Control of Single Phase UPS Inverter Using Fuzzy Gain Scheduling of PI Controller

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Abstract

This paper presents Control of single phase UPS inverter Using Fuzzy Gain Scheduling of PI Controller. This control scheme has Double Loop Current Mode Control Scheme in core. It includes two control loops as inner and outer. The feedback signal of the inner loop is the inductor current of the inverter filter while the feedback signal of the outer loop is the output voltage. Fuzzy Logic Controller (FLC) adjusts the voltage loop PI controller parameters according to the behavior of the output voltage. The input variables of the FLC are voltage error and its derivative. In this study, both Double Loop Current Mode Control Scheme and Current Mode Fuzzy Gain Scheduling of PI Controller are simulated digitally using PSIM and C++ under linear, rectifier-type nonlinear and fluorescent loads. And the results are discussed.

1. Introduction

Uninterruptible power supply (UPS) systems have been used to provide the emergency power to the critical loads such as airline computers and life support systems in hospitals in case of utility power failure [1]. Usually a UPS system consists of a rectifier, a battery bank, a static inverter, and an inductance-capacitance (LC) filter. The task of the inverter is to convert dc to low total harmonic distortion (THD) sinusoidal output. It is typically operated with a pulse-width modulation (PWM) strategy under feedback control to realize the desired output voltage [2]. The performance requirements for UPS systems include good transient response, and regulated sinusoidal output voltage with low total harmonic distortion (THD), even feeding nonlinear loads (especially rectifier load)[3].

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 number 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 [4]. Therefore, to be able to avoid all these problems the digital control schemes are used in this study.

Most industrial processes have employed PID-family controllers for several decades due to their simplicity and their sufficiency in process control applications. It has been recently reported that more than 90% of the industrial controllers used nowadays are PI controllers [5]. In this study, PI controller based Double Loop Current Mode Control Scheme is used to control the inverter first. This scheme is developed using an FLC block to be able to get a better performance for especially nonlinear loads (rectifier load) and sudden load changes. The FLC is used to adjust the voltage loop PI controller parameters. Both control schemes are simulated digitally using PSIM and C++.

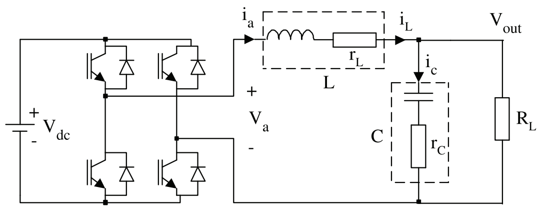

Fig. 1. Basic inverter circuit with an LC filter and R_L load

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 $-V_{dc}$ [6].

PWM inverter is considered as voltage source and the dynamic response of the UPS inverter is mainly determined by the inductance-capacitance (LC) filter [3]. The equivalent block

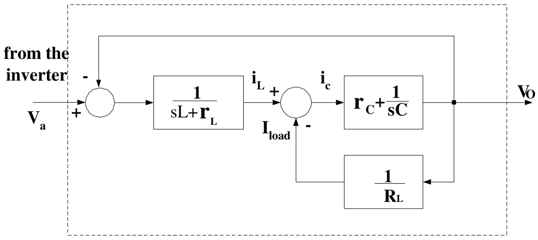

Fig. 2. Equivalent block diagram of the inverter

diagram of the inverter is seen in Fig. 2 [1]. Inverter switching components are considered ideal in this mathematical model of the UPS inverter. UPS inverter should be controlled to get a sinusoidal output waveform across the capacitor under every kind of load. The most important function of the inverter is to regulate the output voltage at a constant voltage and frequency despite the network voltage and the load variations.

2. Double Loop Current Mode Control Scheme Method

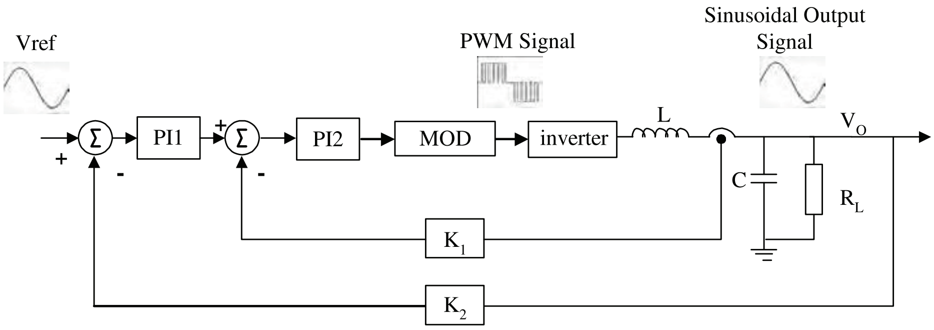

Fig. 3. Double loop current mode control scheme block diagram

The block diagram of the double loop current mode control scheme is shown in Fig. 3. In this Figure, 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 of and a feed forward characteristic which could be used to compensate DC bus ripple and dead time effect, etc. 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 [4].

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 gain over local operating bands [7]. 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 [8].

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 [9].

Current Mode Fuzzy Gain Scheduling of PI Controller presented in this paper is shown in Fig. 4. 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. The objective of this inner loop is to control the state-space averaged inductor current. In this control scheme, PI parameters of the voltage control loop are adjusted by FLC. K_1 and K_2 are taken as unit gains.

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 [9].

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).

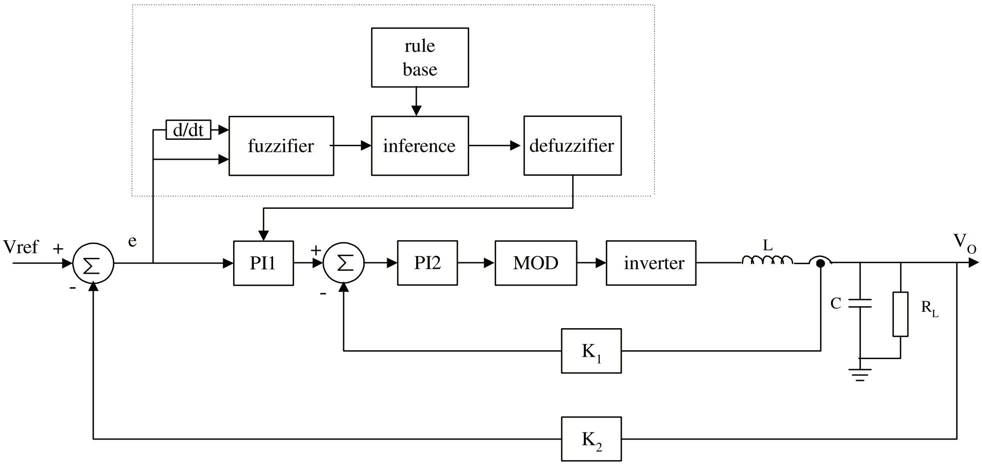

Fig. 4. Block diagram of the current mode fuzzy gain scheduling of PI controller

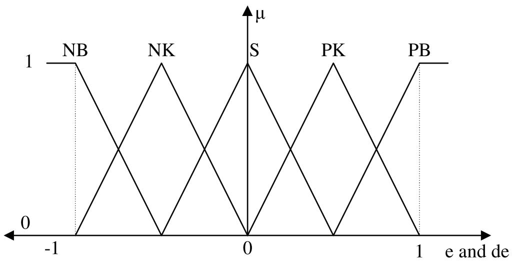

Fig. 5. Membership functions of fuzzy input variables, *e* and *de*

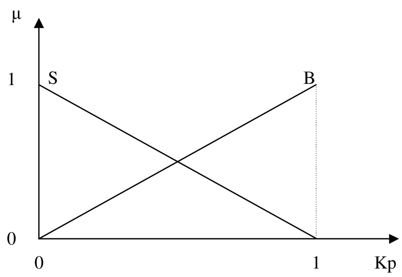

Fig. 6. Membership function of fuzzy output variable

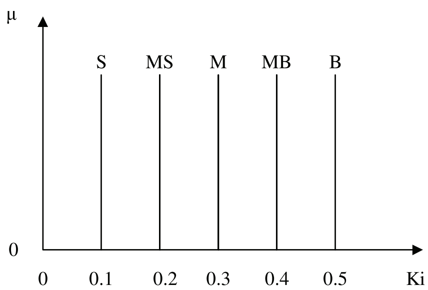

Fig. 7. Membership function of fuzzy output variable, K_i

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).

Table 1. 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 2. 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

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. The fuzzy subsets and the shape of membership function of FLC input and output variables are seen in Fig. 5, Fig. 6 and Fig. 7. The membership functions of input variables are trapezoidal and classical triangular shapes with 50% value of the overlap.The value of each input is normalized in [-1,1] while 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.

Fuzzy control rules are obtained from the behavior of the system and operator's expertise. The rule tables generated are shown in Table 1 and 2. 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.

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.

4. Simulation Results

Current Mode Fuzzy Gain Scheduling of PI Controller explained above is simulated digitally using C++ and PSIM. Simulations are realized under resistive, rectifier type nonlinear and fluorescent loads. System parameters used in simulations are listed in Table 3. Rectifier type nonlinear load is shown in **Fig. 8.** In this figure, L is taken as 770µH.

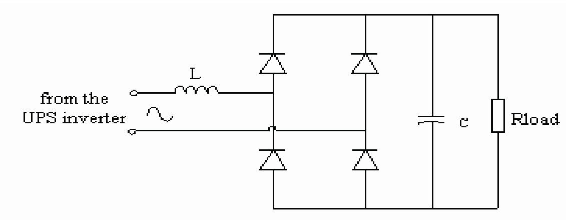

Fig. 8. Rectifier load with R_{load}-C

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 9(a) and Fig 9(f). In simulations, linear load is applied to the inverter with a firing angle of 108°.

Table 3. 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 Table 4, THD values measured in simulations for different kinds of loads are given. In this Table,
I. Cont. : Double Loop Current Mode Control Scheme
II. Cont. : Current Mode Fuzzy Gain Scheduling of PI Control Scheme

Table 4. THD values measured in simulations

	Linear Load (100%)		Nonlinear Load (100%)		Fluorescent Load (50%)	
	I. Cont.	II. Cont.	I. Cont	II. Cont.	I. Cont.	II. Cont.
THD (%)	0.42	0.45	5.39	0.95	0.41	0.38

5. Conclusions

This paper presents Current Mode Fuzzy Gain Scheduling of PI Controller. PI parameters of voltage control loop are adjusted using Fuzzy Logic Controller to get a better THD value, better transient response and better voltage regulation. Both control schemes are simulated digitally under linear, rectifier-type nonlinear and fluorescent loads using PSIM and C++. PI controller parameter of I. control scheme are fixed while PI controller parameters of voltage control loop are adjusted according to the operating conditions in the II. control scheme. Therefore a clear difference of THD values between two control schemes is obtained for rectifier type nonlinear load (Table 4).

Simulation results prove that measured THD values in Current Mode Fuzzy Gain Scheduling Controller are lower and the output voltage regulation quality is better than Double Loop Current Mode Control Scheme.

6. References

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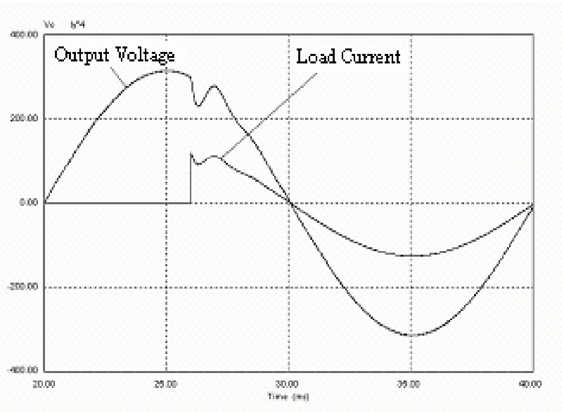
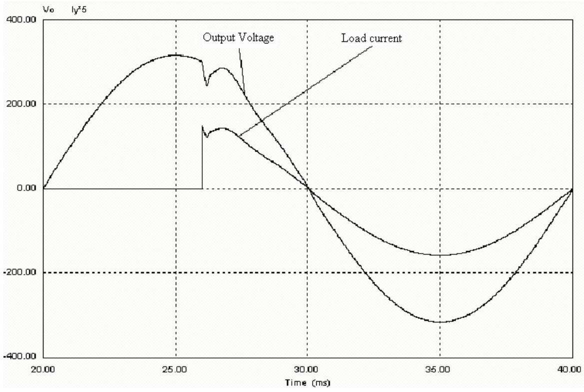
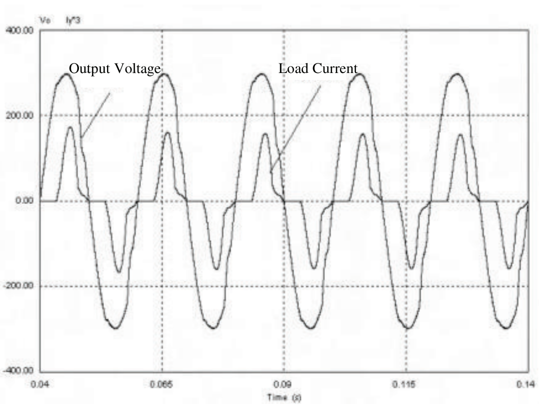


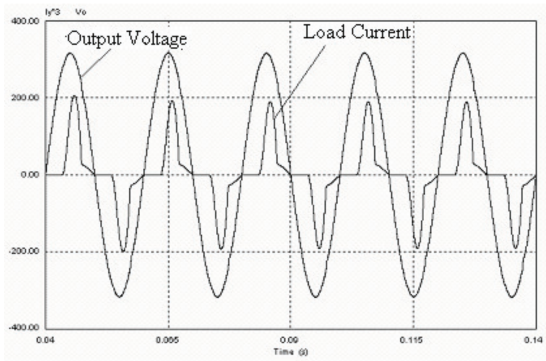
a) Output voltage and load current under linear load for the I. cont. scheme



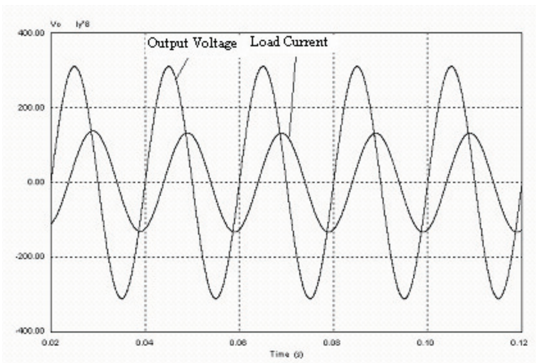
b) Output voltage and load current under linear load for the II. cont. scheme



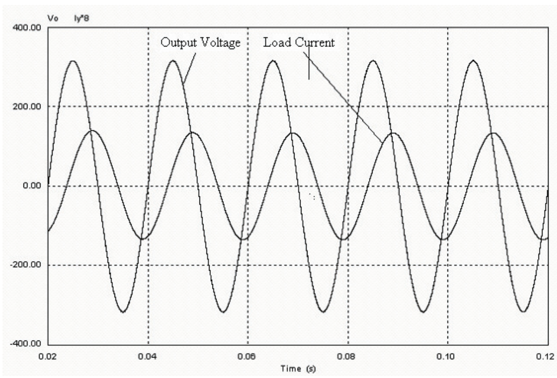
c) Output voltage and load current under nonlinear load for the I. cont. scheme



d) Output voltage and load current under nonlinear load for the II. cont. scheme



e) Output voltage and load current under fluorescent for the I. cont. scheme



f) Output voltage and load current under fluorescent load for the II. cont. scheme

Fig. 9. Simulation results of the I. cont. and the II. cont. schemes under different kinds of loads