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Intelligent UPS Inverter Control Design Using Microcontroller

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Abstract

This paper presents many control algorithms using microcontroller for an uninterruptible power supply (UPS) inverter, in order to provide pure sinusoidal wave 50 Hz, controlled by the PIC-microcontroller. The strategy is to utilize the PIC microcontroller and its special features in controlling the UPS inverter. The first approach accomplished with a classical control Proportional-Integral-Derivative (PID) algorithm. The second approach accomplished with the Fuzzy Logic Control (FLC). The third approach accomplished with nonlinear PID-fuzzy logic controller. The ability of the proposed scheme is validated via a successful implementation on a microcontroller-based UPS inverter. The proposed scheme has shown its robustness on low output voltage distortion, excellent voltage regulation, and it is insensitive to load variation, even under nonlinear loads. Experimental studies are performed to further validate the effectiveness of this scheme. This system may be used with grid-solar energy systems.

Keywords: PID Controller, Fuzzy Logic Control, Nonlinear PID-Fuzzy Logic, Takagi Sugeno, Microcontroller Applications

1. Introduction

Critical systems such as computers, communication systems, medical equipments, and semiconductor manufacturing systems, need a highly reliable electrical source. Uninterruptible power supply (UPS) is often used to supply an emergency ac power with low output voltage distortion, good disturbance rejection, as well as excellent voltage regulation, even under critical loading conditions. UPS systems can be off-line, where the load is connected to the utility under normal operation, and emergency power is provided by the UPS. The on-line configuration is where the UPS inverter powers the load continuously (Annette et al. 1996). Traditionally utilizing a sliding mode control (SMC) scheme and DSP to maintain satisfactory performance of UPS systems has drawn the interest of many researchers (Tsang-Li et al. 2002), but this paper discusses controllers such as PID, fuzzy logic, and a combination of them using PIC-microcontroller.

To further validate its effectiveness, a PWM inverter is constructed and controlled by implementing the proposed controller on microcontroller unit. One can use different microcontroller models according to the program size, variables amount, optional modules, special features, and processor speed. PIC-microcontroller unit is distinguished by some built-in features such as analog to digital converter, serial communication, pulse width modulation PWM module, and ability of dealing with floating point. PIC-microcontroller unit performs many tasks such as reading analog inputs, performing floating point calculations, generating signals, and communicating serially with PC.

From the experimental results, it can be observed that the proposed scheme has a reliable performance as the inverter circuit design reduces the output harmonics which undesirable in UPS systems using passive L–C output filter.

This paper is organized as follows: Section 2: presents the UPS control system description. Section 3: introduces Control Algorithms; 3.1 PID controller, 3.2 Fuzzy logic controller, 3.3 Nonlinear PID-fuzzy logic controller. Section 4: gives the simulation results. Section 5: gives the experimental results. Section 6: presents the conclusion. Section 7: References.

2. UPS Control System Description

A single phase Uninterruptible Power Supply (UPS) control system is presented in figure 1, which consists of pure sin wave generator, signal conditioning for input and output, PIC-microcontroller unit, PWM inverter, and passive L–C filter. The pure sin wave generator works as reference input. Signal conditioning for input and output signals is to make them suitable for PIC microcontroller unit. The program of control algorithm is loaded on PIC-microcontroller unit. Pulse width modulation (PWM) inverter is controlled by microcontroller pulses. Passive L–C filter is to eliminate harmonics and give the desired output voltage. Control program reads reference input signal and feedback output signal, calculates the error, performs the control algorithm, and gives output PWM pulses to control inverter switches.

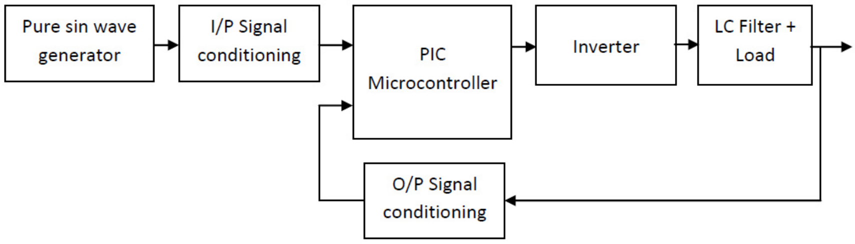


Figure 1. Block Diagram of Single Phase UPS Control

PIC-microcontroller unit performs the following tasks; analog to digital conversion for reference input signal and output feedback signal, triangular wave or saw tooth wave generation which works for PWM operation, and serial communication tasks (Microchip 2002), (Microchip 2006), (Microchip 2001). Dc power for inverter is supplied from battery for UPS set. The output voltage depends on width of modulated pulses which is generated from microcontroller unit, PWM inverter gain, and dc supply voltage. PIC-microcontroller provides the width modulated gating signals to inverter switches which could be insulated gate bipolar transistors (IGBT) or power transistors. A typical single phase full-bridge inverter circuit is shown in figure 2-a, and its load voltage and current waveforms shown in figure 2-b (Muhammad H. Rashid 2004), (Bimal K. Bose 2002). When transistors Q1 and Q3 are turned on simultaneously at the same time, the input voltage V appears across the load, and when transistors Q2 and Q4 are turned on at the same time, the input voltage -V appears across the load (in reverse direction). It should be noted that, this operation must be done inversely. The rms output voltage appears across the load can be expressed as (Muhammad H. Rashid 2004):

$$V_o = \left(\frac{2}{T_o} \int_0^{T_0/2} V^2 dt \right)^{1/2} = V \tag{1}$$

The instantaneous output voltage can be expressed in Fourier series as (Muhammad H. Rashid 2004):

$$V_o = \sum_{n=1,3,5,...}^{\infty} \frac{4V}{n\pi} \sin n\omega t \tag{2}$$

The output voltage of single phase full wave inverter can be expressed as:

$$V(k) = (2d(k) - 1)V_{dc} \tag{3}$$

Where d(k) is the duty ratio and V_{dc} is the dc input voltage of the inverter (Heng Deng et al. 2005).

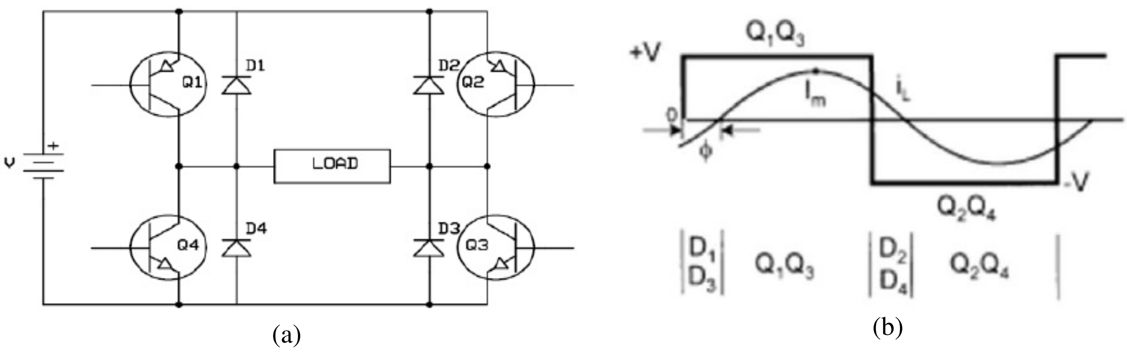


Figure 2. Typical Single Phase Full-Bridge Inverter, (a) Circuit, (b) Waveforms

For harmonics distortion, filter on the output stage have to be attached. Passive L–C filter as shown in figure 3 can be used for harmonics reduction with less reactive power.

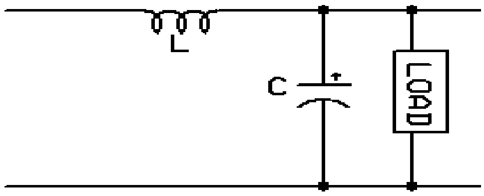


Figure 3. L–C Filter

By applying Kirchhoff voltage law, the transfer function can be derived as (Tsang-Li et al. 2002):

$$\frac{V_c(s)}{V(s)} = \frac{1}{LCS^2 + CS + 1} \tag{4}$$

The n[th] and higher order harmonics would be reduced significantly if the filter impedance is much smaller than that of the load, and a ratio of 1 : 10 is normally adequate (Muhammad H. Rashid 2004),

$$|Z_n| = 10|X_e| \tag{5}$$

Where the filter impedance is $|X_e|$, and $|Z_n|$ is the impedance of the n[th] harmonic voltage. For the system described, which includes the single phase full-bridge inverter and the L–C filter, the capacitor voltage $V_c(t)$ is considered as the variable to be controlled.

3. Control Algorithms

A typical UPS basically consists of an ac-dc converter (rectifier), dc-ac converter (inverter), battery which can be charged by rectifier or by a separated battery charger, and filter to supply a sinusoidal wave output. The inverter is operated with a pulse width modulated (PWM) signals, and there is a feedback signal to the controller to obtain the desired output wave form. Control of the PWM inverter switching is very important to minimize the harmonic content of the output voltage. Control of the PWM inverter is achieved with feedback loop, where the actual output waveform is compared with a pure sinusoidal signal as reference input. The error signal is used to modify the inverter switching and gating signals of transistors to create a PWM representation of an ac sine wave (Annette et al. 1996). Traditional UPS systems employ analog controls present a number of potential drawbacks for both UPS manufacturers and users. Analog controls rely on a large number of discrete components and boards, resulting in a high component amount and a relatively high hardware cost. In addition, because of the number of components that must work together, analog controls rely on a large number of connections. In operation microcontroller compares reference signal with actual reading and then performs calculations to produce controller output values which is compared with high frequency carrier signal to produce gating signals for PWM inverter.

There are many advantages in using a microcontroller chip instead of analog circuitry. In addition, control system upgrades or modifications can be implemented in software, without changes to hard-ware. The UPS systems used microprocessors depend on some external features such as analog to digital modules, but microcontroller has such modules internally.

3.1 PID Controller

Proportional integral derivative (PID) controllers have been widely used for industrial processes due to their simplicity, ease of design, inexpensive cost, and effectiveness. There are number of different ways to apply a PID controller. Since many control systems using PID control have proved satisfactory performance, PID still has a wide range of applications in industrial control.

From a typical structure of a PID control system, where it can be seen that in a PID controller the error signal *e(t)* is used to generate the proportional, integral, and derivative actions, with the resulting signals are weighted and summed to form the control signal *u(t)* which is applied to the plant model. Simulation for PWM inverter system controlled by PID controller on Matlab Simulink is shown in figure4.

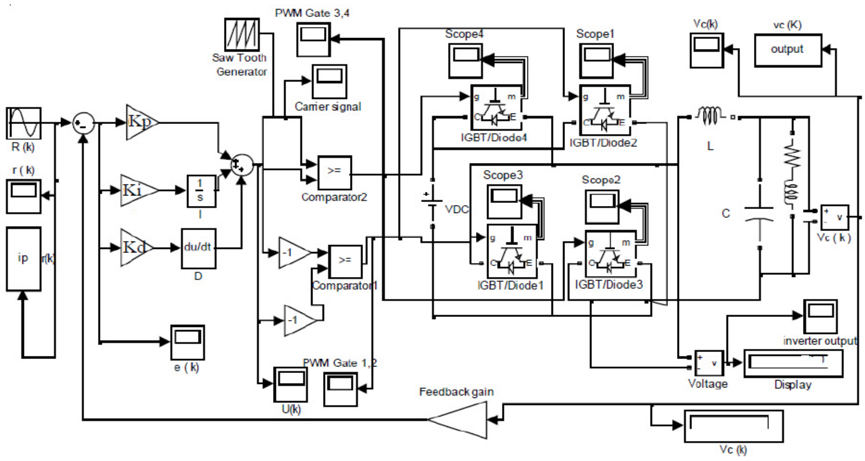


Figure 4. Simulation of PWM Inverter System is Controlled by PID Controller

A mathematical description of the PID controller is:

$$U(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de}{dt} \tag{6}$$

The PID controller will be presented by the following transfer function:

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \tag{7}$$

Where K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain. The digital expression of PID control algorithm is:

$$U(t) = K_p e(t) + K_i \sum e(t) + K_d \frac{e(t) - e(t-1)}{\Delta t} \tag{8}$$

The PID controller is designed by properly choosing K_p, K_i, and K_d. The output should have a small rise time, a small overshoot, a small settling time, and a zero steady-state error. Such a response is, of course, close to the ideal. The difficulty in achieving such a response is the selection (or tuning) of the appropriate K_p, K_i, and K_d for any specific system under control (Katsuhiko Ogata 2002). Selecting the appropriate K_p, K_i, and K_d depends on the design engineer experience. The appropriate values of the parameters K_p, K_i, and K_d of the PID controller may be chosen by trial and error. The flow chart of control algorithm program is shown in figure 5, and the system block diagram controlled by PID controller implemented on a PIC-microcontroller unit is shown in figure 6. The control algorithm is programmed according to flow chart and then loaded to PIC-microcontroller unit to be executed.

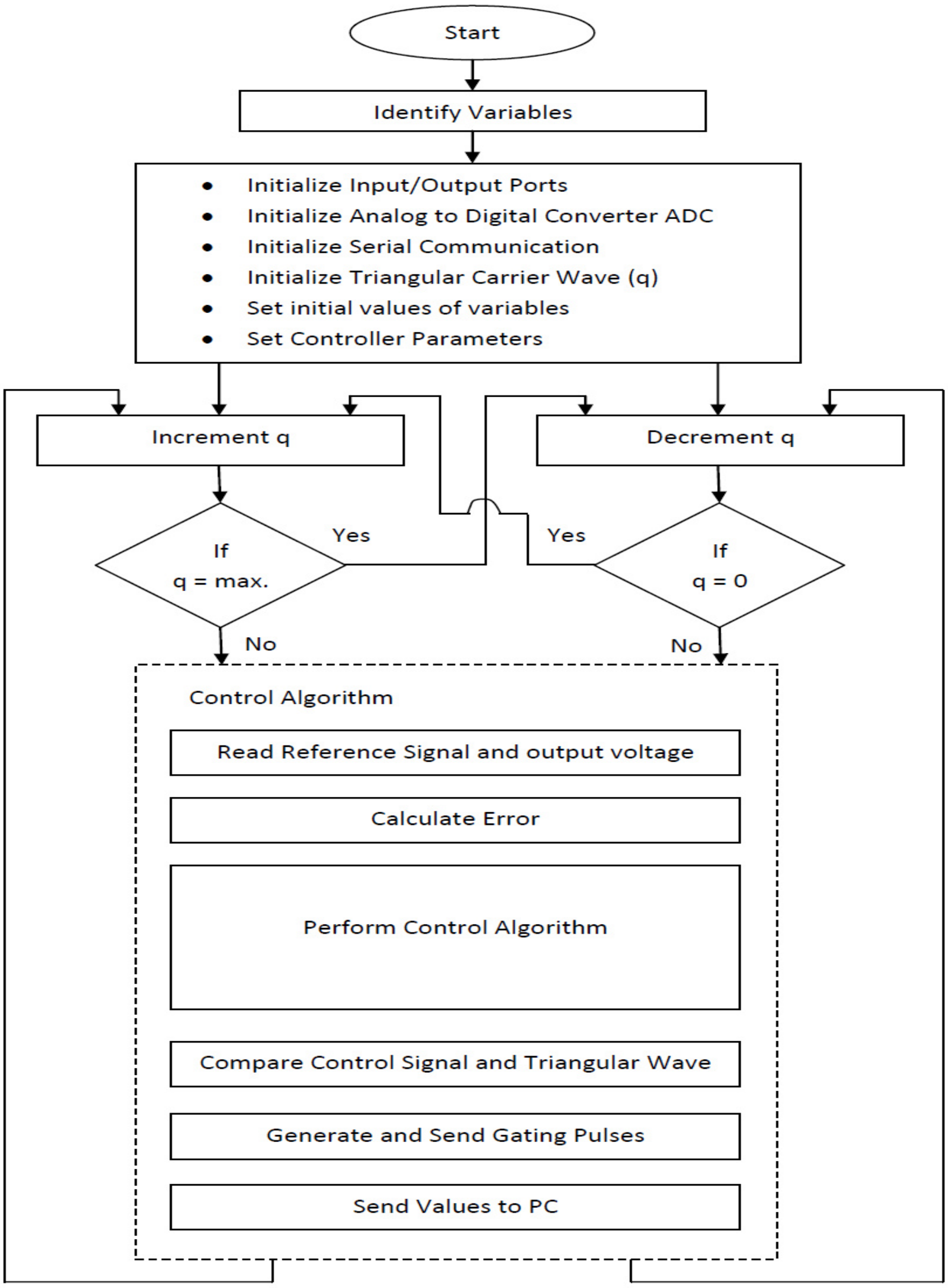


Figure 5. Flow Chart of Control Algorithm Program

An electronic circuit for reference input is designed to produce an analog pure sinusoidal wave signal r. Signal conditioning circuits are designed to provide reference input signal, and feedback signal to the microcontroller unit which has an internal analog to digital converter. The MCU microcontroller unit provides pulses width modulated which are working as gating signals for power transistors of the inverter.

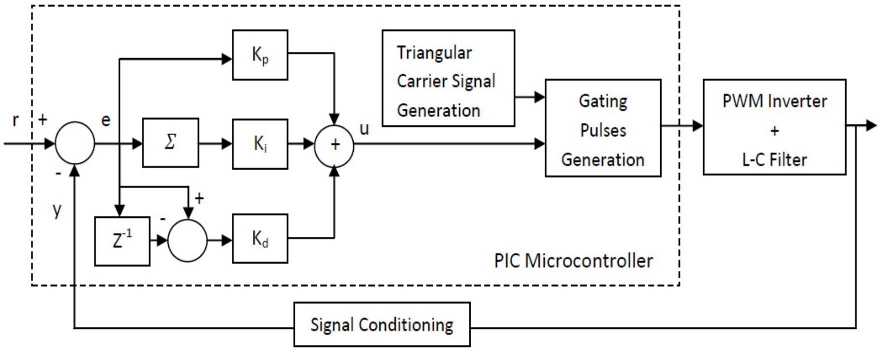


Figure 6. System Block Diagram Controlled by PID Controller

3.2 Fuzzy Logic Controller

A typical fuzzy logic control (FLC) system is shown in figure 7. This block diagram consists of four main blocks fuzzification, knowledge base, fuzzy inference, and defuzzification. The knowledge base consists of two sub blocks a data base, and a rule base. The fuzzy rule base is a set of conditional linguistic sentences or rules. The set of these statements is called rule base, provides information for the appropriate fuzzification. Rule base is constructed from the knowledge of expert engineer, the physical laws of the system, and the data that are collected from the existing controllers. Knowledge base is relating input membership functions and output membership functions to obtain the desired fuzzy control action. Fuzzification is to map the crisp value of the input variable such as error e(t) or change of error ce(t) into linguistic value which is understandable by fuzzy logic control, or it is the operation of transforming a crisp set to a fuzzy set. The fuzzy inference engine is to get the fuzzy output using linguistic rules. Defuzzification converts fuzzy output into crisp value (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000), (Kamyar Mehran 2008), (Jan Jantzen 1998), (Kevin M. Passino et al. 1998).

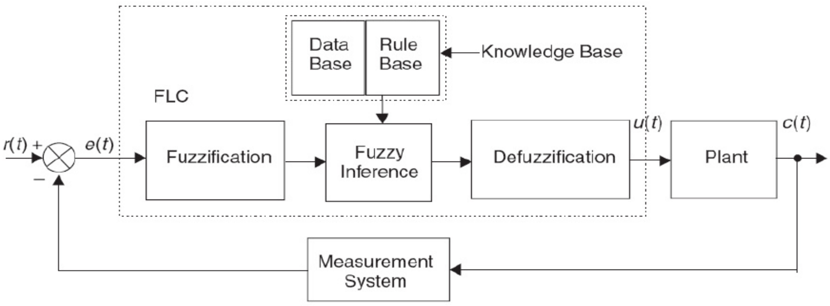


Figure 7. A Typical Fuzzy Logic Control (FLC) System Block Diagram

Usually the inputs which are fuzzified to fuzzy sets are the error e, and the change of error Δe. Figures 8, and 9 show the standard linguistic labels of fuzzy sets, and the fuzzy controller using Mamdani fuzzy modeling for PWM inverter system simulation on Matlab Simulink respectively. Table 1 shows a table of rule base for fuzzy sets.

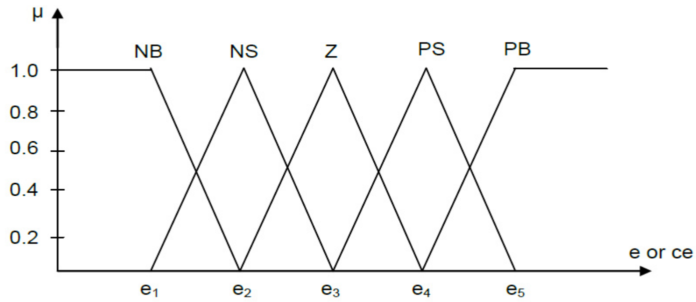


Figure 8. Membership Functions of Error e, and Change of Error ce

Table 1. Fuzzy Sets Rule Base

ce \ e	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

The block diagram of PWM inverter system which is controlled by fuzzy logic control system using PIC-microcontroller is shown in figure 10. The FLC program algorithm flow chart is shown in figure 5. The fuzzification task is to map crisp values of the inputs error e(k) = desired – measured, and the change of error Δe(k) = e(k) - e(k-1) into fuzzy values. Defuzzification requires a scaling for each order, and quantization procedure, which defines the range of values over which the membership functions are characterized. The quantified inputs are converted into suitable linguistic labels. For all the membership functions, the degree of membership is evaluated for each value of the input variable. The knowledge base involves defining the rules represented as statements which are governing the desired relationship between the input and output variables in terms of membership functions.

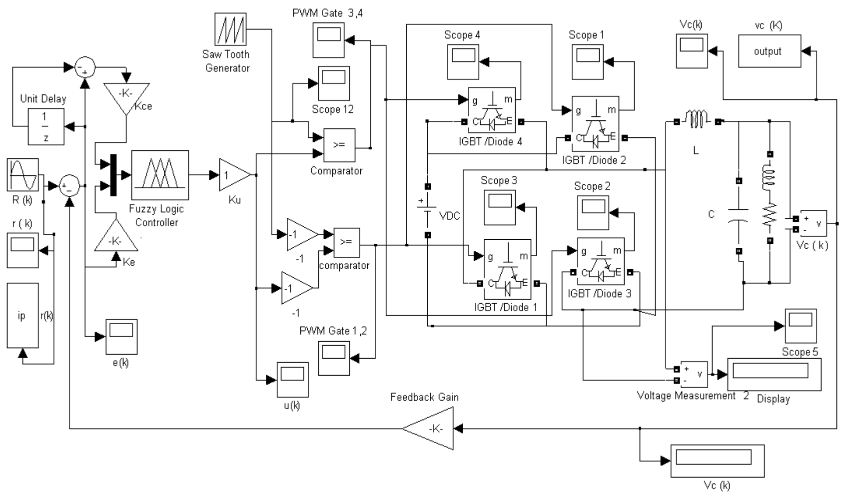


Figure 9. Fuzzy Logic Controller for PWM Inverter

The control statements are represented as a set of IF-THEN rules (Jan Jantzen 1998), (Kevin M. Passino et al. 1998). In this paper the Mamdani fuzzy system type center of area method is used as a defuzzification strategy to calculate the center of area of the inference engine output. The control signal u can be obtained by the following formula:

$$u = \frac{\sum u_i.\mu(u_i)}{\sum \mu(u_i)} \tag{9}$$

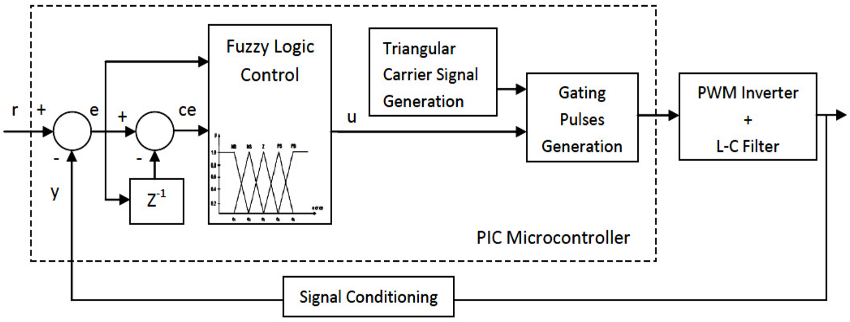


Figure 10. System Block Diagram controlled by FLC System

3.3 Nonlinear PID-Fuzzy Logic Controller

Conventional PID controllers generally do not work well for nonlinear systems (K. S. Tang et al. 2001). The nonlinear PID-fuzzy controller has some advantages such as: it has the same linear structure as the conventional PID controller, the controller is designed based on the classical discrete PID controller using fuzzy logic, and membership functions are simple triangular shaped with only two fuzzy logic IF-THEN rules. The constant control gains of these controllers are tuned manually (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000).

The nonlinear PID-fuzzy logic controller is designed to obtain the PID controller parameters K_p, K_i, and K_d by using fuzzy logic. The basic PI and PD controllers are expressed mathematically as (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000):

$$U^{PD} = K_1 e + K_2 \frac{de}{dt} \tag{10}$$

$$U^{PI} = K_3 e + K_4 \int e \tag{11}$$

Where e is the error signal, u is the control signal, and K_1, K_2, K_3, and K_4 are constant control gains.

The fuzzy logic controller consists of two rules (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000).

If e is small then u is u^{PI}

If e is large then u is u^{PD}

Where small and large are two fuzzy sets defined on the error domain e. Unlike Mamdani fuzzy rules, Takagi Sugeno rules use functions of input variables as the rule consequent. For fuzzy control, a consequent part of Takagi Sugeno rule is u=*f* (e), where *f* ( ) is a real function of any type. This fuzzy logic requires just two membership functions of small and large fuzzy sets of error as shown in figure 11.

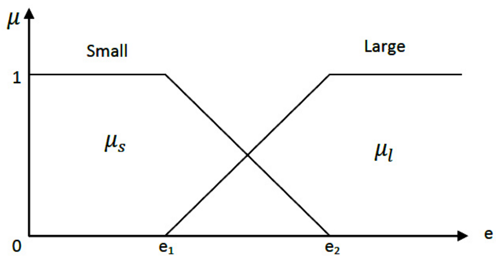


Figure 11. Two Fuzzy sets of error e

$$\mu_S(e) = \begin{cases} 1 & : \quad e \le e_1 \\ \dfrac{(e_2 - e)}{(e_2 - e_1)} & : \quad e_1 < e < e_2 \\ 0 & : \quad e \ge e_2 \end{cases} \tag{12}$$

$$\mu_L(e) = \begin{cases} 0 & : \quad e \le e_1 \\ \dfrac{(e - e_1)}{(e_2 - e_1)} & : \quad e_1 < e < e_2 \\ 1 & : \quad e \ge e_2 \end{cases} \tag{13}$$

Where $\mu_S(e)$ and $\mu_L(e)$ are the membership functions of small and large fuzzy sets of error respectively. The control signal of the PID controller can be obtained by using the centroid method of defuzzification and is expressed as (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000):

$$u = \frac{\mu_S \cdot U^{PI} + \mu_L \cdot U^{PD}}{\mu_S + \mu_L} \tag{14}$$

The PID controller parameters will be nonlinear functions in error e, and can be expressed as (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000):

$$K_p = \frac{\mu_S \cdot K_3 + \mu_L \cdot K_1}{\mu_S + \mu_L} \tag{15}$$

$$K_i = \frac{\mu_L \cdot K_4}{\mu_S + \mu_L} \tag{16}$$

$$K_d = \frac{\mu_S \cdot K_2}{\mu_S + \mu_L} \tag{17}$$

In this algorithm the PID controller parameters K_p, K_i, and K_d are automatically and continuously updated with the magnitude of the error to give a satisfactory response (B. A. Abouzalam et al. 2008), (A. S. Ibrahim 2000). Figure 12 shows the block diagram of PWM inverter system which is controlled by nonlinear PID-fuzzy logic control system using PIC-microcontroller. Simulation for PWM inverter system controlled by nonlinear PID-fuzzy logic controller on Matlab Simulink is shown in figure 13.

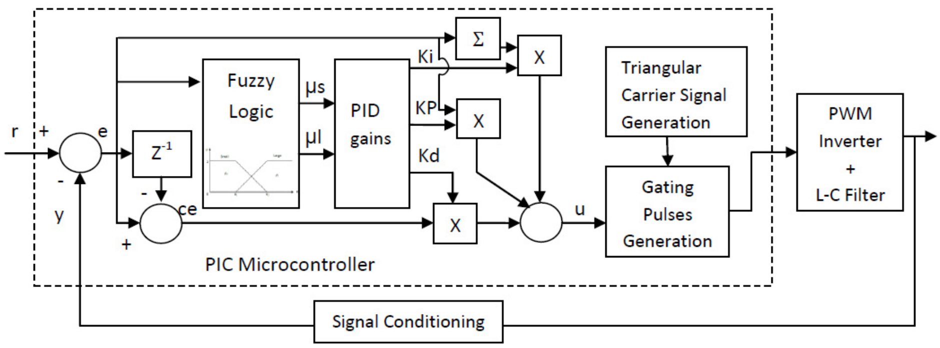


Figure 12. Nonlinear PID-fuzzy logic controller

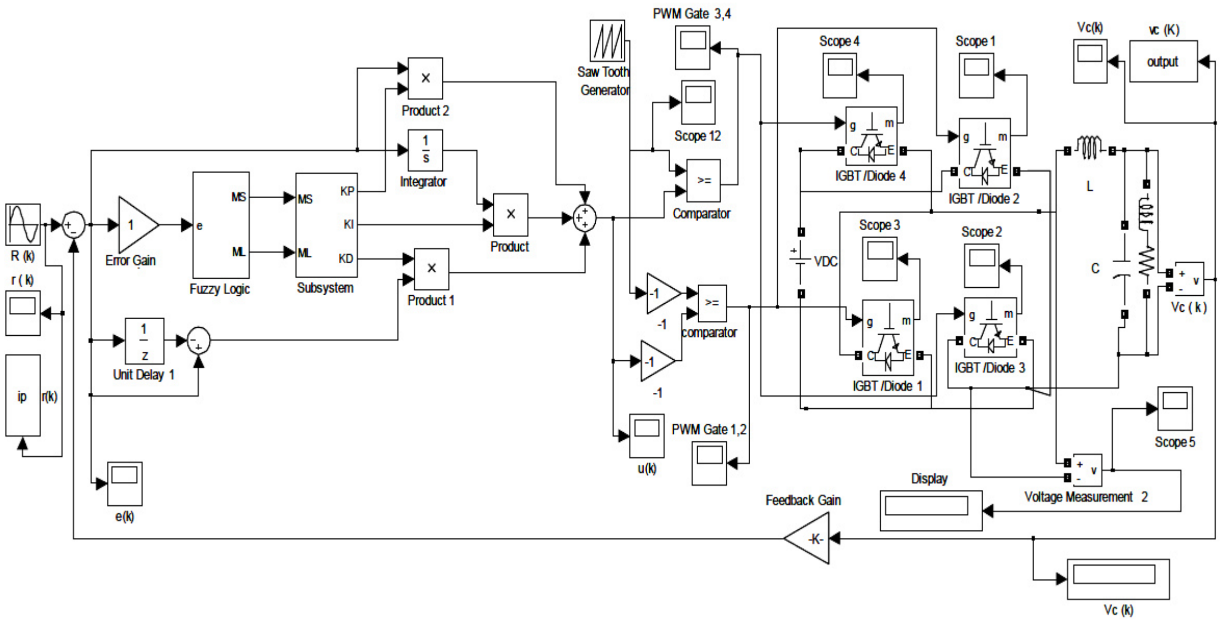


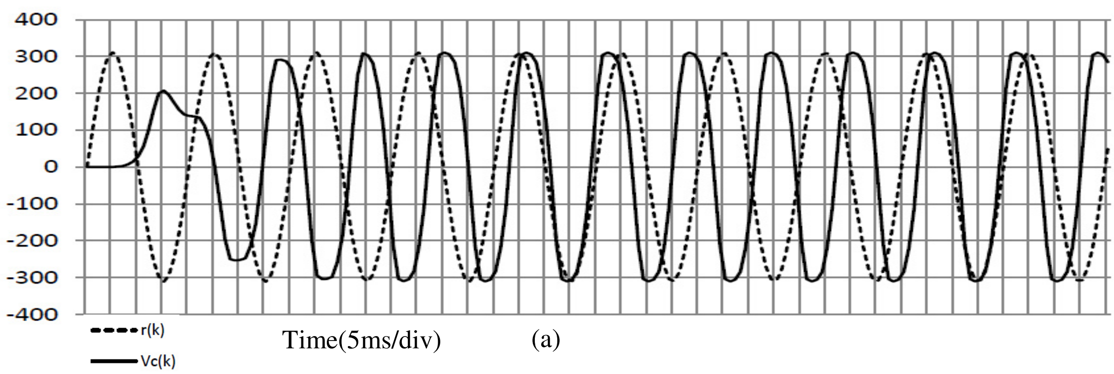
Figure 13. Nonlinear PID-Fuzzy Control of PWM Inverter

The controller gains are nonlinear functions of the normalized error e, and change of error ce. Program flow chart of nonlinear PID-fuzzy logic controller algorithm is as shown in figure 5. The fuzzy logic is used to obtain values of µs, and µl which are used in control equations to obtain the PID controller parameters. The nonlinear PID-fuzzy logic controller has the same linear structure as the conventional PID controllers.

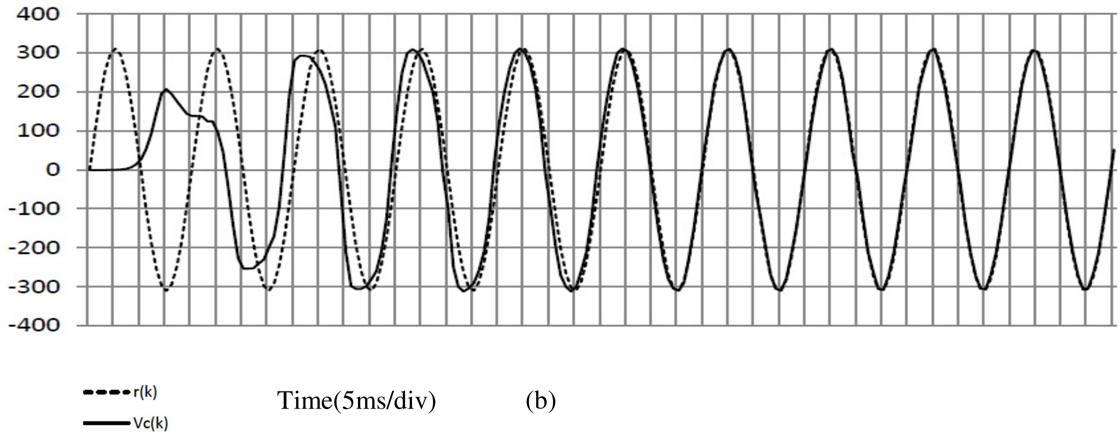
4. Simulation Results

Matlab Simulink is used to make the simulation of control algorithms to control a single phase PWM inverter. The simulation results of three different control algorithms which are PID controller, fuzzy logic controller, and nonlinear PID-fuzzy, are demonstrated respectively in figure 14 (a), (b), and (c). Each figure shows the waveform of output voltage. Where r(k) is the pure sinusoidal wave as reference, and Vc(k) is the filter output which is the variable to be controlled.

The PID controller parameters are Kp=0.5, Ki=0.5, Kd=1.0. The passive L-C filter parameters are L=203 mH, and C=50 µF. From the simulation result of PID controller it is obvious that PID controller has a frequency problem. Fuzzy logic and PID-fuzzy logic controllers provide pure sinusoidal wave 50 Hz in the steady state. It is clear that the nonlinear PID-fuzzy logic controller catches the reference signal faster than fuzzy logic controller. The load is a nonlinear load which is resistive inductive load 100 Ω, 50 mH.



(a)



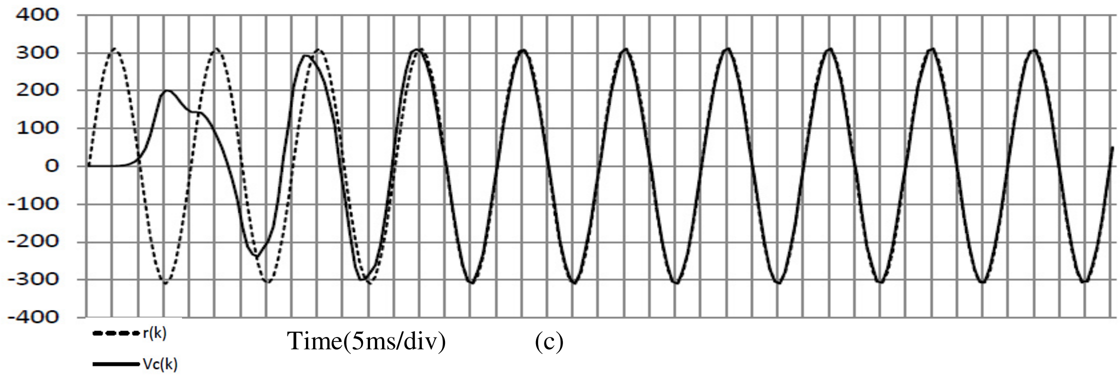
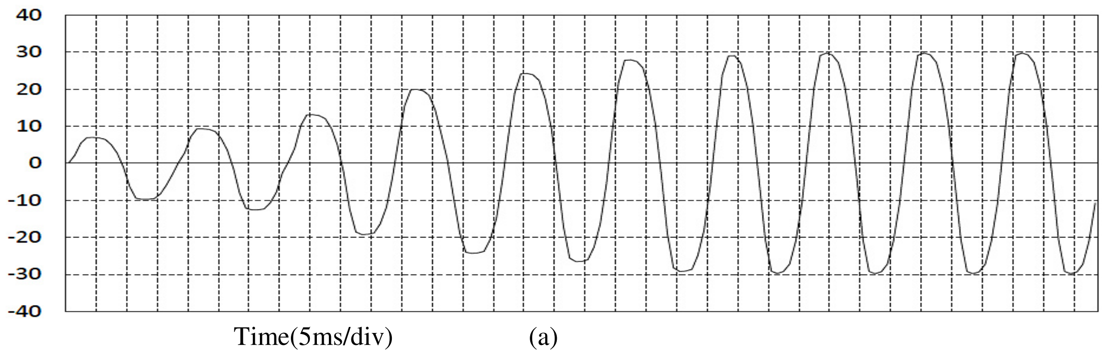
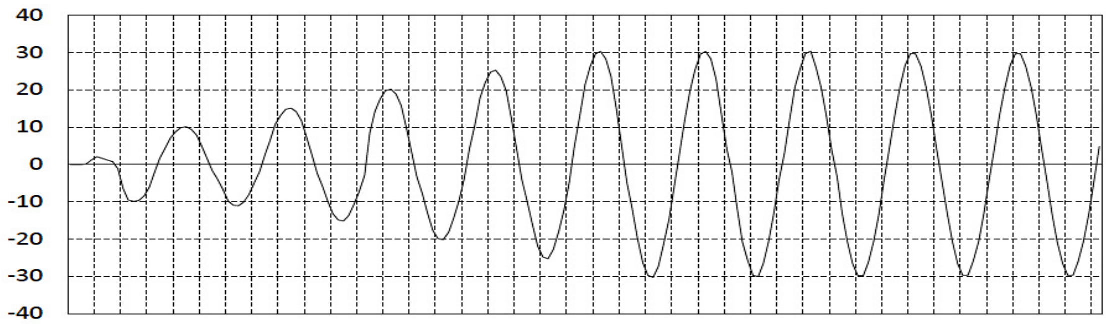


Figure 14. Simulation Results of; (a) PID controller, (b) FLC, (c) Nonlinear PID-Fuzzy

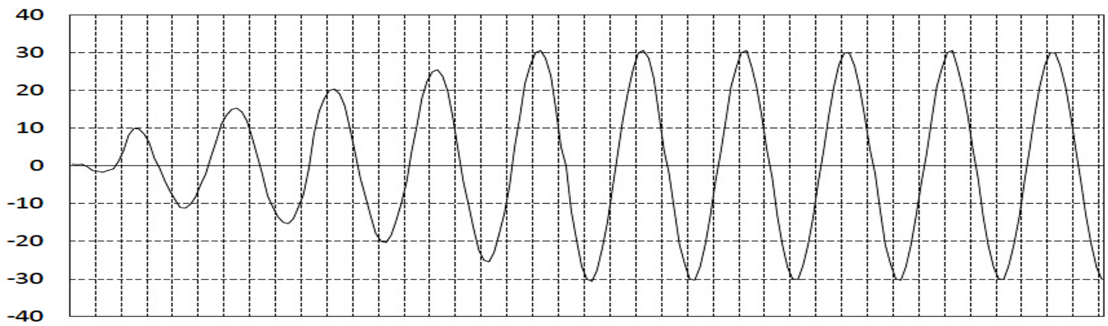
5. Experimental Results

Three controller systems for single phase inverter are designed and implemented to execute the required output of the UPS. A prototype of the uninterruptible power supply (UPS) which is controlled by PIC-microcontroller unit is implemented as shown in figure 1. The PWM inverter consists of four power transistors are working as switching devices, two of them are NPN power transistor TIP102, and the others are PNP power transistor TIP107. Inverter is supplied with battery 24 Vdc. The resonance frequency of the low bass L–C filter is 50 Hz, such filter is designed and implemented with the parameters L=203 mH, and C=50 μF. The control algorithm is implemented on PIC 18F452. The microcontroller unit is accessing 4-byte (32-bit) floating point, operating at 20 MHz, and it has 10-bit analog to digital converter. The control algorithm is implemented by using mikroC PRO (programming language for PIC-microcontroller) on personal computer and then downloaded to the microcontroller unit by using burner software through serial communication. The experimental results are illustrated in figure 15 with nonlinear load. Experimental results were sent back to the personal computer through serial communication for graphical representation.





Time(5ms/div) (b)

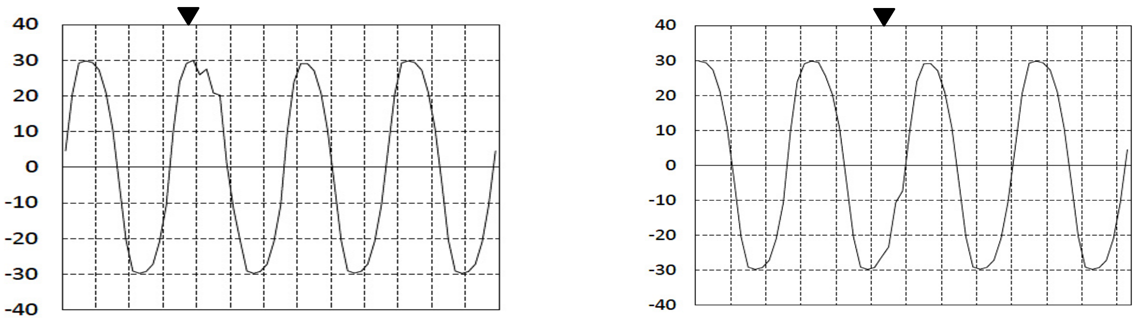


Time(5ms/div) (c)

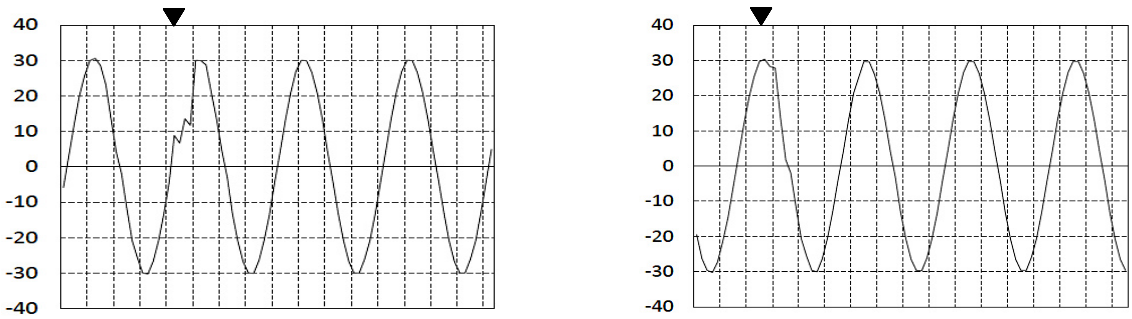
Figure 15. Experimental Output Voltage Results of; (a) PID controller, (b) FLC, (c) Nonlinear PID-Fuzzy

The experimental results for the case where the load is increased by +10% and decreased by -10% are shown in figure 16 (a) and (b) respectively. The robustness of the three control algorithms is demonstrated in the waveforms of the output voltage under +10% and -10% load variations and that the distortion of output voltage can be quickly restored. The experimental results show excellent tracking performance in the steady state operation.

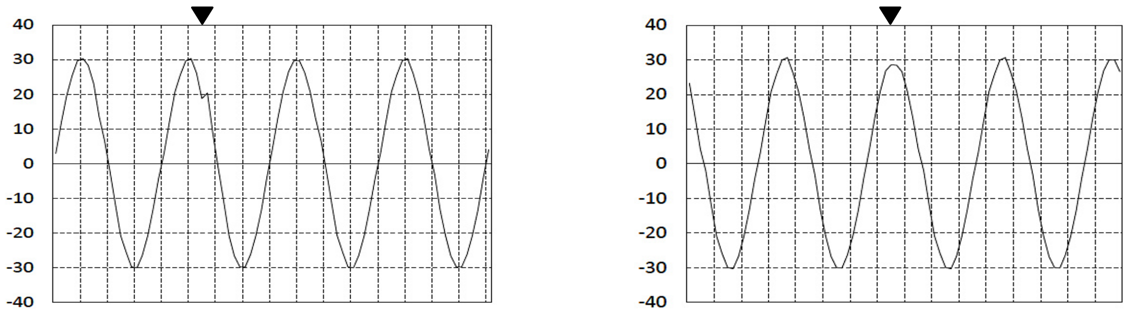
PID



FLC



Nonlinear PID-Fuzzy



(a) (b)

Figure 16. Experimental results of $V_c(k)$ with load variations: (a) +10% of load, (b) -10% of load.

6. Conclusion

In this paper, three methods of UPS control systems are presented. PID controller, fuzzy logic control system, and nonlinear PID-fuzzy logic controller have been performed to control a single phase UPS inverter system. These control systems are simulated on Matlab Simulink. A single phase PWM inverter is constructed, where the control algorithm programs are implemented and the control program is loaded on a PIC-microcontroller unit. The programs of control algorithms are implemented on PIC-microcontroller PIC18F452. Both simulation and experimental results have demonstrated the effectiveness and the robustness of output voltage especially that which belongs to the output of the nonlinear PID-fuzzy logic controller. Such controller is adjusting automatically and continuously PID controller parameters which give the best performance.

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