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IMPLEMENTATION OF GRID CONNECTED SINGLE PHASE INVERTER

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ABSTRACT

A lot of control strategies for grid-connected PWM inverters have been developed. In this work, a control algorithm for a single-phase grid-connected distributed generation (DG) system such as photovoltaic system in which an inverter designed synchronize a sinusoidal current output with grid voltage. The active and reactive power are sequentially controlled by both the load angle and the inverter output voltage magnitude respectively, based on optimal power of the distributed generation (DG) system in use. The system feeds maximum available active power into grid, whereas it also allows the adjustment of reactive power injected into the grid with the help of proposed controller. The proposed system employs a closed-loop feedback with a sinusoidal reference and the pulse-width is determined at every sampling instant, thereby providing a digital closed-loop control of inverter. The fuzzy controller is used to reduce the harmonic distortion and to provide good fundamental regulation. The PWM pattern is determined at every sampling instant by a decision table which is defined by the fuzzy control rules, which depends on reference active and reactive power. The proposed control scheme is verified by simulations for sudden voltage changes, sudden frequency variations and reference power variations.

***Keywords* - Distributed Generation (DG), PWM inverters, Uninterruptible power supplies (UPS), Fuzzy logic controller (FLC), digital closed-loop control.**

I. INTRODUCTION

In industrial countries, the mains power availability and quality is normally acceptable. Nevertheless, it is rarely a constant voltage with sinusoidal waveform and steady frequency. It is littered with voltage spikes, surges and sags and sometimes it fails. The rapid increase in the demand for electricity led to a need for a new source of energy that is cheaper and sustainable with less carbon emissions. Today many renewable energy technologies (commonly Distributed Generation System) such as solar, biomass, wind, fuel cells, hybrid electric vehicles and tidal power are well developed, reliable, and cost competitive with the conventional source of energy. As the use of DG is increasing, it is better to inject the extra available power to the grid so that the reliability and power quality can be improved. However, in this work, DGs which are providing DC output is considered. The dc power is converted to ac power using power electronics and control equipment. There are two types of the DG system; stand-alone power system and grid-connected power system. The stand-alone system is used in off-grid application with battery storage. In the case of residential or rooftop grid connected photovoltaic systems, biomass, fuel cells and hybrid electric vehicles, the electricity demand of the building is met and only the excess power is fed into the grid. Its control function must follow the voltage and frequency of the utility-generated power presented on the distribution line. The feeding of electricity into the grid requires the transformation of DC into AC by a grid controlled inverter. DG grid-tie inverters should be designed to operate within allowable power quality limits.

An important aspect related to the DG system connected to the grid using the proposed system is that it can operate the double functions of active power generator and reactive power compensator. The proper power factor is selected according to active power and reactive power that the grid demands. That is important for compensating the reactive power at peak hours, when the main grid needs a particular amount of reactive power higher than average consumption. Based on the real and reactive power reference values, the fuzzy logic controller obtains the required voltage reference signal which is given to a closed loop controlled PWM inverter. Different closed-loop control schemes of the PWM inverter with instantaneous feedback by using analog techniques has been proposed to achieve good transient response. In the last decade, with the availability of new power switching devices and high performance microprocessors the regulation of inverter systems has become more and more digitized. Deadbeat control, sliding mode control, first approaches with fuzzy control and many others are described in numerous publications. Exact information about the plant model is not necessary to design a fuzzy controller, therefore, it is most suitable for regulating an inverter system with unpredictable loads and reference values.

Traditional analog controllers can be affected by temperature drifts of the components and electromagnetic interference. PID is popular in many controller designs. However one drawback of using PID for controlling DC-AC converters is its fixed set of parameters, which affects the converter's performance. When it comes to digital type of controllers, Fuzzy Logic controller is known for good precision and speed. In Fuzzy, the control algorithm is based on a set of linguistic rules. The power injection to the grid is affected due to the grid-voltage variation, even though it is in allowable range. Hence, the control of power flows when the system has different power injection reference and grid-voltage variation, this control plays an important role in achieving system stability and improvement of system performance in renewable energy applications. The applications of proposed system include house-hold application of DG and in commercial applications with grid connected inverter systems.

II. ACTIVE AND REACTIVE POWER CONTROLLER FOR SINGLE PHASE GRID CONNECTED INVERTER

The idea of active and reactive power controller is proposed in many literatures. The use of a PWM inverter (VSI type) to promote the interface of a DG system with the ac system is a flexible proposal for control of real and reactive power [7]. The idea is to make this system to operate as a controllable voltage source connected in parallel with the power grid. By controlling the inverter output voltage phase angle and amplitude in relation to the grid voltage, it is possible to have the photovoltaic system supplying active and reactive power.

The active and reactive power flows in the system are coupled. In fact, the active power (P) depends predominantly on the phase angle or load angle (δ) between the inverter voltage (V) and system voltages (E), and the reactive power (Q) is a function of the magnitudes of these voltages, as shown in Fig. 1 and equations (1) and (2), where LC is the coupling inductance and f is the system frequency.

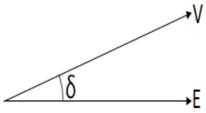

Fig. 1.Voltage phasor diagram

$$P = {}^{EV}/_{X} \sin \delta \text{......................................} \quad (1)$$

$$Q = \frac{EV}{X} \cos \delta - \frac{V\wedge 2}{X} \quad \text{.................................} \quad (2)$$

According to Fig.1 and equations (1) and (2), the power flow adjustment of the inverter unit, connected in parallel with the main grid, can be performed by controlling the inverter voltage magnitude (V) and angle (δ).

A control algorithm for a single-phase grid-connected photovoltaic system in which an inverter designed for grid-connected photovoltaic arrays can synchronize a sinusoidal current output with a grid voltage is proposed in [8]. The active and reactive power are sequentially controlled by load angle and by inverter output voltage magnitude besides a maximum power point tracker (MPPT) always finds optimal power of the PV array in use. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power injected into the grid. The power flow adjustment of the inverter is parallel connected to the main grid, can be performed by controlling the inverter output voltage magnitude (V) and load angle (δ). On the other hand, to inject power to the grid, the value of the DC voltage must be high enough so that the output voltage V can get a value which is equal or greater than the grid peak voltage. So, the active power injected into the grid can be controlled by the phase difference between grid voltage and inverter output voltage (δ). At the same time, the reactive power can be controlled by the inverter output voltage magnitude (V).

III. PROPOSED SYSTEM

The proposed scheme includes the output voltage regulation of a single phase inverter using a fuzzy logic controller implemented with the reference signal obtained from the required voltage magnitude and load angle. The block diagram of the proposed scheme is given in Fig. 2.

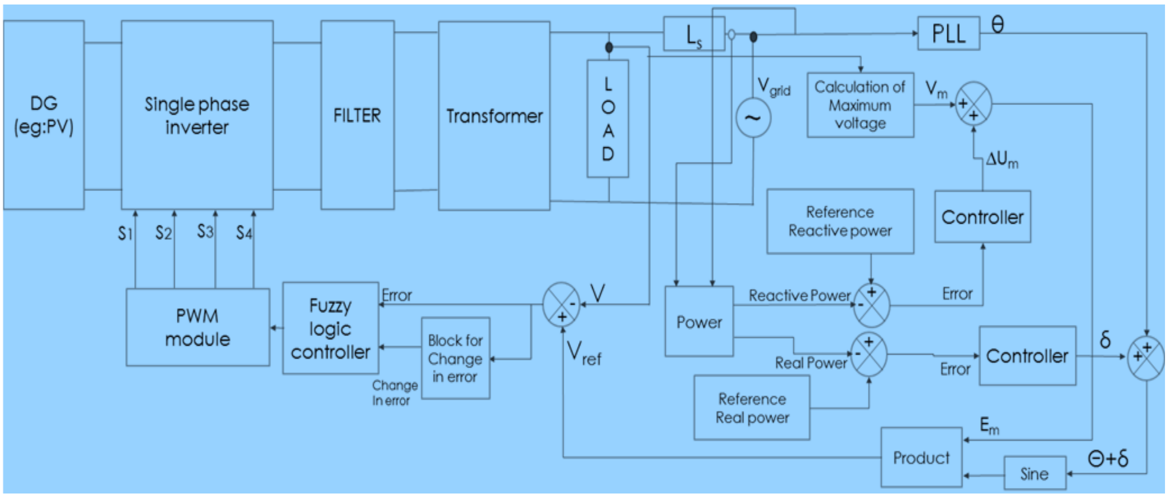

Fig. 2. Block diagram of Overall Set-up

The proposed system consists of three controllers - for voltage regulation of inverter, for real power control and for reactive power control. The voltage magnitude required for the reference signal for inverter voltage regulation is obtained from the reactive power controller. Similarly, the phase difference required for grid voltage and inverter voltage is obtained from real power controller. These are based on equations (1) and (2). The reference power can be obtained from DG system itself or can be set to a fixed reference power. The power injected from the inverter to the grid can be sensed and compared and from the respective controllers, the required voltage magnitude and the load angle can be obtained. The reference voltage signal for the voltage regulation is obtained from the voltage magnitude and load angle. With this reference signal, the inverter output voltage is obtained, which will inject the required real power and reactive power. The output voltage is sensed and the error obtained is fed to controller. The fuzzy logic controller obtains a DC reference value corresponding to the required modulation index.

The system consists of a single phase inverter whose switching pulses are obtained by a fuzzy logic controller. The inverter, the LC filter and the load can be considered as the plant of a control loop where the output voltage is sensed as feedback variable. The reference signal, module to calculate the change in error, fuzzy logic controller are simulated in MATLAB. The output voltage across load is taken as feedback signal and is compared with the reference signal to obtain the error signal. From the present error and the previously stored error, the change in error is obtained. The error and change in error is given to the Fuzzy logic controller. The Fuzzy logic controller calculates the required change in modulation index from the error and the change in error, and thus calculates modulation index. This modulation index is fed to a PWM module and the required pulse width is obtained. The switching method used here is of bipolar strategy, where a switch S1, S2 and S3, S4 operates alternately. The switching will be done such that the output follows the reference signal.

IV. PROPOSED ACTIVE AND REACTIVE POWER CONTROLLER

The proposed control structure for a single-phase inverter connected to the grid is shown in Fig.3. The system consists of DC voltage generator (DG), a single phase inverter and an active and reactive power controller. The control circuit has two parts: the first one controls the active power injected into the grid by the load angle δ, and the second one controls the reactive power through the inverter output voltage magnitude (E). As shown in fig. 3, the reactive power injected to the grid is calculated and compares it with its reference value, originating a reactive power error. This error passes through a controller. This controller generates the required change in voltage magnitude and it is added to grid voltage (E), resulting the inverter reference voltage amplitude (E_m). Thus the controller compensates the reactive power injected into the grid.

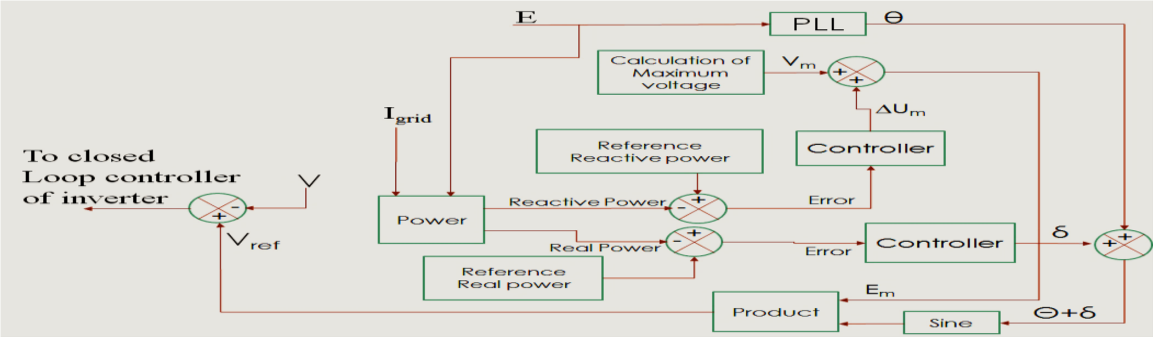

Fig. 3. Block diagram of proposed control scheme

On the other hand, the real power injected to the grid is calculated and compares it with a reference signal, generating an active power error. This error passes through a controller. This controller generates the required change in load angle, originating reference load angle (δ). The load angle is added to grid voltage phase angle (θ), generating inverter output voltage phase angle (δ+θ). Thus the controller compensates the real power injected into the grid. The inverter output voltage amplitude (E_m) is multiplied by sin(δ+θ), resulting the instantaneous value of the inverter reference voltage (V_{ref}) – the DC/AC inverter reference signal, thereby providing real and reactive power control.

V. PROPOSED FUZZY LOGIC CONTROLLER

The fuzzy logic controller includes mainly of membership functions for input and output parameters, rule-base table and de-fuzzification method. The Fuzzy logic controller works with linguistic variables. So the crisp value (physical value) is converted to linguistic variable. For this purpose, a fuzzifier is required. Similarly the obtained fuzzy variable is converted to crisp value. This process is called de-fuzzification. The block diagram representation of fuzzy logic controller is shown in Fig. 4.

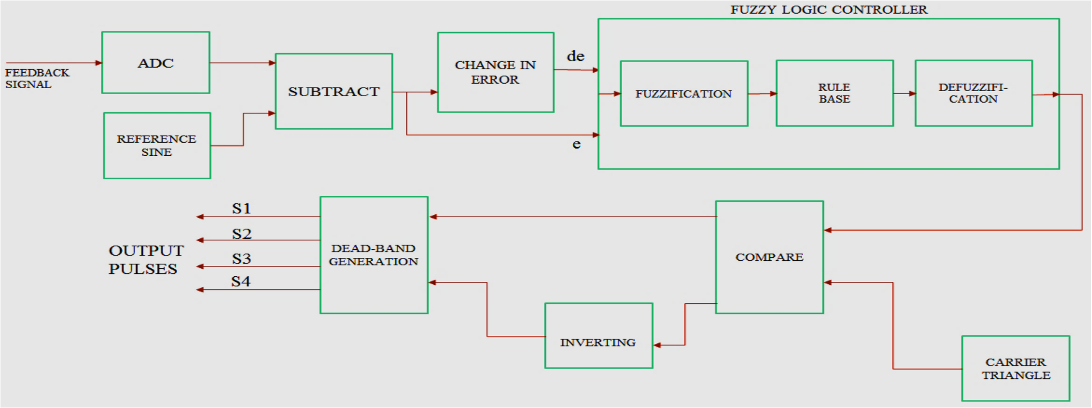

Fig. 4. Block diagram representation of fuzzy logic controller

For the purpose of fuzzification and de-fuzzification, some commonly used functions called membership functions are selected for input and output parameters within a specified range obtained from intuitive tries and from understanding of the system (plant). The proposed Fuzzy logic controller is described in the following sections.

5.1. Design Considerations

The design considerations of high-performance UPS usually includes: high input power factor, low output impedance, fast transient response, high efficiency, high stability and reliability, and low EMI. The basic mechanism of UPS is to convert the dc voltage of the batteries to a sinusoidal ac output through the inverter-LC filter blocks. There are two input parameters (the voltage error and the change in error) necessary to step up or step down the voltage input to desired output voltage. Duty cycle of the PWM module is the output parameter of the FLC and its effect on the output voltage will be fed back to the controller until the desired voltage is satisfied for a specific inverter circuit. Instead of numerical variables, linguistic variables are used in fuzzy logic system and these input variables are being processed to convert real number into fuzzy number. This conversion process is known as fuzzification. In this paper, voltage is considered as its input variables and the corresponding output voltage is fuzzy logic controlled. The error e(k) and change in error ce(k) are the input variables. The voltage error is calculated by subtracting the reference voltage $V_{ref}(k)$ with the actual voltage $V_o(k)$. On the other hand, the change in error is calculated by subtracting the obtained error e(k) from the previous error $[e_{previous}(k)]$. The result will undergo normalization process, so as to use the same FLC for different reference voltage. The normalized error and change in error will then be fuzzified given in Equations (3) and (4).

$$e(k) = V_{ref}(k) - V_o(k) \qquad (3)$$

$$ce(k) = e(k) - [e_{previous}(k)] \qquad (4)$$

The other factors to be considered in the design of controller are the range of input and output parameters in the membership function. This includes the voltage error, change in error and the modulation index. This ranges are fixed with intuitive tries and understanding the system. The selection of number of rules also have significant effect. More number of rules gives better accuracy but needs more number of membership functions, which will result in more memory requirement. Using FPGA, making 49 rules will not limit the memory constraint. So in this work 49 rules are obtained for the controller and so 7 membership functions are selected for input and output parameters.

5.2. Membership Functions

The membership functions are selected on the basis of the system behavior. The triangular membership function is the commonly used membership function. In this work, seven linguistic variables are considered for the voltage error, the change in error and change in modulation index. They are negatively big (NB), negatively medium (NM), negatively small (NS), zero (Z), positively small (PS), positively medium (PM) and positively big (PB). For simplicity, the triangular membership function is used for easy and reduced calculations.

Seven membership functions are preferred for acceptable result. From the studies, it is obtained the range of error membership function can be taken from the positive peak to negative peak of the reference signal. The triangular membership functions formulated for change in error ranges from -10V to 10V. It is chosen such that range have a more centralized set of normalized data, with zero being the central point. The triangular membership functions formulated for the change in modulation index is normalized in the range of -1 to 1. The membership functions are shown in Fig. 5, Fig. 6 and Fig. 7.

It is to be noted that the error and change in error ranges for real power controller and reactive power controller are different. For real power controller, error range is from -78W to 78W and change in error range is from -1.5W to 1.5W and the output (change in δ) range is from -3^0 to 3^0. For reactive power control, error range is from -20VAR to 20VAR and change in error is from -0.12VAR to 0.12VAR and the output (change in voltage shift) is from -1.12V to 1.12V.

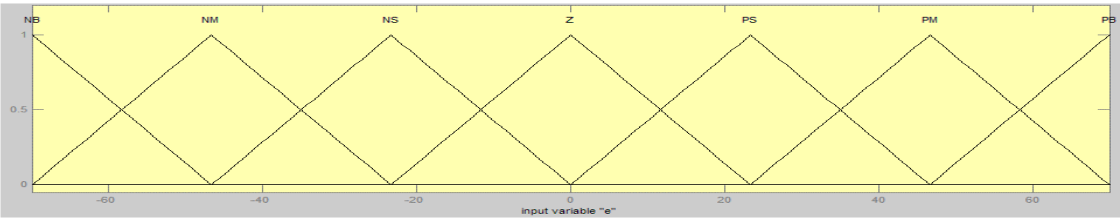

Fig. 5. Membership function for error (e)

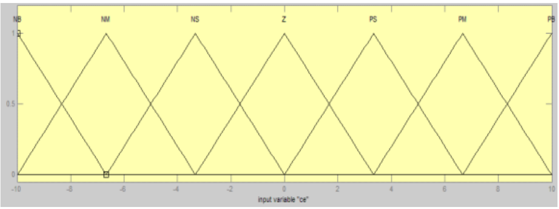

Fig. 6. Membership function for change in error (ce)

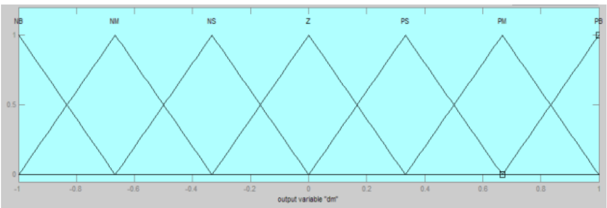

Fig. 7. Membership function for change in modulation index (δ)

It is to be noted that for a specified value of input variable, there will be two linguistic variable and for each linguistic variable, there will be a corresponding membership grade, which is the value of the selected function (here triangular function) corresponding to the input value. So at any instant, for two input variables, there will be four combinations of the input variables.

5.3. Rule-Base Table

The rule-base table represents the controlling action of the Fuzzy logic controller in the form of specific rules. It is generally represented as 'IF THEN' rules as given below.

IF error is ……… AND change in error is ……… THEN modulation index is ……..

For each combination of input parameters, there is a specific rule for the value of modulation index. In the rule-base table, e represents error and ce represents change in error. The linguistic variables for output, change in modulation index are negatively big (NB), negatively medium (NM), negatively small (NS), zero(Z), positively small (PS), positively medium (PM) and positively big (PB).Since there are 7 membership functions for each input parameter, there will be 49 rules. These rules are indicated in a table called rule-base table as shown in table. 1. The rule-base is selected such that when e and ce are zero, the change in modulation index will be zero. Similarly all the rules can be obtained from the rule-base table.

Table. 1. Rule-base table

e ce	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

5.4. De-Fuzzification Method

The last phase of fuzzy logic systems' operation is vital, which is known as de-fuzzification. It is mentioned before, that, for two input variables, where are four combinations. For each combination, there will be a specific rule output for modulation index. So in-order to get the crisp output, a method known as the center-of-area formula is used.

$$crisp\ output = \frac{\begin{array}{c} sum\ of\ product\ of\ area\ under\ the \\ triangular\ function\ for\ each\ linguistic\ variable \\ for\ output\ and\ its\ membership\ grade \end{array}}{sum\ of\ areas\ for\ all\ linguistic\ variables\ for\ output}$$

5.5. L-C Filter Design

A low pass LC filter is required at the output terminal of full bridge VSI to reduce harmonics generated by the pulsating modulation waveform. While designing LC filter, the cut-off frequency is chosen such that most of the low order harmonics is eliminated. To operate as an ideal voltage source, that means no additional voltage distortion under linear or non-linear load, the output impedance of the inverter must be kept zero. Therefore, the capacitance value should be maximized and the inductance value should be minimized at the selected cut-off frequency of the low-pass filter. Each value of L and C component is determined to minimize the reactive power in these components because the reactive power of L and C will decide the cost of LC filter and it is selected to minimize the cost, so it is common that the filter components are determined at the set of a small capacitance and a large inductance and consequently the output impedance of the inverter is so high. With these design values, the voltage waveform of the inverter output can be sinusoidal under steady state condition because the output impedance is zero. The filter is a low-pass type, the resistance R accounts for the internal resistance of the inductor and is very small, which is not shown in figure. Voltage gain is

$V_{out} / V_{in} = 1/ (LCs^2+RCs+1)$ (5)

For a single phase low-pass LC filter, the analysis of the filter is done in the frequency domain and for a typical low-pass filter, the voltage gain is $H(j\omega)=\omega_p^2/(s^2+(\omega_p s/Q)+\omega_p^2)$ (6)

Where ω_p is the natural oscillating frequency and Q is the quality factor. It can be proven that in the case of peaked resonance, or $Q>(1/\surd2)$, the frequency at which $H(j\omega)_{max}$ is maximized and the corresponding maximum are

$$\omega/\omega_p = \surd(1-1/2Q^2) \qquad (7)$$

$$H(j\omega)_{max} = Q/\sqrt{(1-1/4Q^2)} \qquad (8)$$

For sufficiently large Q_s, say $Q>5$, we have $\omega/\omega_p=1$ and $H(j\omega)_{max} = Q$.

By rearranging and comparing, we will get $LC = 1/\omega_p^2$ (9)

$$RC = 1/Q\omega_p \qquad (10)$$

By solving these equations, L,C and R values of the filter can be obtained. Select filter capacitance =470 μF, so filter inductance=20mH.

VI. RESULTS AND DISCUSSION

The proposed system is simulated in the simulation software- MATLAB. The Fuzzy logic controller is obtained by the block-FIS Editor. The system is simulated for a particular real and reactive power reference values. Assuming a normal DG system, the output voltage is considered as 100V (Nominal rating of a solar panel is 24V. Four such panels in series will provide 96V). Therefore the output voltage of the inverter is set at 50V rms so that the voltage variation of DG system due to any reason (eg:-MPPT) will not affect the inverter control. This voltage can be step-up to the rated voltage using a transformer, which also will provide isolation. The nominal power rating of a DG system will be around 1kW. But considering the maximum power that can be transferred to the grid, the real power reference is set at 600W. Assuming a nominal value, the reactive power is set at 150VAR. The simulation circuit for real and reactive power controller is shown in Fig. 8 and Fig. 9

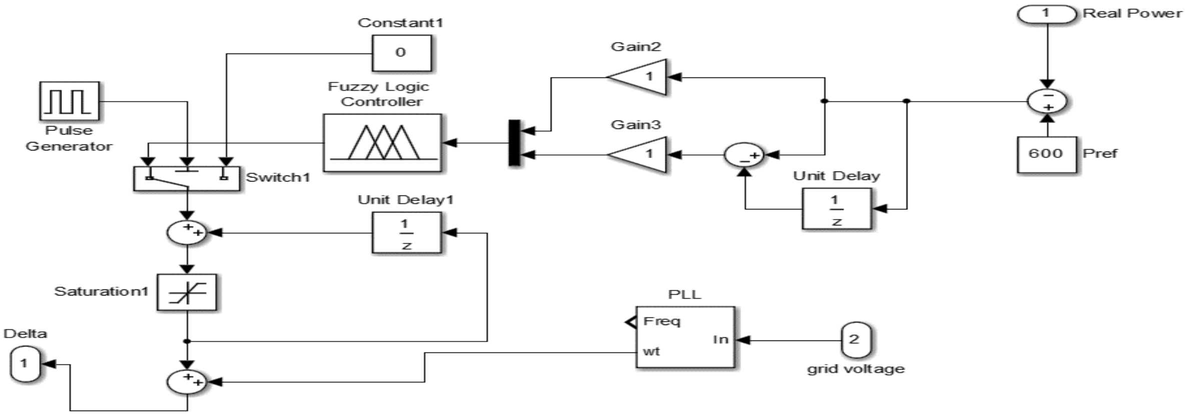

Fig. 8. Simulation diagram of real power controller

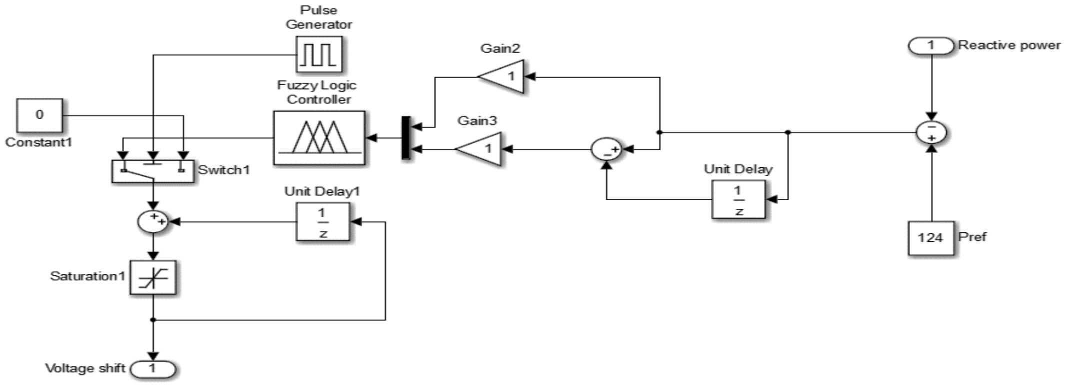

Fig. 9. Simulation diagram of reactive power controller

The simulation results obtained for real and reactive power reference variation are satisfactory, which will provide better real and reactive power transfer and having good transient response. Initially the real power is set as 600W and reactive power is set as 150VAR and the voltage is maintained constant at 230V. At time 2s, the real power reference value is changed to 650W, at 3.5s the reactive power reference is changed to 180VAR, at 5s the real power reference is changed to 550W, at 6.5s the reactive power reference is changed to 120VAR. The results obtained for real and reactive power reference power value variation for the simulation are shown in Fig. 10 to Fig. 12.

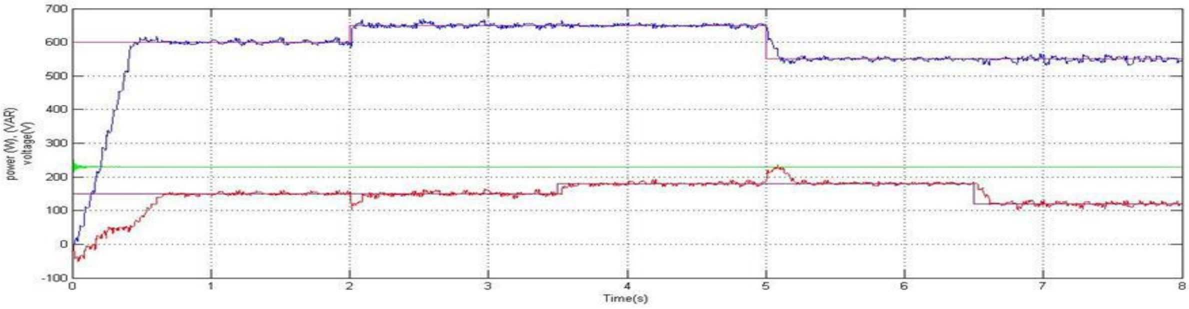

Fig. 10. Real power and reactive power reference power variation

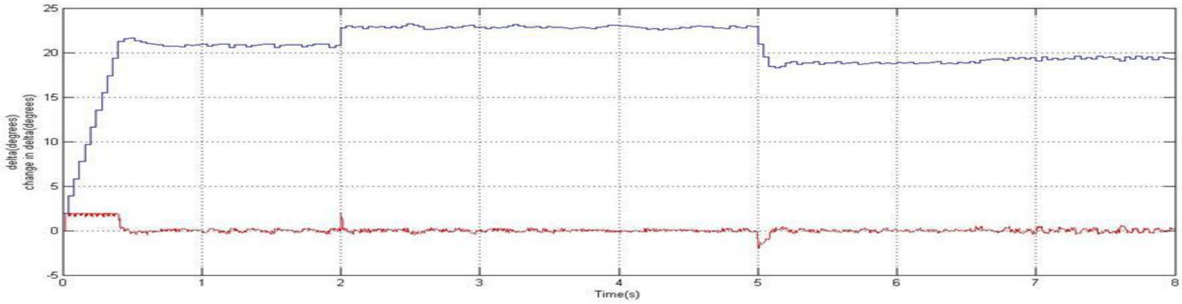

Fig. 11. Load angle with reference power variation

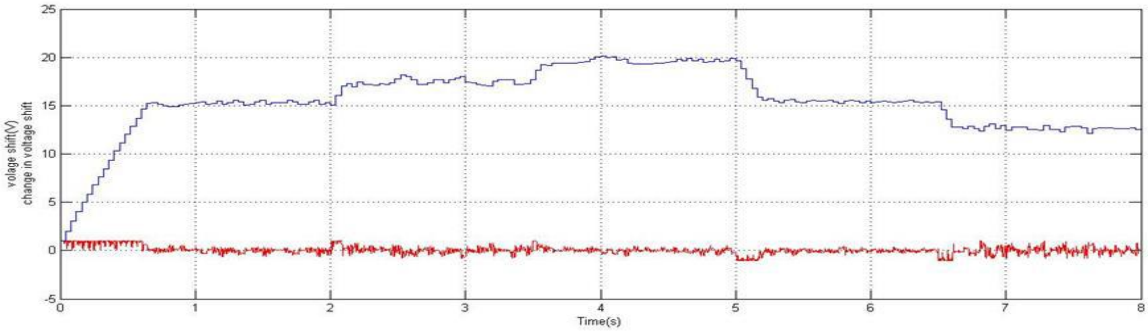

Fig. 12. Voltage amplitude shift with reference power variation

The total harmonic distortion (THD) for the reference variation at point of common coupling (PCC) during different time is shown in table. 2.

Table. 2. Voltage THD for reference power variation

Time in Sec	% of THD at PCC
1	4.2
2	4.59
3.5	4.71
5	4.76
6.5	4.73

The simulation results obtained for voltage variation are satisfactory, which will provide better real and reactive power transfer and having good transient response. Initially the real power is set as 600W and reactive power is set as 200VAR and the voltage is maintained set at 230V. At time 2s, the voltage is changed to 240V and at 3.5s voltage is changed to 220V. The results obtained for real and reactive power reference value variation for the simulation are shown in Fig. 13 to Fig. 16.

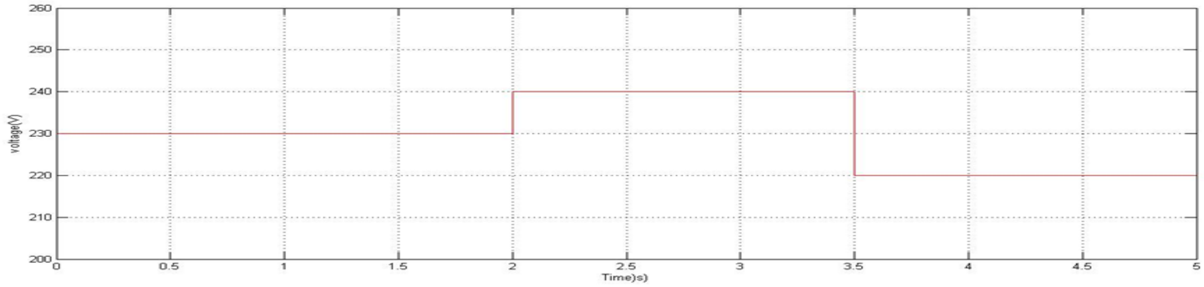

Fig. 13. Voltage variation

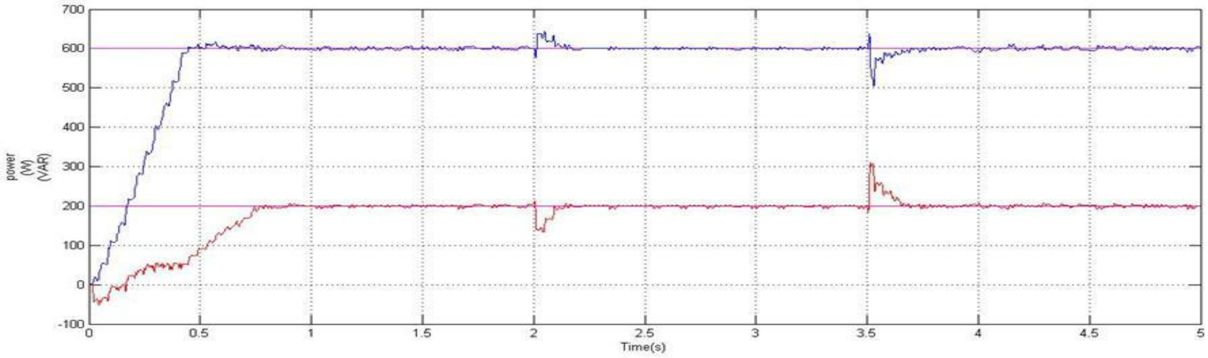

Fig. 14. Real power and reactive power with voltage variation

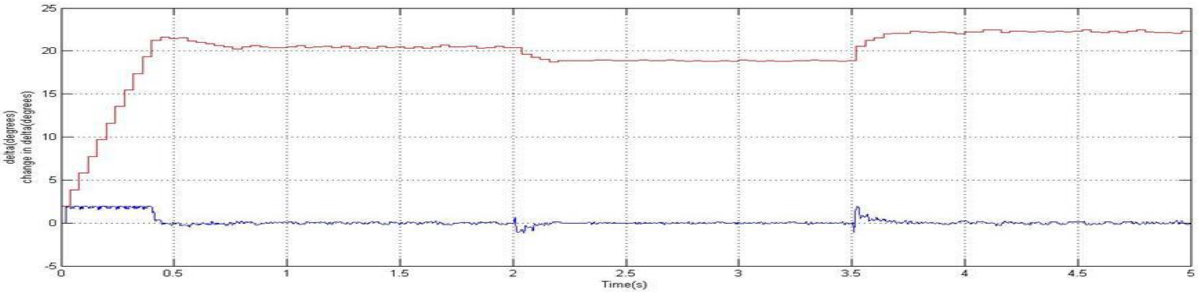

Fig. 15. Load angle with voltage variation

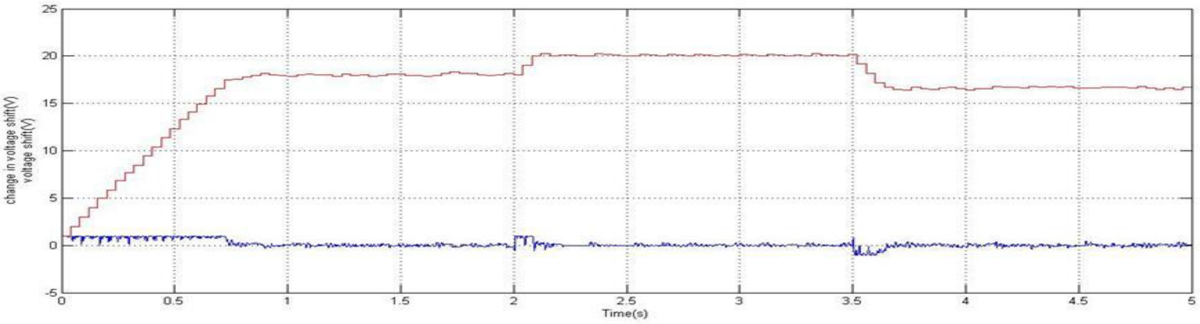

Fig. 16. Voltage amplitude shift with voltage variation

The total harmonic distortion (THD) for the voltage variation at point of common coupling (PCC) during different time is shown in table. 3.

Table. 3. Voltage THD for voltage variation

Time in Sec	% of THD at PCC
1	4.2
2	3.65
3.5	4.18

The simulation results obtained for frequency variation are satisfactory, which will also provide better real and reactive power transfer and having good transient response. Initially the real power is set as 600W and reactive power is set as 150VAR and the voltage is maintained constant at 230V. At time 2s, the frequency is changed to 51Hz and at 3.5s frequency is changed to 49Hz. The results obtained for real and reactive power reference value variation for the simulation are shown in Fig. 17 to Fig. 20.

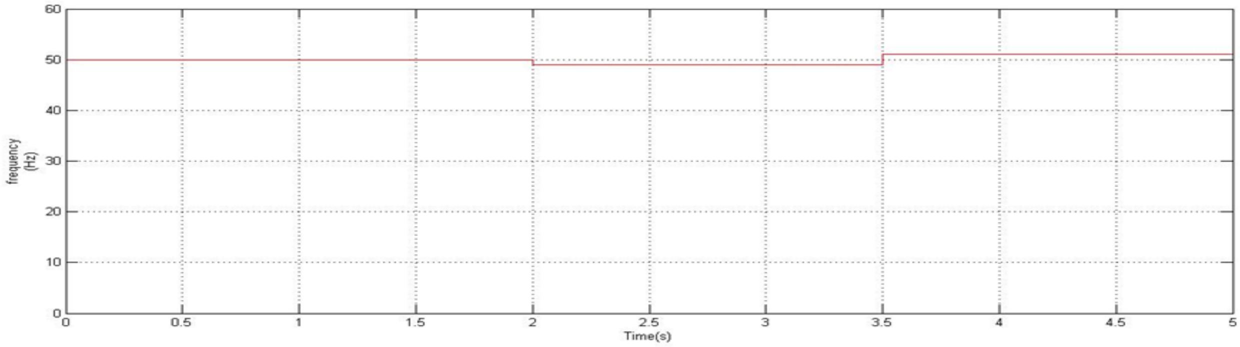

Fig. 17. Frequency variation

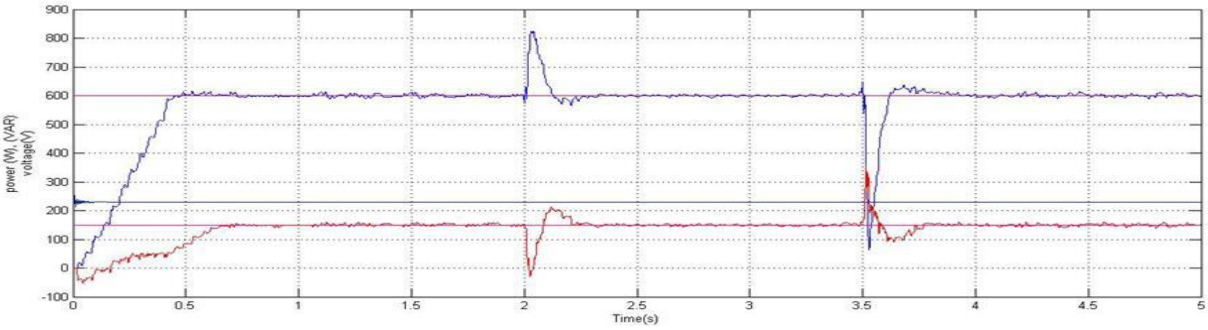

Fig. 18. Real power and reactive power with frequency variation

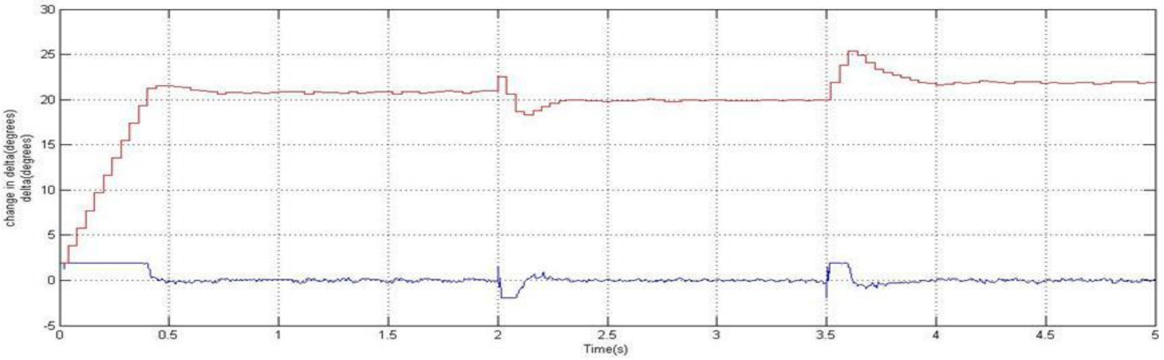

Fig. 19. Load angle with frequency variation

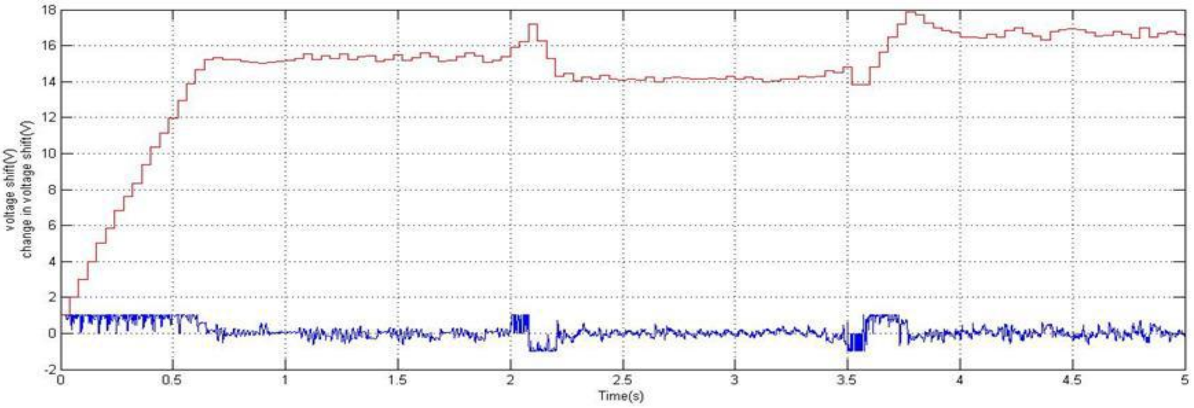

Fig. 20. Voltage amplitude shift with frequency variation

The total harmonic distortion (THD) for the frequency variation at point of common coupling (PCC) during different time is shown in table. 4.

Table. 4. Voltage THD for frequency variation

Time in Sec	% of THD at PCC
1	4.2
2	3.46
3.5	4.65

VII. CONCLUSION

The grid connected inverter with real power and reactive power control has been presented. The performance of closed loop control of inverter is obtained in simulation. In a PWM waveform generated by using a fuzzy logic controller, it is able to control processes very fast with good performance. The performance of the system is determined by simulating of fuzzy logic controller in the simulation software-MATLAB. The results obtained from simulation of system are satisfactory and acceptable. The performance of real power and reactive power control is obtained in simulation. The grid connected system is implemented in simulation software-MATLAB. The real power and reactive power control is obtained by fuzzy logic due to the following advantages: In the design of a fuzzy controller, exact knowledge about the plant model is usually not necessary, therefore, the fuzzy controller possesses an inherent characteristics of robustness. The system performance is checked with different reference power values, voltage variation and frequency variation. The results obtained are satisfactory and transient performance is acceptable. The whole system has a good stable and dynamic capability. Besides that the system also has a high practicality value.

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