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Power Quality Improvement by Using Fuzzy Controlled Four Leg Inverter for Renewable Energy Sources

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Abstract - The active power filter for non-linear loads along with control scheme and also implemented with Four Leg Voltage Source Inverter (VSI) using predictive control scheme is presented. Renewable energy resources (RES) are being increasingly connected to Distribution Systems by utilizing Power electronic Converters. This paper presents control strategy for achieving maximum benefits from these grid interfacing inverters when installed in 3phase 4wire distribution systems. The inverter is controlled to perform as a multifunction device by incorporating active power filter functionality. The inverter can thus be utilized as:1)power converter to inject power generated from RES to the grid, and 2)shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. All of these functions may be accomplished either individually or simultaneously. This new control concept is demonstrated with extensive MATLAB/Simulink simulation studies. In extension we use Renewable Energy sources such as PV/Wind as the input to the four leg inverter which is used to improve power quality. The controller used in the base paper is conventional PI controller and this can be replaced with intelligent controller like Fuzzy controller.

Key Words: Fuzzy, Active power filter, current control, four-leg converters, predictive control.

1. INTRODUCTION

The increasing energy demand, increasing costs and exhaustible nature of fossil fuels, and global environment pollution have generated huge interest in renewable energy resources. Other than hydroelectric power, wind and solar are the most useful energy sources to satisfy our power requirements. Wind energy is capable of producing huge amounts of power, but its availability can't be predicted. Solar power is available during the whole day but the solar irradiance levels change because of the changes in the sun's intensity and shadows caused by many reasons. Generally solar and wind powers are complementary in nature. Therefore the hybrid photovoltaic and wind energy system has higher dependability to give steady power than each of them operating individually. Other benefit of the hybrid system is that the amount of the battery storage can be decreased as hybrid system is more reliable compared to their independent operation.

Renewable energy source (RES) integrated a distribution level [2] is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ) issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network. With the advancement in power electronics and digital control technology, the DG systems can now be actively controlled to enhance the system operation with improved PQ at PCC.

However, the extensive use of power electronics based equipment and non-linear loads at PCC generate harmonic currents, which may deteriorate the quality of power. Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed. In [3],[6] an inverter operates as active inductor at a certain frequency to absorb the harmonic current. But the exact calculation of network inductance in real-time is difficult and may deteriorate the control performance. A similar approach in which a shunt active filter acts as active conductance to damp out the harmonics in Distribution network is proposed in [11]. In [14], a control strategy for renewable interfacing inverter based on – theory is proposed. In this strategy both load and inverter current sensing is required to compensate the load current harmonics.

The non-linear load current harmonics may result in voltage harmonics and can create a serious PQ problem in the power system network. Active power filters (APF) are extensively used to compensate the load current harmonics and load unbalance at distribution level. This results in an additional hardware cost. However, in this paper authors have incorporated the features of APF in the, conventional inverter interfacing renewable with the grid, without any additional hardware cost. Here, the main idea is the maximum utilization of inverter rating which is most of the time underutilized due to intermittent nature of RES. It is shown in this paper that the grid-interfacing inverter can effectively be utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.);2) load reactive power demand support; 3)current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system.

This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure [4],[5]. The complete description of the selected current reference generator implemented in the active power filter is also presented. Finally, the proposed active power filter and the effectiveness of the associated control scheme compensation are demonstrated through simulation and validated with experimental results obtained in a 2 kVA system.

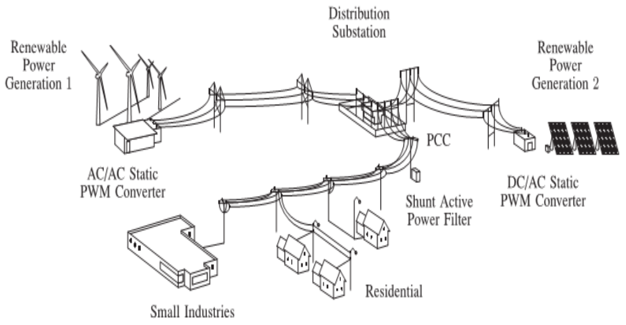


Fig.1. stand-alone hybrid power genaration system with shunt APF.

2. FOUR-LEG CONVERTER MODEL

Fig. 1 shows the configuration of a typical power distribution system with renewable power generation. It consists of various types of power generation units and different types of loads. Renewable sources, such as wind and sunlight, are typically used to generate electricity for residential users and small industries. Both types of power generation use ac/ac and dc/ac static PWM converters for voltage conversion and battery banks for long term energy storage. These converters perform maximum power point tracking to extract the maximum energy possible from wind and sun. The electrical energy consumption behavior is random and unpredictable, and therefore, it may be single- or three-phase, balanced or unbalanced, and linear or nonlinear. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter [3], and a first-order output ripple filter, as shown in Fig.3. This circuit considers the power system equivalent impedance Z_S, the converter output ripple filter impedance Z_f, and the load impedance Z_L.

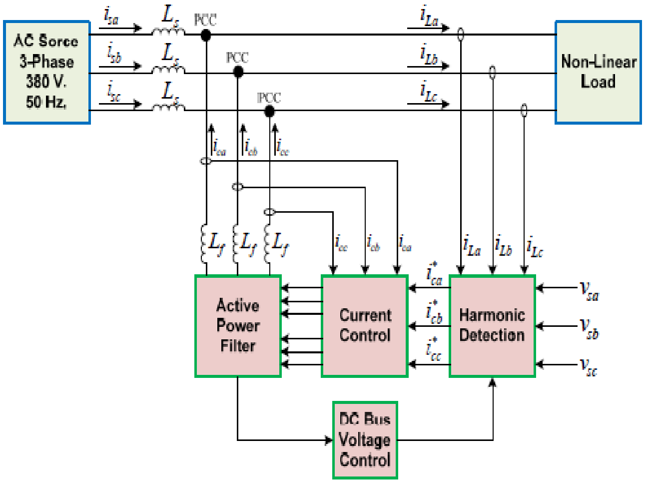


Fig. 2 Three – phase shunt active power filter.

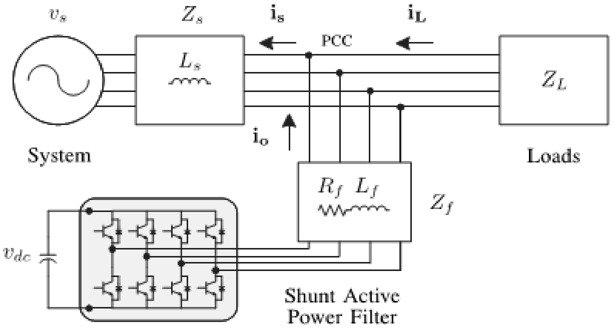


Fig. 3. Three-phase equivalent circuit of the proposed shunt active power filter.

The four-leg PWM converter topology is shown in Fig. 4. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from 8 (23) to 16 (24), improving control flexibility and output voltage quality, and is suitable for current unbalancecompensation.

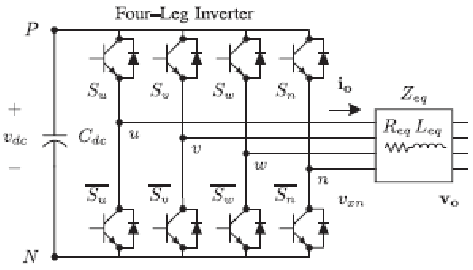


Fig 4.. Two-level four-leg PWM-VSI topology.

The voltage in any leg *x* of the converter, measured from the neutral point (*n*), can be expressed in terms of switching states, as follows:

$$v_{xn} = S_x - S_n\, v_{dc}\,, \qquad x = u, v, w, n. \tag{1}$$

The mathematical model of the filter derived from the equivalent circuit shown in Fig. 3 is

$$V_0 = v_{xn} - R_{eq}\, i_0 - L_{eq} \frac{di_0}{dt} \tag{2}$$

$$Z_{eq} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f \tag{3}$$

For this model, it is assumed that $ZL \le Zs$, that the resistive part of the system's equivalent impedance is neglected, and that the series reactance is in the range of 3-7%p.u.,which is an acceptable approximation of the real system. Finally, in(2).

$R_{eq} = R_f$ **and** $L_{eq} = L_s + L_f$.

3. *DIGITAL PREDICTIVE CURRENT CONTROL*

The block diagram of the proposed digital Predictive current control [1] scheme is shown in Fig.5.This control scheme is basically an optimization algorithm and therefore, it has to be implemented in a microprocessor. Consequently, the analysis has to be developed using discrete mathematics in order to consider additional restrictions such as time delays and approximations [6].

$$\frac{dx}{dt} \approx \frac{x[k+1] - x[k]}{T_S} \tag{4}$$

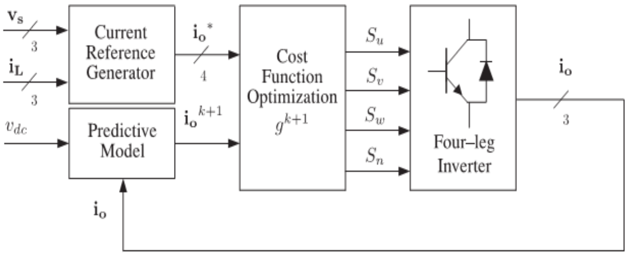


Fig.5. Proposed predictive digital current control block diagram.

The 16 possible output current predicted values can be obtained from (2) and (4) as

$$i_0[k+1] = \frac{T_s}{L_{eq}}(v_{xn}[k] - V_0[k]) + \left(1 - \frac{R_{eq} T_s}{L_{eq}}\right) i_0[k] \tag{5}$$

The main characteristic of predictive control is the use of the system model to predict the future behavior of the variables to be controlled. The controller uses this information to select the optimum switching state that will be applied to the power converter, according to predefined optimization criteria. The predictive control algorithm [4] is easy to implement and to understand, and it can be implemented with three main blocks, as shown in Fig. 5.

4. CURRENT REFERENCE GENERATION

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. This scheme presents a fast and accurate signal tracking capability This characteristic avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance [8].The current reference signals are obtained from the corresponding load currents as shown in Fig.6. This module calculates the reference signal currents required by the converter to compensate reactive power, current harmonic and current imbalance. The displacement power factor (sin φ(L)) and the maximum total harmonic distortion of the load (THD(L)) defines the relationships between the apparent power required by the active power filter, with respect to the load, as shown

$$\frac{S_{APF}}{S_L} = \frac{\sqrt{\sin\emptyset_{(L)} + THD_{(L)}{}^2}}{\sqrt{1 + THD_{(L)}{}^2}} \tag{6}$$

Where the value of THD (L) includes the Maximum compensable harmonic current, defined as double the sampling frequency fs. The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency. The dq-based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the sin(wt) and cos(wt) signals. By using dq transformation, the d current component is synchronized with the corresponding phase-to neutral system voltage, and the q current component is phase shifted by 90◦. The sin(wt) and cos(wt) synchronized reference signals are obtained from a synchronous reference frame (SRF) PLL[9].

The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. Tracking errors are eliminated, since SRF-PLLs are designed to avoid phase voltage unbalancing, harmonics (i.e., less than 5% and 3% in fifth and seventh, respectively), and offset caused by the nonlinear load conditions and measurement errors [10].

Equation (5) show the relationship between the real currents iLx(t)(x= u, v, w) and the associated dq components (id and iq).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \quad (7)$$

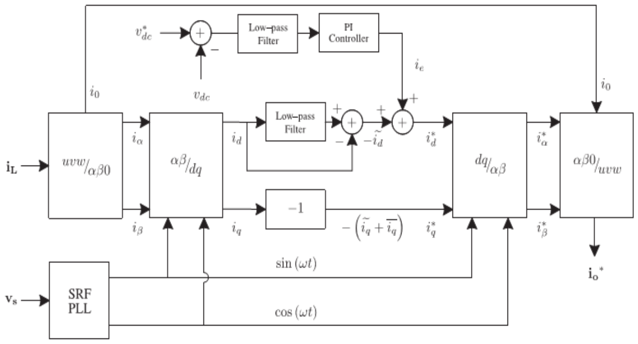


Fig. 6. dq-based current reference generator block diagram

The current that flows through the neutral of th load is compensated by injecting the same instantaneous value obtained from the phase currents, phase-shifted by 180◦, as shown next

$$i_{on}^* = -(i_{Lu} + i_{Lv} + i_{Lw}) \quad (8)$$

One of the major advantages of the dq-based current reference generator scheme is that it allows the implementation of a linear controller in the dc voltage control loop. However, one important disadvantage of the dq-based current reference frame algorithm used to generate the current reference is that a second order harmonic component is generated in id and iq under unbalanced operating conditions. The amplitude of this harmonic depends on the percent of unbalanced load current (expressed as the relationship between the negative sequence currentiL,2 and the positive sequence currentiL,1).The second-order harmonic cannot be removed from id and iq, and therefore generates a third harmonic in the reference current when it is converted back to abc frame. Fig. 7 shows the percent of system current imbalance and the percent of third harmonic system current, in function of the percent of load current imbalance. Since the load current does not have a third harmonic, the one generated by the active power filter flows to the power system.

The dc-voltage converter [1],[7] is controlled with a traditional PI controller. This is an important issue in the evaluation, since the cost function (6) is designed using only current references, in order to avoid the use of weighting factors. Generally, these weighting factors are obtained experimentally, and they are not well defined when different operating conditions are required. Additionally, the slow dynamic response of the voltage across the electrolytic capacitor does not affect the current transient response. Forth is reason, the PI controller represents a simple and effective alternative for the dc-voltage control. The dc-voltage remains constant (with a minimum value of √ 6vs (rms)) until the active power absorbed by the converter decreases to a level where it is unable to compensate for its losses.

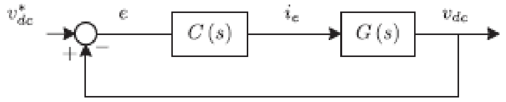


Fig.7. DC-voltage control block diagram.

5. FUZZY LOGIC CONTROLLER

Fuzzy logic arose from a desire to incorporate logical reasoning and the intuitive decision making of an expert operator into an automated system . The aim is to make decisions based on a number of learned or predefined rules, rather than numerical calculations. Fuzzy logic incorporates a rule-base structure in attempting to make decisions. However, before the rule-base can be used, the input data should be represented in such a way as to retain meaning, while still allowing for manipulation. Fuzzy logic [12],.[13] is an aggregation of rules, based on the input state variables condition with a corresponding desired output. A mechanism must exist to decide on which output, or combination of different outputs, will be used since each rule could conceivably result in a different output action.

Fuzzy logic can be viewed as an alternative form of input=output mapping. Consider the input premise, x, and a particular qualification of the input x represented by Ai. Additionally, the corresponding output, y, can be qualified by expression Ci. Thus, a fuzzy logic representation of the relationship between the input x and the output y could be described by the following

R1: IF x is A1 THEN y is C1

R2: IF x is A2 THEN y is C2

....

....

Rn: IF x is An THEN y is Cn

where x is the input (state variable), y is the output of the system, Ai are the different fuzzy variables used to classify the input x and Ci are the different fuzzy variables used to classify the output y. The fuzzy rule representation is linguistically based. Thus, the input x is a linguistic variable that corresponds to the state variable under consideration. Furthermore, the elements Ai are fuzzy variables that describe the input x. Correspondingly, the elements Ci are the fuzzy variables used to describe the output y. In fuzzy logic control, the term "linguistic variable" refers to whatever state variables the system designer is interested in. Linguistic variables that are often used in control applications include Speed, Speed Error, Position, and Derivative of Position Error. The fuzzy variable is perhaps better described as a fuzzy linguistic qualifier. Thus the fuzzy qualifier performs classification (qualification) of the linguistic variables. The fuzzy variables frequently employed include Negative Large **(NL)**, Positive Small**(PS)** and Zero**(ZO)**. Several papers in the literature use the term "fuzzy set" instead of "fuzzy variable", however; the concept remains the same. Table illustrates the difference between fuzzy variables and linguistic variables. Once the linguistic and fuzzy variables have been specified, the complete inference system can be defined. The fuzzy linguistic universe, U, is defined as the collection of all the fuzzy variables used to describe the linguistic variables.

The Fuzzy Inference System (FIS) The basic fuzzy inference system (FIS) can be classified as:

Type 1 Fuzzy Input Fuzzy Output (FIFO)

Type 2 Fuzzy Input Crisp Output (FICO)

Type 2 differs from the first in that the crisp output values are predefined and, thus, built into the inference engine of the FIS. In contrast, type 1 produces linguistic outputs. Type 1 is more general than type 2 as it allows redefinition of the response without having to redesign the entire inference engine. One drawback is the additional step required, converting the fuzzy output of the FIS to a crisp output. Developing a FIS and applying it to a control problem involves several steps:

1. fuzzification
2. fuzzy rule evaluation (fuzzy inference engine).
3. defuzzification.

The total fuzzy inference system is a mechanism that relates the inputs to a specific output or set of outputs. First, the inputs are categorized linguistically (fuzzification), then the linguistic inputs are related to outputs (fuzzy inference) and, finally, all the different outputs are combined to produce a single output (defuzzification). Fig.8. shows a block diagram of the fuzzy inference system

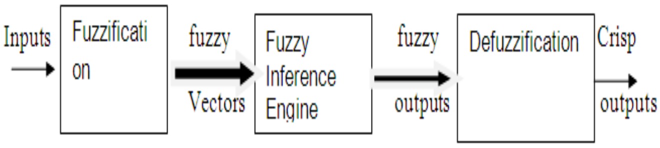


Fig.8. Fuzzy Interface System

1.Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference signal and output signal can be assigned as Negative large (**NL**), Negative Medium (**NM**), Negative Small (**NS**), Zero (**ZO**), Positive small (**PS**), Positive Medium (**PM**), Positive large (**PL**). The triangular membership function is used for fuzzifications. The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy number).

2.Defuzzification:

The rules of fuzzy logic controller 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). This selection of strategy is a compromise between accuracy and computational intensity.

3. Fuzzy Rule viewer:

e \ $\dot{e}$	NL	NM	NS	ZO	PS	PM	PL
NL	NL	NL	NL	NL	NM	ZO	PS
NM	NL	NL	NL	NM	ZO	PS	PM
NS	NL	NL	NM	ZO	PS	PM	PL
ZO	NL	NM	ZO	PS	PM	PL	PL
PS	NM	ZO	PS	PM	PL	PL	PL
PM	ZO	PS	PM	PL	PL	PL	PL
PL	PS	PM	PL	PL	PL	PL	PL

e is V_{dc}, $\dot{e}$ is change in error in V_{dc}.

5. SIMULATIONS & RESULTS

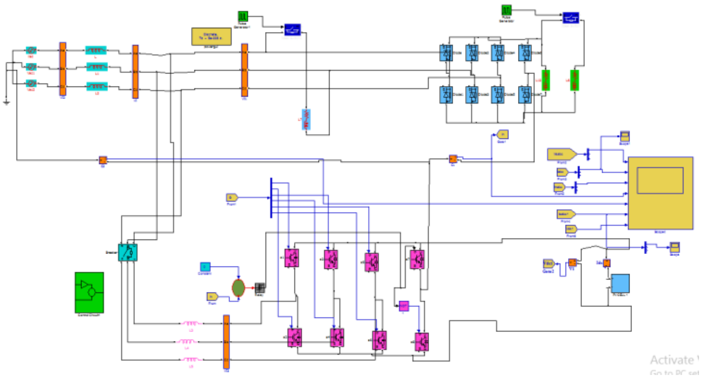


Fig.9.Simulink model of Predictive control scheme with 4-leg (VSI)Active Power Filter

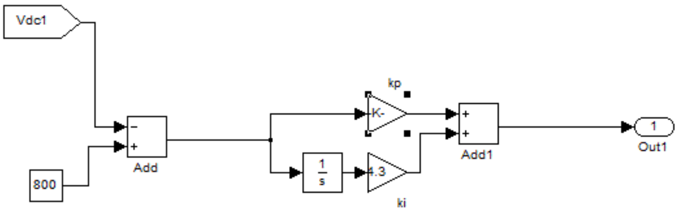
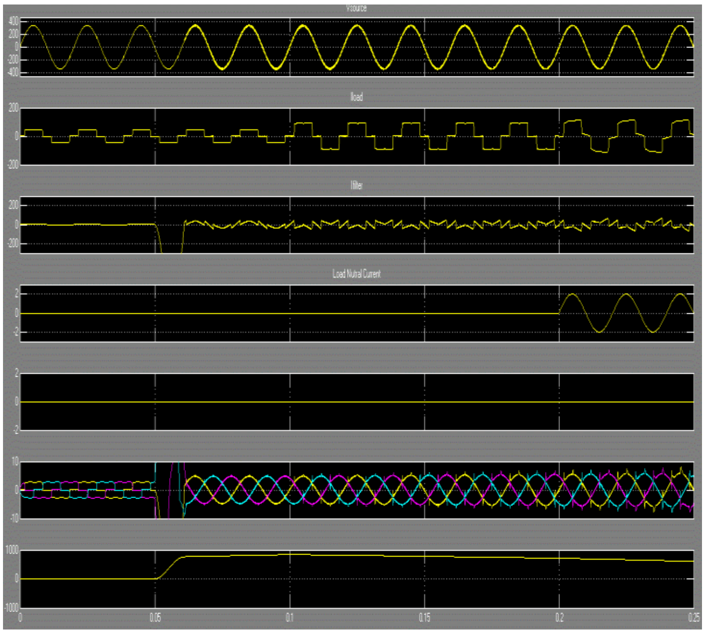


Fig.10.Simulink model of PI controller based APF



The above figure shows the ***output wave forms*** of the proposed scheme with PI controller, Here Initially APF is OFF condition from 0 to 0.05 sec and APF is ON condition from 0.05 to 0.25 sec from that we are observing the out puts of

(a) phase to neutral source voltage and ***(b) load current*** and (***c) filter current*** and ***(d) load neutral current*** and ***(e) source neutral current*** and ***(f) source current*** and finally ***(g) DC voltage***.

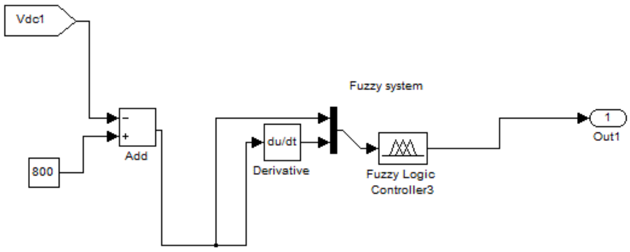
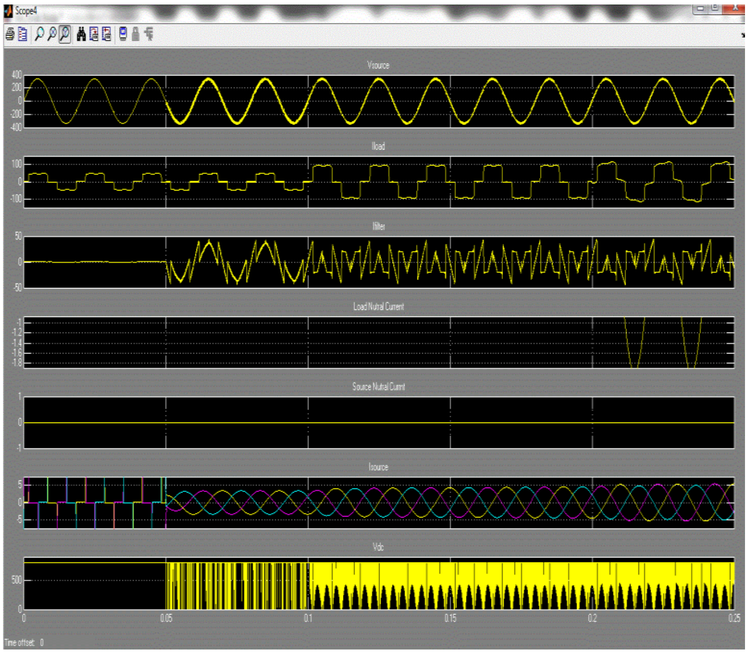
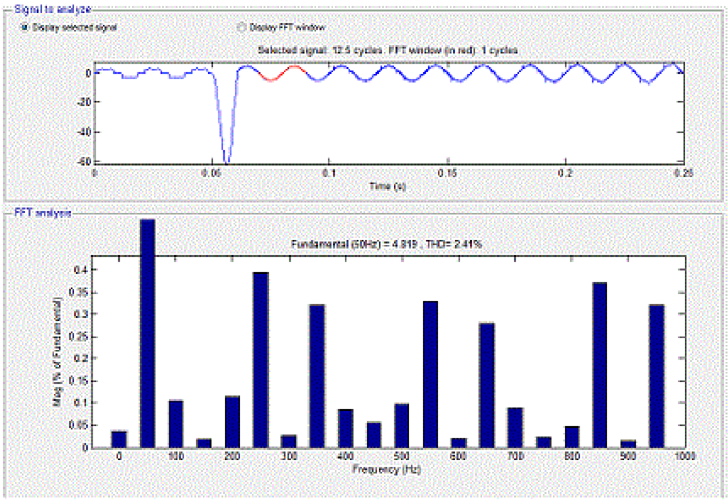


Fig.11.Simulation of Fuzzy Controller based APF.

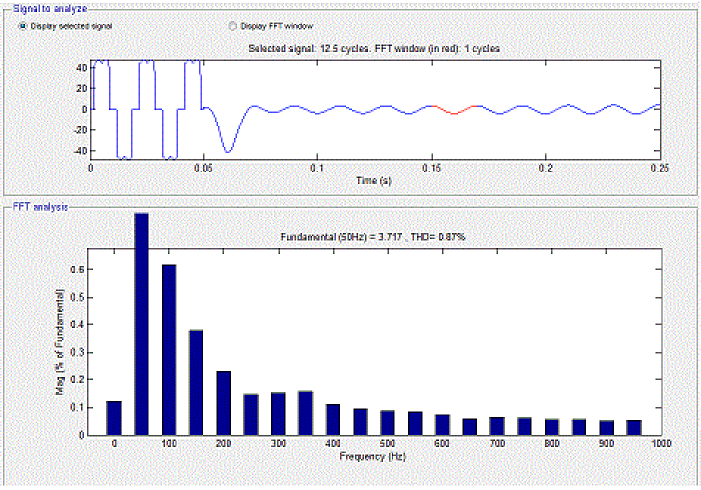


The above figure shows the ***output wave forms*** of the proposed scheme with Fuzzy control technique, Here Initially APF is OFF condition from 0 to 0.05 sec and APF is ON condition from 0.05 to 0.25 sec from that we are observing the out puts of ***(a) phase to neutral source voltage*** and ***(b) load current*** and ***(c) filter current*** and ***(d) load neutral current*** and ***(e) source neutral current*** and ***(f) source current*** and finally ***(g) DC voltage.***



(a)Signal Analysis of Source Current with PI (b) FFT Analysis of Source current with PI.

The above figure shows the total harmonic distortion based on ***PI controller*** for this condition the ***total harmonic distortion (THD)*** is ***2.41.***



(a)Signal Analysis of Source Current with Fuzzy

(b) FFT Analysis of Source current with Fuzzy

The above figure shows the total harmonic distortion based on ***Fuzzy control*** technique for this condition the ***total harmonic distortion (THD)*** is ***0.87.***

7. CONCLUSION

In this concept fuzzy controlled active power filter for renewable energy source is improved dynamic current harmonics and a reactive power compensation scheme for power distribution systems with generation from renewable sources has been proposed to improve the current quality of the distribution system. ***PI*** *is replaced with the* ***fuzzy controller*** to perform the speed operation of the converter. Advantages of the proposed scheme are related to its simplicity, modeling, and implementation. The use of a predictive control for the converter current loop proved to be an effective solution for active power filter applications. Finally this concept proposed ***the fuzzy controller is better controller compare to the PI controller*** is obtained by the ***simulation results***.

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9.BIOGRAPHIES

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