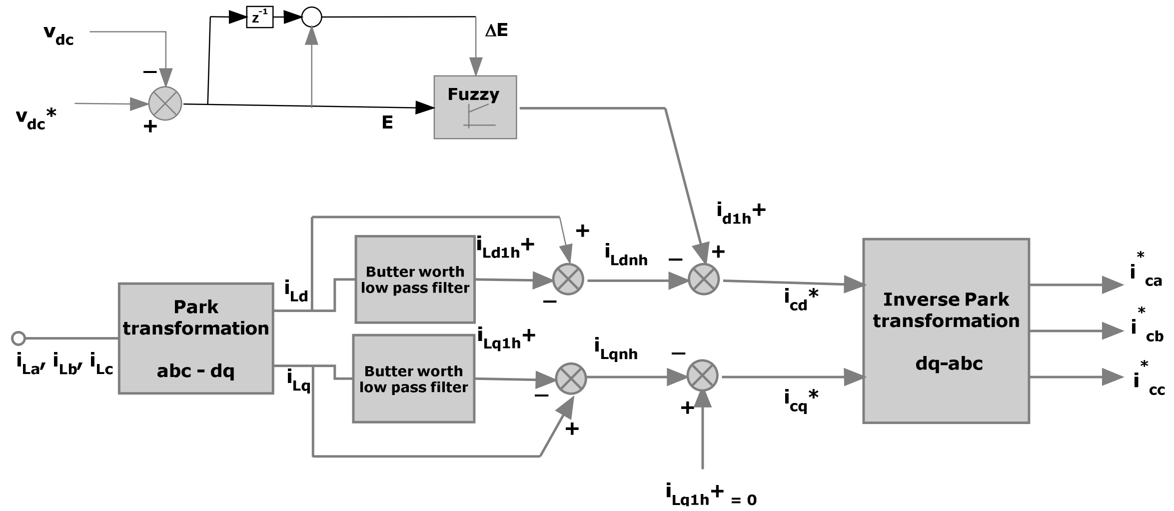


Fig.1. Reference current extraction with i_d-i_q method with Fuzzy controller

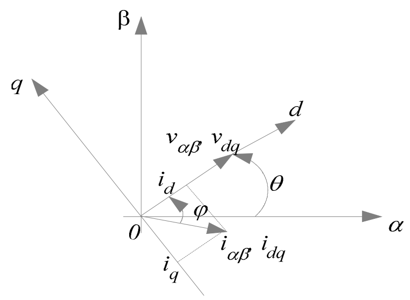


Fig.2. Instantaneous voltage and current vectors.

Since the reference source current must to be in phase with the voltage at the PCC (and have no zero-sequence component), it will be calculated (in α-β-0 coordinate) by multiplying the above equation by a unit vector in the direction of the PCC voltage space vector (excluding the zero-sequence component):

$$\begin{bmatrix} i_{c\alpha ref} \\ i_{c\beta ref} \\ i_{0ref} \end{bmatrix} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \right)_{dc} \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \tag{6}$$

The reference signals thus obtained are compared with the actual compensating filter currents in a hysteresis comparator, where the actual current is forced to follow the reference and provides instantaneous compensation by the APF [9] on account of its easy implementation and quick prevail over fast current transitions. This consequently provides switching signals to trigger the IGBTs inside the inverter. Ultimately, the filter provides necessary compensation for harmonics in the source current and reactive power unbalance in the system.

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) [10].

III. CONSTRUCTION OF FUZZY LOGIC CONTROLLER

Fig.3 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller [11], 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.

The bock diagram of Fuzzy logic controller [12] is shown in **Fig 4**. It consists of blocks

- Fuzzification Interface
- Knowledge base
- Decision making logic
- Defuzzification

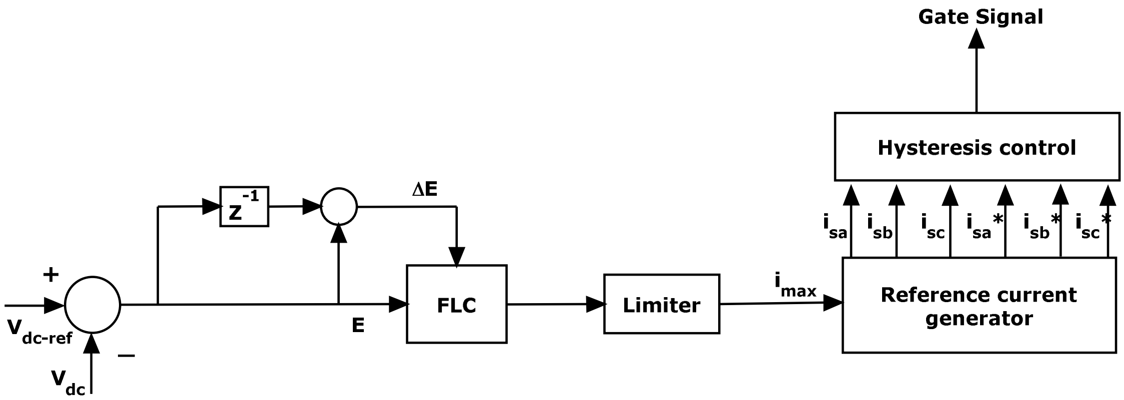


Fig 3 Proposed Fuzzy Inference System

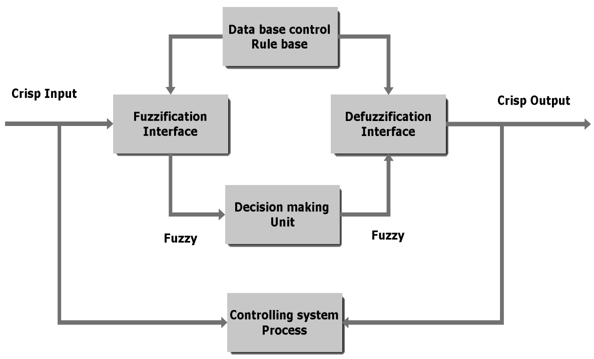


Fig.4 Block Diagram of Fuzzy Logic Controller (FLC)

TABLE 1. RULE BASE

E \ ΔE	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

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database [13]. Firstly, input Error E and change in Error 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 5.**

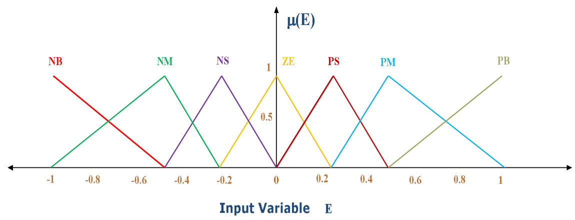


Fig. 5 Input Variable 'E' Normalized Membership Function.

IV. 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 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 [14] and Hardware-In-the-Loop (HIL) applications are increasingly recognized as essential tools for engineering design and especially in power electronics and electrical systems.

Fig.6 RTDS Hardware

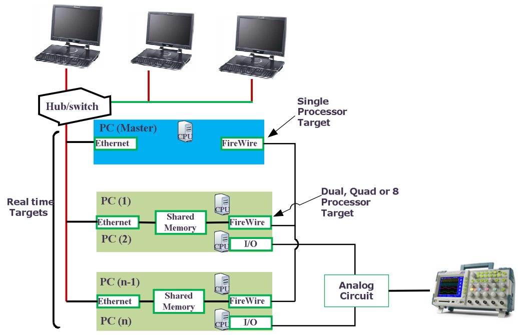
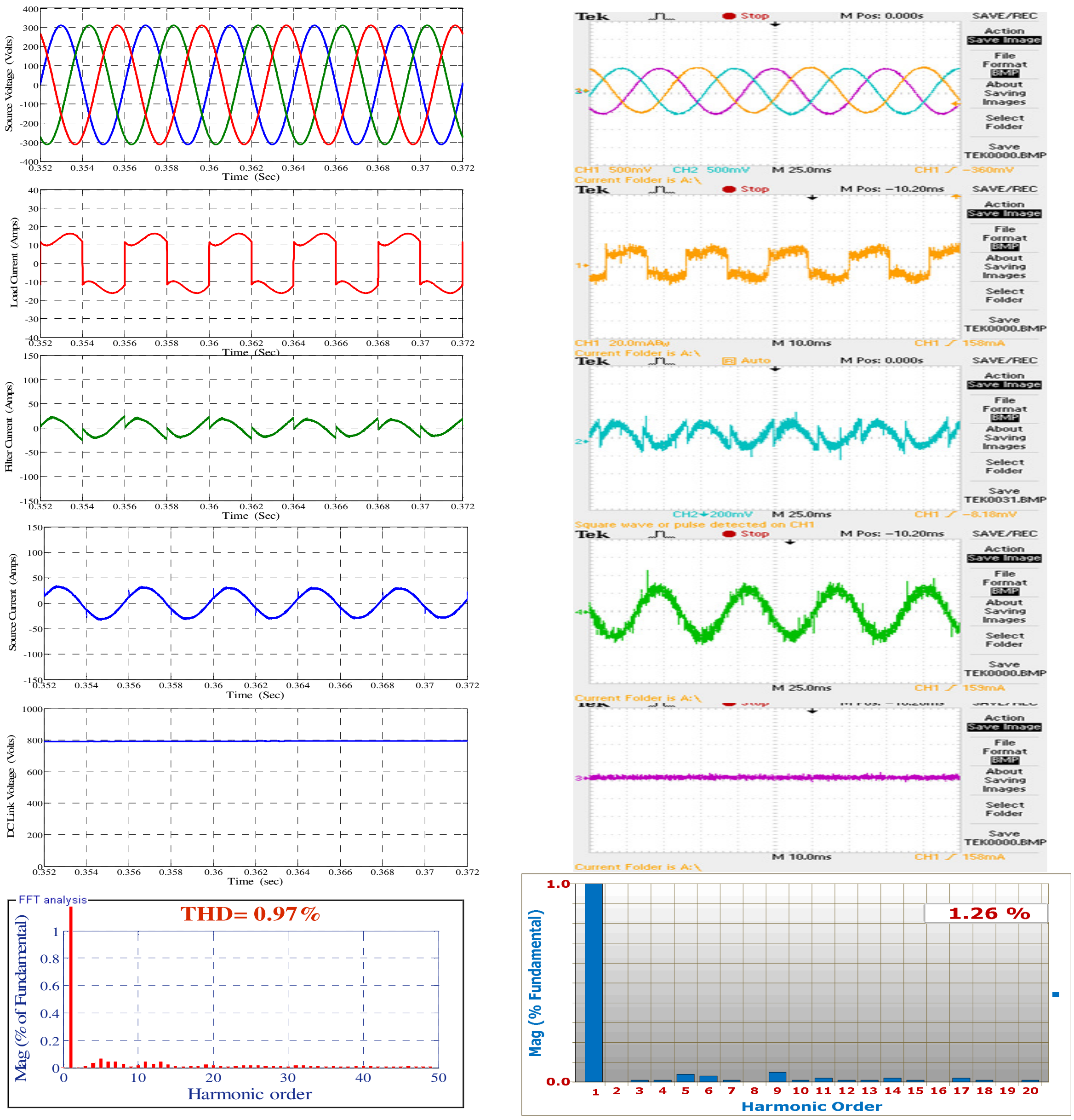


Fig 7. RT-LAB Simulator Architecture

V. SIMULATION AND RTDS RESULTS

3ph 4w Bal Sin I_d-I_q with Fuzzy Controller (MATLAB Simulation)

3ph 4w Bal Sin I_d-I_q with Fuzzy Controller (RT DS Hardware)



(a) **(b)**

Fig 8. I_d-I_q with Fuzzy Logic controller Under Balanced Sinusoidal

(a) Matlab Simulation (b) RTDS Hardware

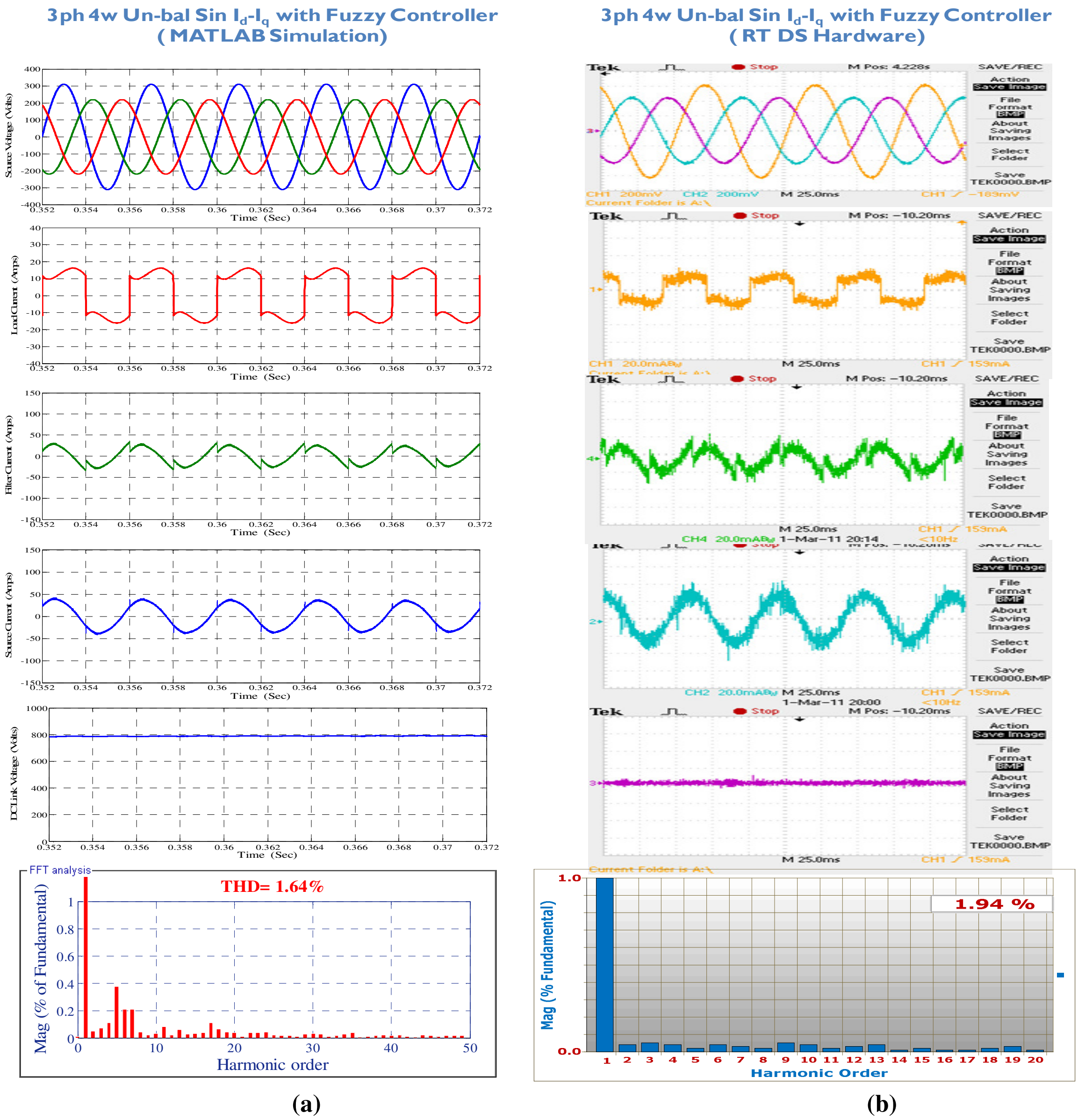


Fig 9. I_d-I_q with Fuzzy Logic controller Under Un-balanced Sinusoidal
(a) Matlab Simulation (b) RTDS Hardware

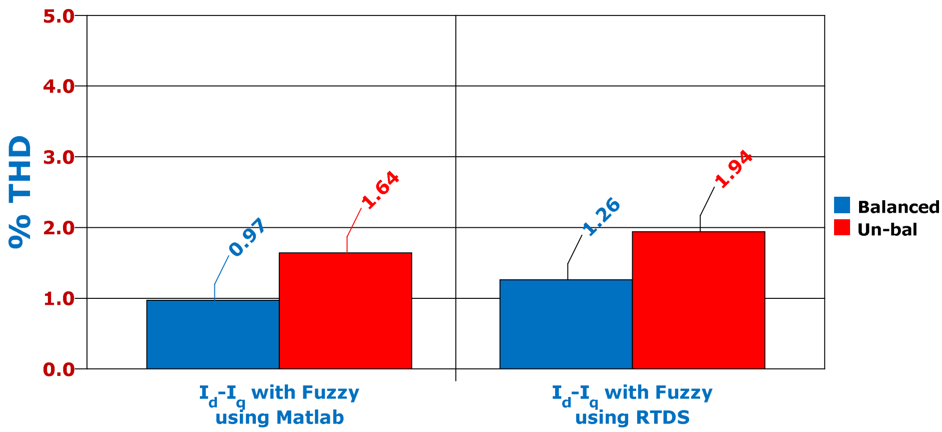


Fig. 10 THD for id-iq method with Fuzzy Logic Controller using Matlab and RTDS Hardware

Fig.8 illustrates the performance of Shunt active power filter under balanced sinusoidal voltage condition, THD for i_d-i_q method with Fuzzy Controller using Matlab simulation is 0.97% and using RT DS Hard ware is 1.26%.

Fig.9 illustrates the performance of Shunt active power filter under un-balanced sinusoidal voltage condition, THD for i_d-i_q method with Fuzzy Controller using Matlab simulation is 1.64% and using RT DS Hard ware is 1.94%.

VI. CONCLUSION

In the present paper instantaneous active and Reactive current control strategy with Fuzzy controller is developed to mitigate the current harmonics in three phase four wire system using Matlab/simulink environment and it verified with 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. The p-q control strategy is unable to yield an adequate solution when source voltages are not ideal. In i_d-i_q method angle 'θ' is calculated directly from main voltages and thus enables the method to be frequency independent. Thus large numbers of synchronization problems with un-balanced and non-sinusoidal voltages are also avoided. Addition to that DC voltage regulation system valid to be a stable and steady-state error free system was obtained.

REFERENCES

[1] Akagi H. H Akagi, kanazawa, and nabae "instantaneous reactive power compensators comprising Switching devices without energy storage components" IEEE Trans On Industry Applications, Vol. Ia-20, No. 3, pp 625-630, 1984.

[2] L. Gyugyi, E.C. Strycula, "Active AC power filters", *IEEE IIAS Annual Meeting*, pp. 529-535, 1996

[3] Mikkili. Suresh, A.K. Panda, S. Yellasiri, "Fuzzy controller based 3phase 4wire shunt active Filter for mitigation of current harmonics with combined p-q and Id-Iq control strategies", *Journal of Energy and Power Engineering*, Vol. 3, No. 1, pp. 43-52, 2011

[4] Akagi H. "New Trends in Active Filters for Power Conditioning" in *IEEE Trans on Industrial Appls* Nov./Dec.1996. Vol.32, No.6, pp.1312-1322

[5] M Suresh, A. K. Panda, S. S. Patnaik, S. Yellasiri, "Comparison of two compensation control strategies for shunt active power filter in three-phase four-wire system, *IEEE PES Innovative Smart Grid Technologies (ISGT),* pp.1-6, 2011, DOI: 10.1109/ISGT.2011.5759126.

[6] F.Z. Peng, G.W. Ott Jr, D.J Adams, "Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for three-phase four-wire systems", *IEEE Transactions on Power Electronics,* Vol. 13, No. 5, pp. 1174-1181, 1998

[7] V. Soares, P. Verdelho, G. Marques, "Active power filter control circuit based on the instantaneous active and reactive current id –iq method", *IEEE Power Electronics Specialists Conference*, Vol. 2, pp. 1096-1101, 1997

[8] M.I.M. Montero, E.R. Cadaval, F.B. Gonzalez, "Comparison of control strategies for shunt active power filters in three-phase four wire systems", *IEEE Trans on Power Electronics*, Vol. 22, No. 1, pp. 229-236, 2007.

[9] M. Aredes, J. Hafner, K. Heumann, "Three-phase four-wire shunt active filter control strategies", *IEEE Transactions on Power Electronics,* Vol. 12, No. 2, pp. 311 – 318, 1997

[10] P. Rodriguez, J.I. Candela, A. Luna, L. Asiminoaei, "Current harmonics cancellation in three-phase four-wire systems by using a four-branch star filtering topology", *IEEE Transactions on Power Electronics,* Vol. 24, No. 8, pp. 1939-1950, 2009

[11] P. Salmeron, R.S. Herrera, "Distorted and unbalanced systems compensation within instantaneous reactive power framework", *IEEE Transactions on Power Delivery,* Vol. 21, No. 3, pp. 1655-1662, 2006

[12] Suresh Mikkili, A.K. Panda "PI and Fuzzy Logic Controller based 3-phase 4-wire Shunt active filter for mitigation of Current harmonics with I_d-I_q Control Strategy" *Journal of power Electronics (JPE),* vol. 11, No. 6, Nov. 2011

[13] Jain S. K. et al. "Fuzzy logic controlled shunt active power filter for power quality improvement" *IEEE Proceedings Electric Power Applications* Sept 2002. Vol.149, No.5.

[14] Suresh Mikkili, A.K. Panda, "RTDS Hardware implementation and Simulation of 3-ph 4-wire SHAF for Mitigation of Current Harmonics with p-q and Id-Iq Control strategies using Fuzzy Logic Controller," *International Journal of Emerging Electric Power Systems*: be press, Vol. 12: No. 5, Article 5, Aug. 2011.

BIOGRAPHIES

Anup Kumar Panda:. He received the B.Tech in Electrical Engineering from Sambalpur University, India in 1987. He received the M.Tech in Power Electronics and Drives from Indian Institute of Technology, Kharagpur, India in 1993 and Ph.D. in 2001 from Utkal University. Join as a faculty in IGIT, Sarang in 1990. Served there for eleven years and then join National Institute of Technology, Rourkela in January 2001 as an assistant professor and currently continuing as a Professor in the Department of Electrical Engineering. He has published over forty five articles in journals and conferences. He has completed two MHRD projects and one NaMPET project. Guided three Ph.D. scholars and currently guiding four scholars in the area of Power Electronics & Drives.

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, Applications of Soft Computing Techniques.

Mikkili.Suresh was born in Bapatla, Andhra Pradesh, India on 5th Aug 1985. He received B.Tech degree in Electrical and Electronics Engineering from JNTU University Hyderabad in May 2006 and Masters (M.Tech) in Electrical Engineering from N.I.T Rourkela, India in May 2008. He has worked as a Asst. Prof in Electrical Engineering in distinguished engineering colleges from June 2008 to July 2010. He is currently pursuing Ph.D degree in Electrical Engineering at N.I.T Rourkela, India.

His main area of research includes Power quality improvement issues, Active filters, and Applications of Soft Computing Techniques.