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CONTROL OF UPS INVERTER USING CURRENT MODE FUZZY GAIN SCHEDULING OF PI CONTROLLER

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ABSTRACT
This paper presents Control of UPS inverter Using Fuzzy Gain Scheduling of PI Controller. This control scheme has Double Loop Current Mode Control Scheme in core. This scheme includes two control loops as inner and outer control loops. Inner control loop uses inductor current of inverter filter as feedback while outer control loop uses inverter output voltage as feedback. Fuzzy Logic Controller (FLC) is used to adjust the voltage loop PI controller parameters. The voltage error, *e* and its derivative, *de* are used as input variables of the FLC. In this study, Double Loop Current Mode Control and Fuzzy Gain Scheduling of PI Controller are simulated digitally using PSIM and C++ under linear, rectifier type nonlinear and fluorescent loads. And the results show that Fuzzy Gain Scheduling of PI Controller can provide low THD and better regulation quality especially under rectifier type nonlinear and fluorescent loads.

KEY WORDS
UPS inverter, fuzzy logic controller, power system control

1. Introduction

Uninterruptible Power Supplies (UPS) are used to produce clean and uninterrupted power to the critical loads such as medical/life support systems, computer systems, communication systems, etc. A typical UPS system consists of a battery (dc source), a dc-ac inverter, and an LC filter. The role of the inverter for UPS is to regulate the output voltage waveform with constant voltage and constant frequency although the variations of the line source or loads. The quality of UPS can be evaluated by THD value of output voltage and characteristic of transient response.

UPS power quality depends on the choice of PWM inverter control methods. Traditional analogue control methods are generally used in PWM inverter design. However there are a number of disadvantages in an analogue system, for example, temperature drifts and aging effect of the components, more component numbers for the system, necessity for making adjustment to many physical parts, and sensibility to Electro Magnetic Interference (EMI). When an analogue circuit is affected by temperature drift or EMI noise, it could cause a number of problems such as dc offset in output voltage, change of output switching frequency, increase of output voltage harmonics and so on [1]. Therefore, to be able to avoid all these disadvantages the digital double loop control scheme is used in this study.

In this study, An FLC is added to the double loop current mode control scheme to adjust the voltage loop PI controller parameters. This control scheme is simulated digitally using PSIM and C++. The input variables of the FLC are voltage error and its derivative. The output of the FLC is the voltage loop PI controller parameters.

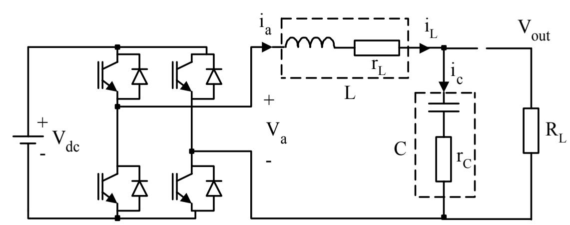


Fig 1. Circuit diagram of basic inverter circuit with an LC filter and R_L.

Basic inverter circuit with an LC filter and load, R_L is given in Fig..1. In this Figure, the full bridge inverter, LC filter, and load are considered as the plant to be controlled. r_C is the equivalent series resistor (ESR) of the capacitor, while r_L is the ESR of the inductor. Single phase PWM inverter modulates a DC bus voltage V_{dc} into a cycle by cycle average output voltage V_a. The amplitude of V_a is directly proportional to the commanded duty cycle of the inverter and the amplitude of the dc bus voltage V_{dc}. Therefore, the range of V_a changes between $+V_{dc}$ and $-V_{dc}$ [2].

2. Double Loop Current Mode Control Scheme

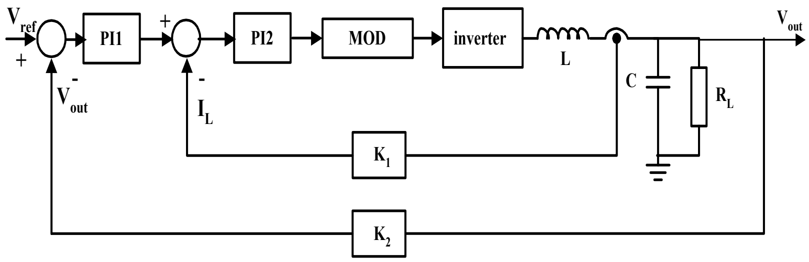


Fig 2. Block diagram of Double Loop Current Mode Control Scheme.

The block diagram of the Double Loop Current Mode Control Scheme is shown in Fig. 2. This control scheme includes two control loops as inner current and outer voltage loops. In this scheme, voltage error which is the difference between the reference sine wave and the output voltage is fed to the PI voltage regulator PI1. The output signal of this regulator which is the reference signal of the inner current control loop is compared with the inductor current. The difference is fed to the PI current regulator PI2. In MOD (PWM modulator) block, the output of this regulator is compared with a triangular wave (20 KHz) to generate PWM signals. And these PWM signals determine the duty cycles of the switches in the inverter.

3. Current Mode Fuzzy Gain Scheduling of PI Controller

Most industrial process control continues to rely upon 'classical', or 'conventional' proportional, integral, derivative (PID) control. Gain scheduling is the most common PID advancement used in industry to overcome nonlinear process characteristics through the tailoring of controller gains over local operating bands [3]. When the controlled process is nonlinear, a fixed gain PID controller cannot usually give satisfactory control performance at some operating points, since the controller parameters must be adjusted following a change in operating conditions. Therefore, one way to improve the control performance of a PID controller on highly nonlinear process is to vary the controller parameters according to the process operating conditions. This is known as gain scheduling control [4].

Deadbeat-controlled PWM inverter has very fast response for load disturbances and nonlinear loads. But in deadbeat control approach, the control signal depends on a precise PWM inverter load model and the performance of the system is sensitive to parameter and load variations. Repetitive control generates high-quality sinusoidal output voltage whereas its dynamic response is very slow [5].

Current Mode Fuzzy Gain Scheduling of PI Controller presented in this paper is shown in Fig. 3. It has Double Loop Current Mode Control Scheme in core and includes two control loops as inner current and outer voltage loops. The filter inductor current and output voltage are sensed as feedback. In this scheme, note that the output inductor is hidden within the inner current control loop. This simplifies the design of the outer voltage control loop and improves UPS performance in many ways, including better dynamics and a feedforward characteristic which could be used to compensate DC bus ripple and dead time effect, etc. The objective of this inner loop is to control the state-space averaged inductor current. The current mode control requires a circuit for measurement of inductor current i_L, however, in practice such a circuit is also required in voltage mode control systems, for protection of the IGBT against excessive currents during transients and fault conditions [1]. In this control scheme, PI parameters of the voltage control loop are adjusted by FLC.

In this study, the advantages of FLC and Double Loop Current Mode Control are combined in the same control scheme. The FLC can handle nonlinearity and does not need accurate mathematical model. It is represented by if-then rules and thus can provide an understandable knowledge representation. FLC converts linguistic control strategy to an automatic control strategy. Linguistic control strategy is based on expert knowledge and experience [5].

Inverter output voltage error and change of this error are input variables of the FLC. The input variables, voltage error, $e(k)$ and its derivative, $de(k)$ are calculated using the equations (1) and (2). Two rule tables are composed for the gain K_p and K_i. FLC is used to adjust the PI parameters of voltage control loop.

$$e(k) = V_{ref}(k)-V_{out}(k) \qquad (1)$$
$$de(k) = [e(k)-e(k-1)]/T \qquad (2)$$

In equation (1) and (2),

$V_{ref}(k)$: reference sine wave,
$V_{out}(k)$: inverter output voltage,
T : sample time (100µs).

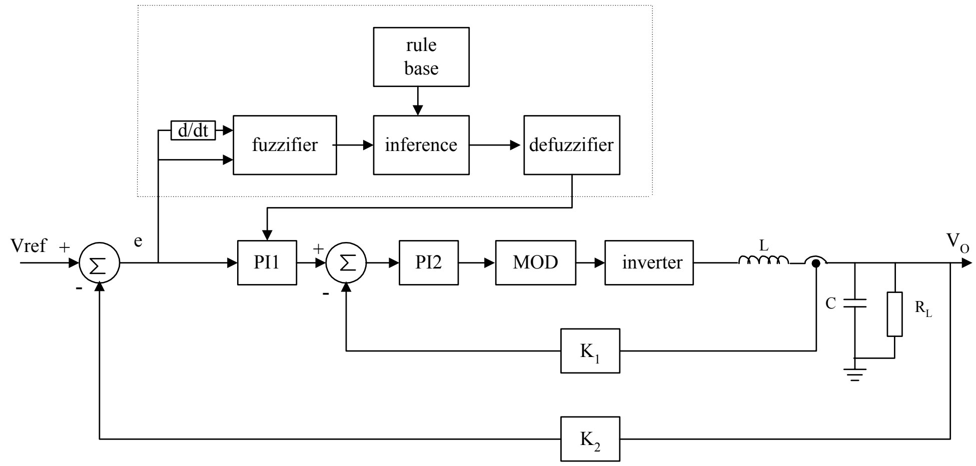


Fig 3. Block diagram of Current Mode Fuzzy Gain Scheduling of PI Controller.

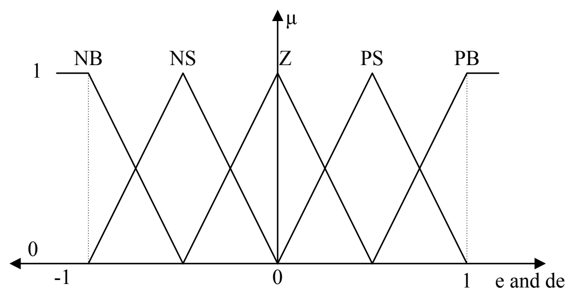


Fig 4. Membership function of fuzzy input variables, *e* and *de*.

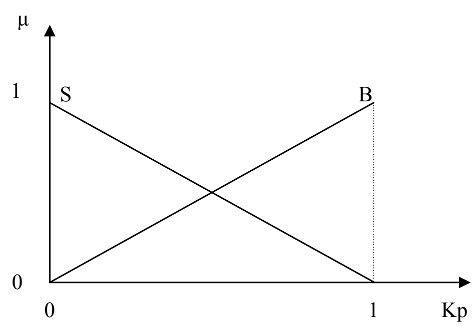


Fig 5(a). Membership function of fuzzy output variable, K_P.

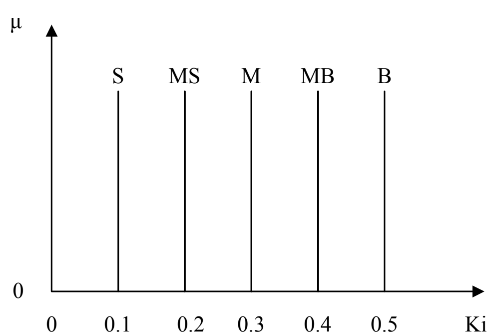


Fig 5(b). Membership function of fuzzy output variable, K_i.

A typical fuzzy process can be divided into three steps: the fuzzification, the inference and the defuzzification. The task of the fuzzification is to to transform the nonfuzzy measurements of the input variables into the fuzzy linguistic range [6]. In this study, universe of discourse of two inputs (*e* and *de*) and one of the outputs (K_i) are divided into five fuzzy subsets while universe of discourse of the output K_p is divided into two fuzzy subsets (Small, S and Big, B). The fuzzy subsets of *e* and *de* are Negative Big, NB, Negative Small, NS, Zero, Z, Positive Small, PS and Positive Big, PB. And, fuzzy subsets of the output, K_i are Small, S, Medium Small, MS, Medium, M, Medium Big and Big, B. The fuzzy subsets and the shape of membership function of FLC input and output variables are seen in Fig. 4, Fig. 5(a) and (b). The membership functions of input variables are trapezoidal and classical triangular shapes with 50% overlap. The value of each input is normalized in [-1,1] while the value of the output, K_p is normalized in [0,1] and the other output, K_i is normalized in [0,0.5] by using suitable scaling factors.

The next step of fuzzy process is the inference mechanism. As fuzzy control rely on knowledge or experience, process behavior is analyzed to establish a set of rules with IF…AND…THEN statements. A typical rule example is:

IF the voltage error (*e*) is **N**egative **B**ig (NB)
AND change of voltage error (*de*) is **P**ositive **S**mall (PS)
THEN the voltage loop proportional (K_P) is **B**ig (B)

These rules define a fuzzy relationship between the observed values of the voltage error, change of voltage error and the outputs, K_p and K_i. Fuzzy control rules are obtained from the behavior of the system and operator's expertise. The rule tables generated are shown in Table 1(a) and (b). MAX-MIN method is used as the inference method. The output membership function of each rule is given by MIN operator while the combined fuzzy output is given by MAX operator.

Table 1(a). Rule table for K_p.

change of voltage error (de)

voltage error (e)		NB	NS	Z	PS	PB
	NB	B	B	B	B	B
	NS	B	S	B	S	S
	Z	S	S	B	S	S
	PS	S	S	B	B	B
	PB	B	B	B	B	B

Table 1(b). Rule table for K_i.

change of voltage error (de)

voltage error (e)		NB	NS	Z	PS	PB
	NB	B	B	B	B	B
	NS	S	S	MS	B	MS
	Z	M	M	M	M	M
	PS	MS	B	MB	MB	B
	PB	B	B	B	B	B

The last step is defuzzification process. In defuzzification process, the input for the defuzzification is the fuzzy set (the aggregate output fuzzy set) and the output is a crisp number. Centroidal defuzzification method (center of gravity method (COG)) is used for defuzzification in this paper. Output denormalization converts the normalized value of the control output variable into physical domain. The equation for the COG method is given in equation (3).

$$U_o = \frac{\sum_{j=1}^{n} U(U_j)U_j}{\sum_{i=1}^{n} U(U_j)} \tag{3}$$

In equation (3), U_o is determined by means of a gravity center of the area under the membership function curve of the fuzzy output and $U(U_j)$ is a membership grade of Uj [7].

4. Simulation Results

Current Mode Fuzzy Gain Scheduling of PI Controller explained above is simulated using PSIM and C++. Simulations are realized under resistive, rectifier type nonlinear and fluorescent loads. System parameters used in simulations are listed in Table 2. Rectifier type nonlinear load is used as nonlinear load and this load is shown in Fig. 6. In this figure, L is taken as 770μH.

Table 2. System parameters used in simulations.

V_O (output voltage)	50Hz, 220 V_{RMS}
V_{DC} (DC bus voltage)	360 V
f_S (sampling frequency)	20 kHz
L (filter inductor)	700 μH
C (filter capacitor)	30 μF
r_L (ESR of the inductor)	0.05 Ω
r_C (ESR of the cap.)	0.02 Ω
Resistive load	10 Ω, (5 kVA100%)
Nonlinear load (rectifier type)	5 kVA (100%)
Fluorescent load	2.6 kVA (50%)

In this study, the sampling frequency of the current control loop is taken as 20 kHz while the sampling frequency of voltage control loop is taken as 10 kHz. Simulation results of Double Loop Current Mode Control Scheme and Current Mode Fuzzy Gain Scheduling of PI Controller for different kinds of loads are shown between Fig 7(a) and Fig 7(f). In simulations, linear load is applied to the inverter with a firing angle of 108°.

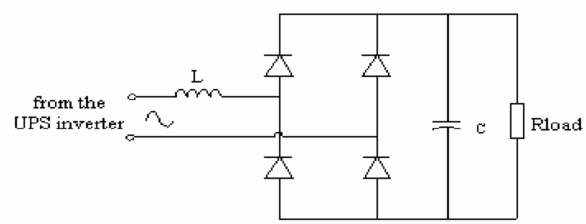


Fig. 6. Rectifier load with R_{load}-C.

Table 3. THD values measured in simulations.

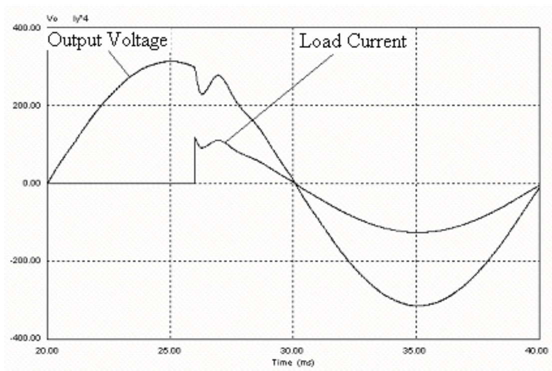
	Linear Load (100%)		Rectifier type Nonlinear Load (100%)		Fluorescent Load (50%)	
	D.L.C.M.C.S.	C.M.F.G.S.PI C.	D.L.C. M.C.S.	C.M.F. G.S.PI C.	D.L.C. M.C.S.	C.M.F. G.S.PI C.
THD (%)	0.42	0.45	5.39	0.95	0.41	0.38

In Table 3, THD values measured in simulations for different kinds of loads are given. In this Table,

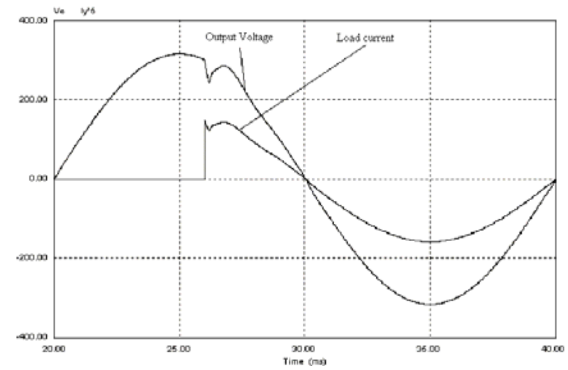
D.L.C.M.C.S. : Double Loop Current Mode Control Scheme
C.M.F.G.S.PI C. : Current Mode Fuzzy Gain Scheduling of PI Controller.

5. Conclusion

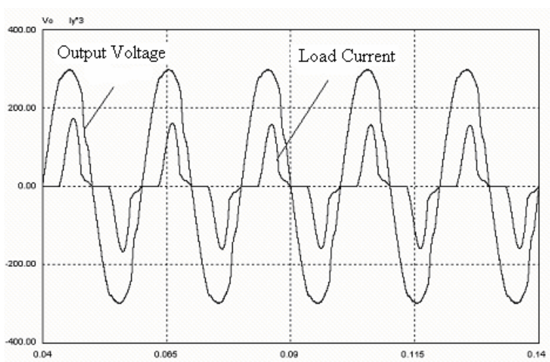
In this paper, Current Mode Fuzzy Gain Scheduling of PI Controller is presented. This control scheme includes Double Loop Current Mode Control Scheme in core and PI parameters of voltage control loop are adjusted using Fuzzy Logic Controller. These two control schemes are simulated under linear, rectifier type nonlinear and fluorescent loads using PSIM and C++. The output voltage error and its derivative are used as input variables of the FLC. And K_p and K_i are the output variables of the FLC. As it is seen in Table 3, measured THD values of Current Mode Fuzzy Gain Scheduling of PI Controller are lower than the THD values of Double Loop Current Mode Control Scheme except the linear load. But, Current Mode Fuzzy Gain Scheduling of PI Controller is clearly better under rectifier type nonlinear load. This difference can be seen in Fig. 7 c) and d). In conclusion, these results prove that Current Mode Fuzzy Gain Scheduling of PI Controller could enable low THD values, good voltage regulation and faster dynamic response to rectifier type nonlinear load.



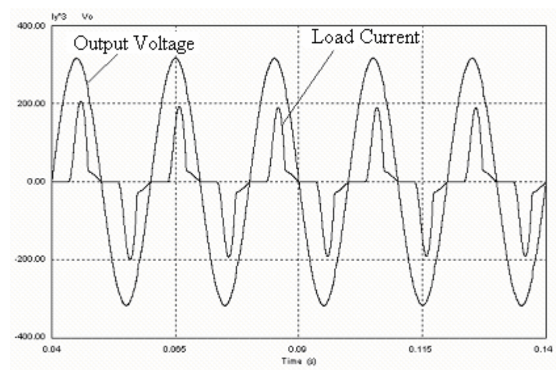
a). D.L.C.M.C.S Simulation result under linear load.



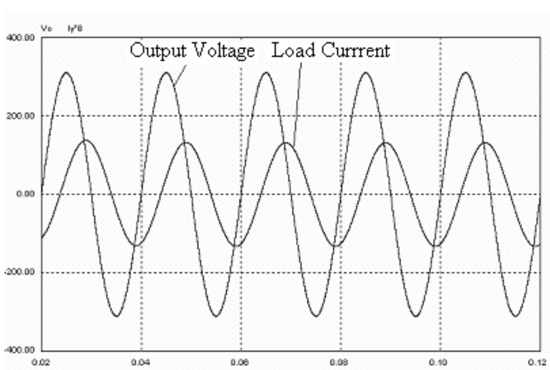
b). C.M.F.G.S.PI C. Simulation result under linear load.



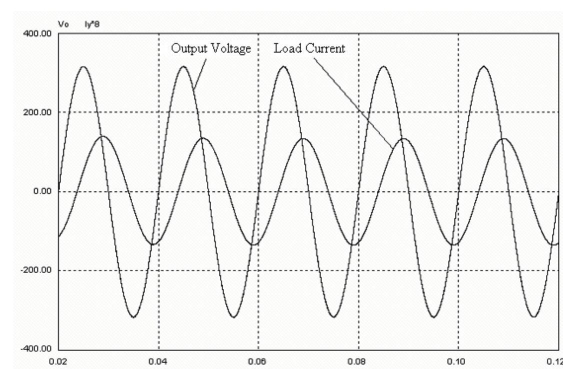
c). D.L.C.M.C.S Simulation result under nonlinear load.



d). C.M.F.G.S.PI C. Simulation result under nonlinear load.



e). D.L.C.M.C.S Simulation result under fluorescent load.



f). C.M.F.G.S.PI C. Simulation result under fluorescent load.

Fig. 7. Simulation results of output voltage and load current for two control schemes.

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