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Designing a power inverter and comparing back-stepping, sliding-mode and fuzzy controllers for a single-phase inverter in an emergency power supply

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ABSTRACT

In recent years, there has been a high demand for high-power inverters. Unlike a rectifier, an inverter with a high-power electronic oscillator is able to convert direct current (DC) into alternating current (AC) in different forms. Regarding this point, the current paper presents an analysis and design of fuzzy logic control (FLC) applied to an inverter of a single-phase voltage source using LC filter and voltage sensor. Also, three modes of inverter voltage non-linear control (back-stepping, sliding and fuzzy modes) have been simulated and compared. The results of simulation indicated that the suggested FLC could attenuate and reduce total harmonic distortion (THD) under linear loading conditions.

Keywords: *THD, fuzzy logic, sliding mode, back-stepping, inverter*

1 INTRODUCTION

A DC to AC inverter is an electrical device which is designed for producing AC power at a desirable current, frequency or voltage. In some applications where DC voltage is low (e.g., in batteries, solar panels or fuel cells), inverters are used to convert DC into AC in devices with the ability to turn off AC power. One example of such use is conversion of electrical energy from a car battery to run a lap top, TV or cell phone. Most inverters act in two ways:

1. Converting DC input into AC input for reaching the main voltage via transformer and

2. Converting low voltage DC into high voltage DC and then DC wave into AC wave through Paul's H driver method.

Voltage and supply current relationships at inverter circuit outputs are taken into account. In a voltage source inverter (VSI), DC input voltage remains steadily constant and is independent of the increased consumption of load current. An inverter determines load voltage in case the load specifies the increased current. In a current source inverter (CSI), the output current is a constant value with a DC current input and load impedance determines the output voltage. Inverters come in a variety of types with different outputs: square wave, modified sinusoidal wave and pure/true sinusoidal wave (see fig.1) and square output wave with high harmonics [13].

AC loads like motors and transformers are not efficient. The unit square wave is known to be a pioneer of inverter development. A modified square wave or modified sinusoidal waveform is an inverter similar to an output square waveform but different in that the output gets close to zero volt for a period of time prior to negative or positive change. It is characterized by simplicity, inexpensiveness and compatibility with most electronic appliances. A pure sine wave inverter approximately generates an output sinusoidal waveform (harmonics less than 5%).

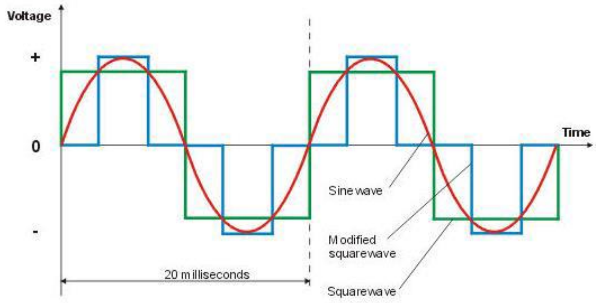

Fig.1. square output of the inverter

Most inverters have classical Proportional-Integral (PI) controllers, which do not suit all applications because the output signal is not in pure sinusoidal waveform. Harmonic distortion wave in/at loads causes a high power loss.

Fuzzy logic controllers (FLCs) are now being far more popular than the conventional ones. They can work on uncertain inputs in a more robust and non-linear manner; in fact, the commonly applied power inverters have a high THD, thereby being low in quality. For this reason, this paper aimed at evaluating an inverter yield at an output waveform using fuzzy logic control, which is a new method applied to controllers to minimize the output distortion so as to keep it at an acceptable level. The designed inverter output should be in pure sinusoidal form.

2 Converter Modeling

Depiction of a single-phase PWM Converter associated with a LC filter

The single-phase PWM converter for a load (fig.1) consists of two arms with bi-directional switches (insulated-gate bipolar transistor (IGBT) or metal–oxide–semiconductor field-effect transistor (MOSFET) with an anti-parallel diode) and plays a complementary role. The μ control signal, which is produced by a PWM generator, obtains values in a finite set of {1-, 1} *and summarizes* $\mu 1$ *and* $\mu 2$ *binary* orders from the two switching cells in μ = μ1 - μ2.

$$\begin{cases} 1: \mu 1 = 1 \text{ and } \mu 2 = 0 \rightarrow (K1, K'2) ON \text{ and } (K2, K'1) OFF \\ -1: \mu 1 = 0 \text{ and } \mu 2 = 1 \rightarrow (K2, K'1) ON \text{ and } (K1, K'2) OFF \end{cases}$$

Mathematical modeling of the inverter using LC filter

Math equations can be written via node/cycle rules:

$$L\frac{diL}{dt} = v_{AB} - v_S \quad (1)$$

$$C\frac{\mathrm{dvS}}{dt} = i_L - i_S \quad (2)$$

The output voltage from vAB converter can have two values depending on the switching mode; thus, it has the μ control signal.

$$v_{AB} = \begin{cases} E \; when \; only \; (K1, K'2) \; are \; ON \; ie \; \mu = 1 \\ -E \; when \; only \; (K2, K'1) \; are \; ON \; ie \; \mu = -1 \end{cases}$$

therefore, resulting in:

$$v_{AB} = \mu E \quad (3)$$

This switching model is a system with a variable structure: vAB is not a continuous variable; it can have two discontinuous values of E and –E. Consequently, it does not suit an uninterrupted control law design. To solve this problem, the average model has usually been applied (extensively for modeling of stable converters). The proposition (which is verified for the most part in this case) is that the switching period is far shorter, as compared to the system's dynamics. As a result, the formulation is as follows:

$$C\,\dot{x}_1 = x_2 - i_S \quad (4)$$

$$L\,\dot{x}_2 = u_E - x_1 \quad (5)$$

where $\boldsymbol{x1}$ and $\boldsymbol{x2}$ represent the medium values in a period of sampling taken from Vs output voltage of the two ends of C capacitor and iL denotes the current in L inductor. The values for the control variable stand between 1 and -1, indicative of the medium value of the μ control signal, which is formed by the modulated square-shaped pulse width.

3 Design of the Controller

This is a multi-purpose research: design of three controllers to allow the converter to provide a sinusoidal voltage with a completely fixed frequency and amplitude irrespective of load. The output signal must be a *function of a reference signal* $x1(t) = V\sqrt{2}\sin(\omega t)$

where V= 230V and *f*= 50HZ (ω = 2πf), denoting RMS value and frequency of the reference sinusoidal wave signal, respectively.

Designing the back-stepping controller In control theory, back-stepping is a technique developed by P.V. Kokotovic et al., about 1990 for designing stability controls in certain non-linear dynamic systems, which are composed of subsystems radiated out from irreducible subsystems that can be stabilized by applying other methods. With respect to this recursive structure, the designer can take up the design process at the known stable system and "back out" new controllers which stabilize each outer subsystem. This process ends after taking several steps and attaining final external control, thereby being known as back-stepping [9] [10].

Step 1:

Z1 error is defined as follows:

$$z_1 = C\,(x_1 - x_1^*) \quad (6)$$

Its dynamic is obtained via the following relationships:

$$\dot{z}_1 = C\,(\dot{}_1 - \dot{x}_1^*) \quad (7)$$

$$\dot{z}_1 = x_2 - i_S - C\dot{x}_1^* \quad (8)$$

Given the Lyapunov function as bellow,

$$V_1 = \frac{1}{2} z_1^2 \quad (9)$$

its derivative with respect to time will be

$$V'_1 = \dot{z}_1 z_1 \quad (10)$$

And choosing:

$$\dot{z}_1 = -k_1\, z_1 \quad \rightarrow \quad z_1(t) = z_1(0)e^{-k_1 t}$$

Where k1 is a positive constant value and leads to a Lyapunov function with a negatively defined dynamic; this formulation is made:

$$V'_1 = -k_1\, z_1^2 \quad (11)$$

Thus, the asymptotic stability is obtained and Z1 is driven to zero in an ascending manner. In the system (7), x2 is similar to a virtual control input. As a consequence, Z1 can be stabilized at zero if

Then, from (8) and (10), these formulas are obtained

$$x_2^* = -k_1\, z_1 + i_S + C\dot{x}_1^* \quad (12)$$

Where x2* is deemed as a constant function. A new error variable is obtained between virtual drive and its desirable value

$$z_2 = x_2 - x_2^* \quad (13)$$

From the equations (7), (12) and (13), it can be concluded that

$$\dot{z}_1 = -k_1 z_1 + z_2 \quad (14)$$

Step 2:

The derivative of Z2, which is computed with respect to change to time, is given by:

$$\dot{z}_2 = \dot{x}_2 - \dot{x}_2^* \quad (15)$$

$$\dot{z}_2 = \frac{1}{L}(uE - x_1) - \dot{x}_2^* \quad (16)$$

Considering a real time control system, the problem regarding the stabilization of the already explained system in equations (14) and (16) can be understood by means of the Lyapunov function below:

$$V_2 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 \quad (17)$$

$$V'_2 = \dot{z}_1 z_1 + \dot{z}_2 z_2 \quad (18)$$

$$V'_2 = -k_1 z_1^2 + z_2(z_1 + \dot{z}_2) \quad (19)$$

The following equations are applied:

$$(z_1 + \dot{z}_2) = -k_2 z_2 \quad (20)$$

$$V'_2 = -k_1 z_1^2 - k_2 z_2^2 < 0 \quad (21)$$

Thus the equations (16) and (20) pave the way for developing a back-stepping control regulator:

$$\boldsymbol{u} = -\frac{L}{E}\left(\boldsymbol{z_1} + \boldsymbol{k_2 z_2} - \frac{x1}{L} - \dot{\boldsymbol{x}}_2^*\right)$$

The system (Z1, Z2) will reach total asymptotic stability if a control law ($V'2 < 0$) is implemented.

Designing a sliding mode controller

In control theory, motion-state (sliding mode) control is a nonlinear control method that changes the dynamics of a nonlinear method via a discontinuous control signal, which makes the system "move and slide" along a cross-section of the system's natural behavior. The feedback-state control law is not a continuous function of time. Instead, it can switch from one continuous structure to another depending on the position of current in the state-space. As a result, the motion-state control is a variable structure control method. Multiple-control structures are designed so as to always direct the trajectory towards an adjacent area, which has a different control structure; thus no final trajectory would completely exist within a control structure. Instead, it will move along the boundaries of control structures. The sliding motion of the system along the boundaries is called a sliding mode and the geometrical locus composed of these boundaries is called the sliding surface [11] [12].

Sliding mode controllers are applied (as an example) for controlling electrical drives which are operated by replacing power converters. A variety of studies have been directed towards this subject.

The purpose of control is always the same: the designed controller must always allow the UPS converter to provide the system with sinusoidal voltage with a completely constant frequency and amplitude irrespective of load. The output voltage must be a function of the reference signal

$$x1*(t) = V\sqrt{2}\sin(\omega t)$$

$$z = C(x_1 - x_1^*) \quad (23)$$

$$\dot{z} = C(\dot{x}_1 - \dot{x}_1^*) \quad (24)$$

$$\dot{z} = x_2 - i_S - C\dot{x}_1^* \quad (25)$$

$$\dot{z} = \frac{1}{L}(uE - x_1) - \frac{diS}{dt} - C\dot{x}_1^* \quad (26)$$

$$S(x) = k\,z + \frac{dz}{dt} \quad (27)$$

$$S'(x) = k\frac{dz}{dt} + \frac{d2z}{dt2} \quad (28)$$

$$S'(x) = k(x_2 - i_S - C\dot{x}_1^*) + \frac{1}{L}(uE - x_1) - \frac{diS}{dt} - C\dot{x}_1^* \quad (29)$$

$$V_1 = \frac{1}{2} S_2 \quad and \quad V_1 = S'\,S$$

$$S' = -\beta(S) \quad \rightarrow \quad V_1 = -\beta|S| < 0 \quad (30)$$

$$u = x_1\,E + \frac{L}{E}\left(-\beta(S) - k(x_2 - i_S - C\dot{x}_1^*)\right) + LE\left(\frac{diS}{dt} + C\dot{x}_1^*\right) \quad (31)$$

Designing the fuzzy logic controller

Fuzzy logic (FL) is a direct, intuitive control system methodology with no *dependence* on mathematical modeling. It receives specific data from different sensors and converts them into functions with fuzzy identities via fuzzification process, during which the data are processed and sorted drawing on a fuzzy (If-Then) rule set in an inference motor. To arrive at a definite conclusion, the fuzzy output is assigned a crisp value through defuzzification process. Fuzzy controller is implemented via fuzzy logic toolbox for the inverter system. This toolbox allows the production of input membership functions, fuzzy control law and output membership functions [14].

To implement the fuzzy controller, the system must have two inputs and one output (as shown in Fig.2) as well as a triangular membership function (Fig. 3).

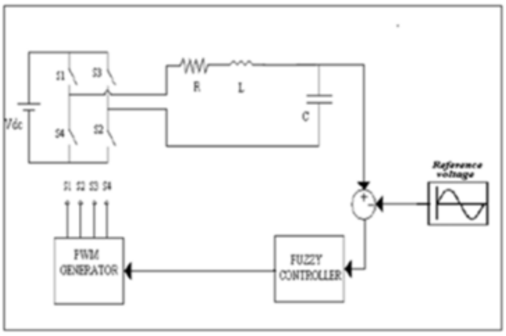

Fig.2. Schematic of a single-phase inverter with a fuzzy controller

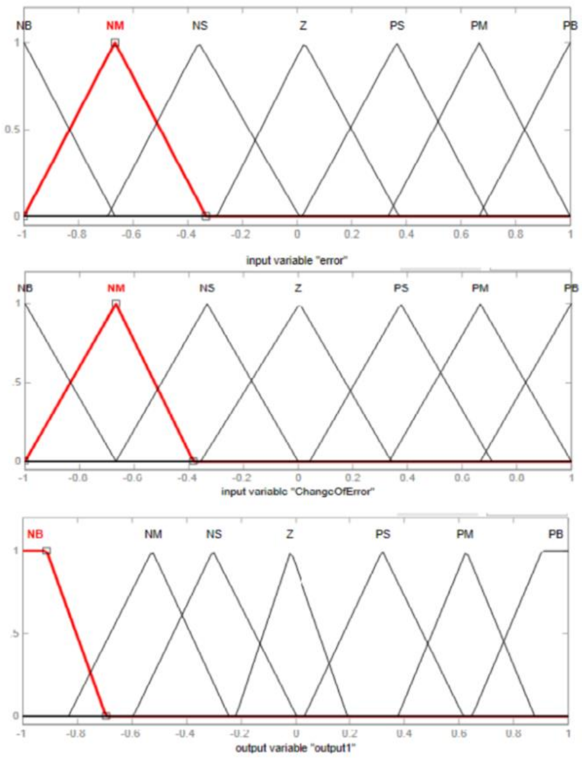

Fig.3. Fuzzy membership functions for the inputs and output

where PB stands for positive big, PM for positive medium, PS for positive small, Z for zero and NB for negative big,

[1] The Input is shown as error (e) and change in error as Δe

[2]

[3]

[4]

[5]

[6]

[7]

The membership function A7*7 has 49 member functions; the rules are depicted in table 1:

Table 1: fuzzy membership function rules

CE \ E	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

4 Simulation results

In this section, simulation of MATLAB software is implemented for the proposed systems and studies on non-linear back-stepping, sliding and fuzzy mode controllers are analytically compared with regard to the impact of harmonic distortion on voltage and load current.

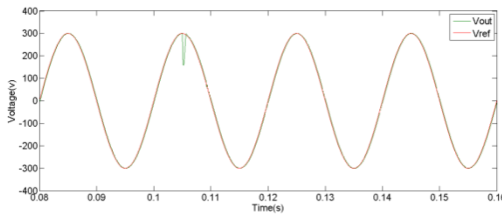

Fig.4. Results from the simulation of the inverter using the backstepping controller

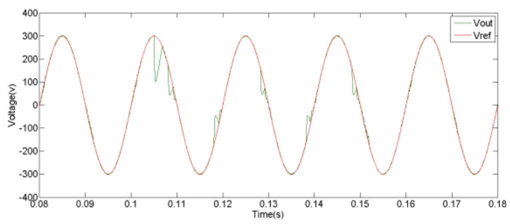

Fig.5. Results from the simulation of the inverter using the sliding mode controller

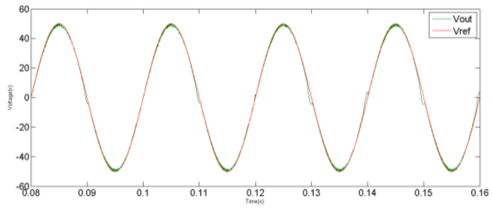

Fig.6. Results from the simulation of the inverter using the fuzzy mode controller

5 Conclusion

The current paper examined a stable converter control in a DC-AC power supply. Two aims were pursued:

*1.*Designing FLC using three different methods. The control law, which stabilizes the system, provided a good tracking of the output voltage (its reaching a desirable value) of a sinusoidal reference variable and ensured good adjustments in the presence of a robust variety of loads.

2. Generating an analytical comparison of the performance and yield of the three controllers:

back-stepping and sliding and fuzzy modes.

According to the simulation results, all the three designed controllers provide a good *robust tracking* of the output voltage but it is the first controller (back-stepping) which has the best performance. The sliding mode controller is robust but hardly gives any well-defined orders. Fuzzy controller has a better response time as compared to the two others but it is deficient in that when there is a change in the loads or in the reference source, the existent current in the inductor is not controllable. However, it is to note that the synthesis of a good-yielding back-stepping controller is much more complicated than a fuzzy one. In this research, this synthesis was done at different stages with regard to the given control system. The ki constants were selected in an approximate way after many tests were conducted.

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