THE EFFECTIVE VOLTAGE CONTROL SCHEME OF THE INVERTER FOR A STATIC POWER SUPPLY

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ABSTRACT - In this paper, an effective control scheme of a single phase UPS inverter is proposed to have no steady state error of the output voltage and the fast response for the load request. The cosine wave tranfer function is proposed to control the output voltage. This controller clearly removes errors of magnitude and phase both in the steady state. On the other hand, a current controller is proposed to reduce the transient time of the voltage control and to improve the bad distorted factor of the output voltage waveform by the load fluctuation and the presences of nonlinear parameters in the plant. The current controller is designed parallel to the voltage controller and performs separately from it.

1.INTRODUCTION

It is normally hard for the UPS system to supply pure sinusoidal ac voltage when its loads are mostly nonlinear like a rectifier which has a high crust factor in its current. Because the UPS is not a ideal voltage source, that is, has an inner impedance, the voltage get to be cut down at the instant that the load current increases highly. This is harmful for some loads. The diminished voltage makes supplying low power to the loads, which results in their malfunction. Nowadays, a AVR(Auto Voltage Regulator) is used for those sensitive loads, but using both of the UPS and the AVR is not good way economically. On the other hand, A special load can take some surge in its voltage and current by sudden increasing or decreasing of load in another line connected with the same system. It is caused that the UPS system does not supply necessary power fast and sufficiently at the instant of load change.

In order to get the fast dynamic response of the output voltage of the UPS, the instantaneous control scheme has been used, which gives much faster voltage control then the average value control scheme. But, by itself only, the instantaneous voltage control has not satisfied for the fastness of the control against load fluctuations. Because, the controller can not take notice of the load fluctuation without sufficient error of the output voltage. There have been lots of trial to solve the problem by current feedback control. Those control scheme, in some applications have a double control loop which is made with an inner current loop and an outer voltage loop. The double loop controller is usually designed including PI controllers for voltage and current regulation, which yields steady state errors in the outputs. In spite of the presence of the inner current error, the outer voltage regulator is designed as if the inner current control is perfectly achieved. This means that the voltage controller get still the limitation of the precision of the control even though it has taken one more step for the speed of the control. In this paper, a (co)sine wave tranfer function is proposed to control the output voltage. This controller clearly removes errors of magnitude and phase both in the steady state. On the other hand, a current controller is proposed to reduce the transient time of the voltage control and to improve the bad distorted factor of the output voltage waveform by the load fluctuation and the presences of nonlinear parameters in the plant. The current controller is designed parallel to the voltage controller and performs separately from it.

2.THE SYSTEM MODELLING

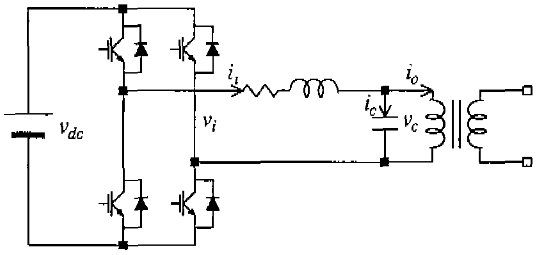


Fig.1 UPS inverter circuit

Fig.1 shows the single phase UPS inverter circuit. The inverter transforms the DC linked voltage to PWM waves, which are expressed as v_i. The LC filter transfers v_o which has been refined as a fundamental 60Hz sinusoidal wave to the load. The R in the figure is an equivalent series resistor in the inductor of the filter. The system in the figure is expressed as following equations.

$$i_i = \frac{1}{R+sL}(v_i - v_o) \tag{1}$$

$$v_o = \frac{1}{sC}(i_i - i_o) \tag{2}$$

Fig.2 shows the block diagram drawn from above equation.

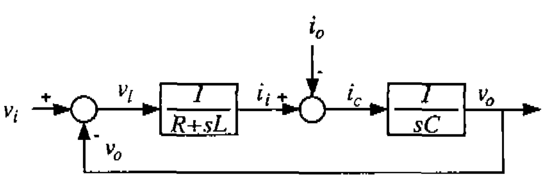


Fig.2 Plant block diagram of UPS Inverter.

Let the output signal from a voltage controller is v_i^*, which is the modulation wave of the IGBT inverter which makes the PWM waves v_i. Even though v_i includes harmonics derived from switching, but most harmonics are filtered and the fundamental frequency is only our interest, so we will let the v_i be same with v_i^*.

3.VOLTAGE CONTROLLER

The references of the output voltage v_o^* is given as the following equation.

$$v_o{}^* = V_{om}\sin(\omega t) \tag{3}$$

On the other hand, the transfer function of the v_o/v_i is the following and fig.3 is its Bode plots.

$$\frac{v_o}{v_i} = \frac{1}{LCs^2 + RCs + 1} \tag{4}$$

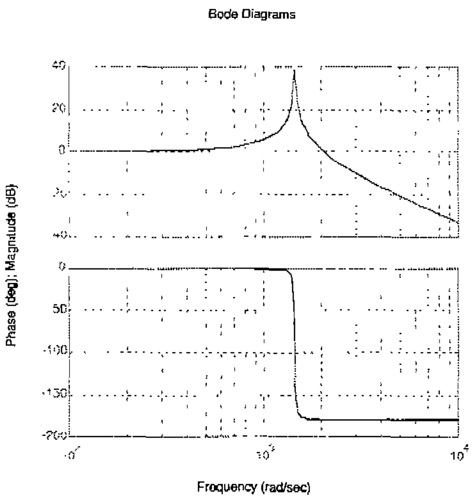


Fig.3 The bode plot of the plant.
$(R = 0.02\Omega, L = 0.0012\text{H}, c = 0.0004\text{F})$

PI voltage controller

If we have put our desired reference as the input signal v_i, the output voltage would appear with some errors of a magnitude and a phase against the reference by the equ.4. $v_e = v_c^* - v_c$ expresses the error, in order to reduce it, generally negative feedback control technique with PI controller can be used. The input signal of the PI controller can be expressed as the following.

$$v_i{}^* = \frac{k_p s + k_i}{s} v_e \tag{5}$$

According to equ.4 and 5, the transfer function of v_o/v_o^* is derived as the following.

$$\frac{v_o}{v_o{}^*} = \frac{k_p s + k_i}{LCs^3 + RCs^2 + (k_p + 1)s + k_i} \tag{6}$$

The above transfer function indicates that the controller gain should be as large as possible to minimize the output voltage error. However, the greater the gain is, the more sensitive and the more unstable the system must be. Since some unknown parameters, moreover, can exist in the system, the controller's gain is to be up to experiment to be set.
Anyhow, any selected controller's gain is not satisfies to get rid of the output voltage error. Let's keep in mind that the output voltage error can not but exist always according to R, L, and C, even though the controller's gain is selected as optimum.

Steady state error

If a negative feedback controller is T_{sin}, and a plant is P, the transfer function of an output y against an input r is the following

$$\frac{y}{r} = \frac{T_{sin}P}{1 + T_{sin}P} \tag{7}$$

,where

$$T_{sin} = \frac{k_s\omega}{s^2 + \omega^2}.$$

The above equation would be transformed into the following.

$$\frac{y}{r} = \frac{k_s\omega P}{s^2 + \omega^2 + k_s\omega P} \tag{8}$$

If the reference r is expressed as a sine function with an angle velocity ω, we can exchange s with $j\omega$. Then we can notice that the equ. 8 is 1. This means that the steady state error of the fundamental output with ω is zero. This controller is very useful in UPS inverter because of the CVCF(Constant Voltage and Constant Frequency) of the output voltage. This controller is called 'sine wave transfer function (controller)', because the controller T_{sin} forms itself into Laplas transform of sinωt. 'Cosine wave transfer function' T_{cos} is available in the same case. Selection is depend on the plant applied so that the system is to be more stable.

Let's the voltage controller is the following equation

$$v_i{}^* = T_{cos}(v_o{}^* - v_o) + v_o{}^* \qquad (9)$$

,where

$$T_{cos} = \frac{k_s s}{s^2 + \omega^2}.$$

From the above equation, the transfer function of the output voltage against the reference voltage is given as following.

$$\frac{v_o}{v_o{}^*} = \frac{s^2 + k_s s + \omega^2}{\binom{LCs^4 + RCs^3 + (1 + LC\omega^2)s^2 + \cdots}{(RC\omega^2 + k_s)s + \omega^2}} \qquad (10)$$

The bode diagram of the proposed voltage controller with cosine wave transfer function is shown in Fig.4. Knowing in the figure, the magnitude is 0dB and the phase is 0 degree at frequency = 60Hz($\omega = 377$).

Affect of the resonance of the LC filter

Showing in Fig.3, the plant of the LC filter has a resonance at $\omega = 1/\sqrt{LC}$. An affect from that appears like an oscillation of the output voltage at the instant of load sudden change.
The gain of the transfer function of the plant at the resonant frequency is given like the following.

$$\left|\frac{v_o}{v_i^*}\right|_{\omega = \frac{1}{\sqrt{LC}}} = \frac{1}{R}\sqrt{L/C} \qquad (11)$$

It can be minimized by increasing R, which is a coefficient of s of the system. In order to change the coefficient of s, a feedback loop can be inserted additively in the voltage control loop.

$$\begin{aligned} v_i{}^* &= T_{cos}(v_o{}^* - v_o) + v_o{}^* + kv_o s \\ v_i{}^* &= T_{cos}(v_o{}^* - v_o) + v_o{}^* + k_r i_c \qquad (12) \end{aligned}$$

With the feedback gain k, the transfer function of v_o/v_i^* is the following.

$$\frac{v_o}{v_o{}^*} = \frac{s^2 + k_s s + \omega^2}{\binom{LCs^4 + (RC + k)s^3 + (1 + LC\omega^2)s^2 + \cdots}{[(RC + k)\omega^2 + k_s]s + \omega^2}} \qquad (13)$$

In the case of that the k_r is set with 0.5, the gain plot of the transfer function is like fig.4.

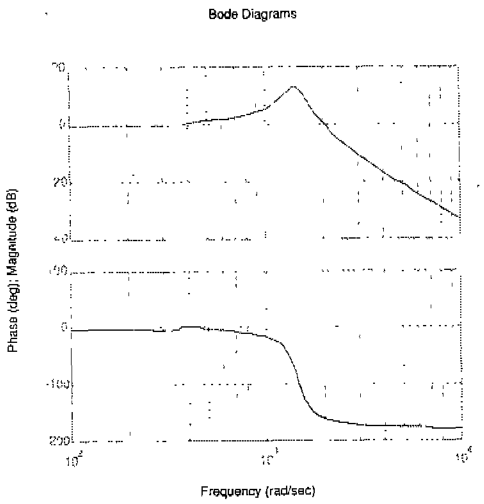


Fig.4 Bode plot of the system with the proposed voltage controller.

4.CURRENT CONTROLLER

In practical case, there are some nonlinear parameters in the plant, which make the THD of the output voltage much higher than in the case of simulation. For the improvement of the output voltage wave form, in this paper, a current controller is inserted parallel with the voltage controller. The current controller would reduce the effect from load fluctuation which disturbs the capacitor current. Furthermore It is really helpful to reduce the transient time of the voltage control. The capacitor reference is the following.

$$i_c{}^* = \omega C V_{om}\cos(\omega t) \qquad (14)$$

From fig.2 the capacitor current is expressed as the following.

$$i_c = \left(\frac{1}{Ls + R}\right)(v_i - v_o) - i_o \qquad (15)$$

The proposed current controller is the following.

$$v_i{}^* = k_p(i_c{}^* - i_c) + v_o \qquad (16)$$

Ignoring the load current i_o, the transfer function is derived as the following from equ. 15 and 16.

$$\frac{i_c}{i_c{}^*} = \left(\frac{k_p}{R + k_p}\right)\frac{1}{\tau s + 1} \qquad (17)$$

τ in the equation is $\frac{L}{R + k_p}$. This equation give the decision of the gain k_p for the current controller. We get 0.2ms for the τ in this paper.

5.THE PROPOSED CONTROLLER

The proposed controller is expressed as the following equation.

$$v_i^* = T_{cos}(v_o^* - v_o) + v_o^* + k_r i_c + k_p(i_c^* - i_c) + v_o \quad (18)$$

The control block diagram is shown in fig.5.

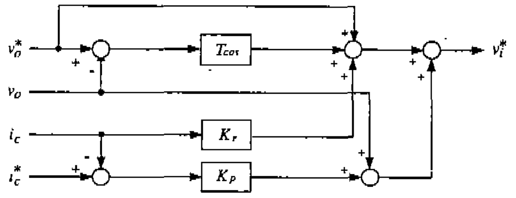


Fig.5 The proposed control block diagram.

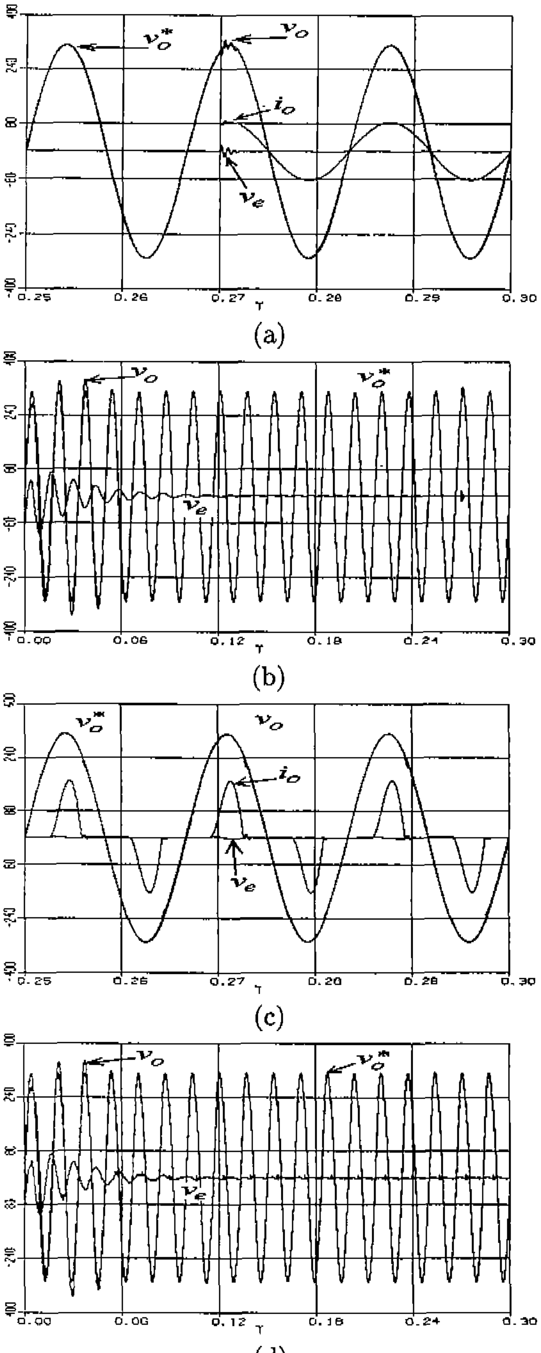
6.SIMULATION AND EXPERIMENTAL RESULTS

Simulation results are shown in fig 6. In the figure, (a) and (b) are in the case under register load. The load is changed so rough at $t = 0.27$ when the output voltage is on top of the wave. The output voltage error v_e fluctuates little and disappears soon. The fluctuation height is in 5% of the output voltage and the recovery time is in 2ms. (b) shows the process to the steady state. (c) and (d) are in the case under a rectifier load. The output voltage is almost zero under the current with very high crust factor. The sinusoidal wave transfer makes the output voltage unite together with its reference at the steady state.

The fig 7 and fig 8 show the experimental results. In fig 7.(a), the output voltage looks so stiff in spite of the sudden load change. (b) demonstrates that the steady state error of the output voltage is getting almost zero by the proposed controller. The fig 8.(a) shows the output voltage and current waveform under a rectifier load. (b) and (c) is the spectrum analysis of the output voltage under a rectifier load.

7.CONCLUSTION

This paper proposed a voltage controller with a current controller paralleled with for single phase UPS inverter to remove steady state error, have short recovery time under the sudden load change, and get pure sinusoidal output voltage under the nonlinear load.



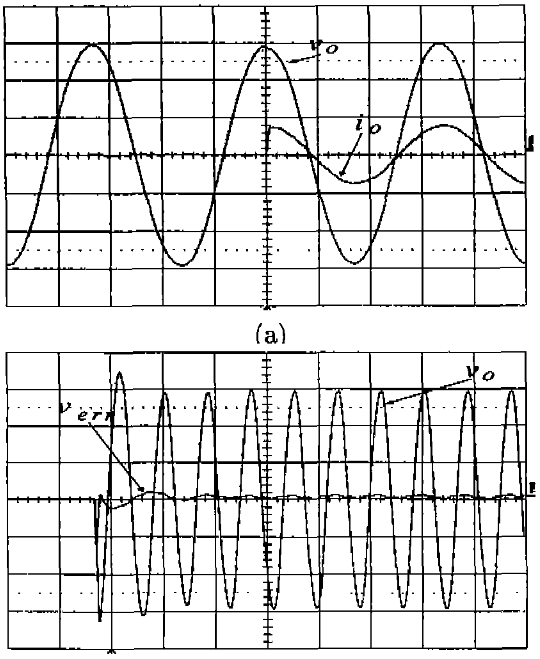
(a)

(b)

(c)

(d)

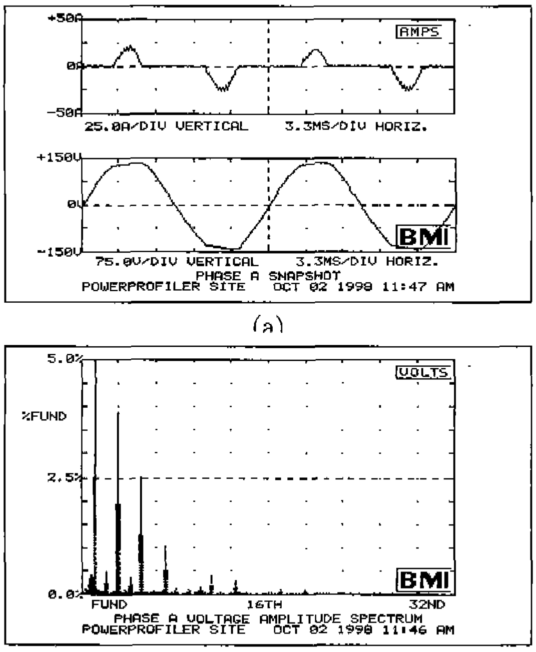
Fig.6 Simulation results : (a) shows the output voltage and the current waveform under a resistor load change. (b) shows the waveform of the output voltage and the steady state error under a resistor load. (c) is the waveform of the output voltage and the output current under a rectifier load. (d) shows the waveform of the output voltage and the steady state error under a rectifier load.



(a)

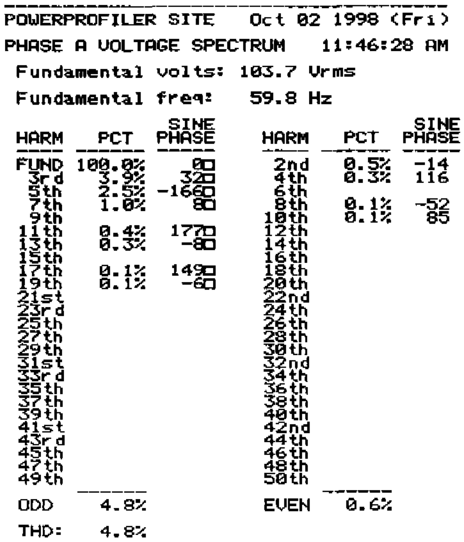
(b)

Fig.7 Experimental results : (a) shows the output voltage and the current waveform under a resistor load change(50V/div, 14A/div). (b) shows the waveform of the output voltage and the steady state error(50V/div,50V/div).



(a)

(b)



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POWERPROFILER SITE   Oct 02 1998 (Fri)
PHASE A VOLTAGE SPECTRUM   11:46:28 AM
 Fundamental volts: 103.7 Vrms
 Fundamental freq:   59.8 Hz
                 SINE                 SINE
 HARM    PCT    PHASE    HARM   PCT   PHASE
 ----  ------   -----    ----  ------ -----
 FUND 100.0%      0□      2nd   0.5%   -14
  3rd   3.9%     32□      4th   0.3%   116
  5th   2.5%   -166□      6th
  7th   1.0%      8□      8th   0.1%   -52
  9th                    10th   0.1%    85
 11th   0.4%    177□     12th
 13th   0.3%     -8□     14th
 15th                    16th
 17th   0.1%    149□     18th
 19th   0.1%     -6□     20th
 21st                    22nd
 23rd                    24th
 25th                    26th
 27th                    28th
 29th                    30th
 31st                    32nd
 33rd                    34th
 35th                    36th
 37th                    38th
 39th                    40th
 41st                    42nd
 43rd                    44th
 45th                    46th
 47th                    48th
 49th                    50th
       ------                  ------
 ODD    4.8%             EVEN   0.6%

 THD:   4.8%
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(c)

Fig.8 Experimental results : (a) is the waveform of the output voltage and the output current with a rectifier load.(B) and (c) are the result of the spectrum analysis of UPS system with a rectifier load

References

[1] T. Kawabata, T. Muyashita and Y. Yamamoto, "Digital control of three-phase PWM inverter with LC filter"", IEEE Trans. Power Electron., vol. 6, no. 1, pp. 62-72, 1991

[2] R.W.De Doncker and J. P. Lyons, "Control of three phase power supplies for ultra low THD", in Conf. Rec. IEEE APEC /91, pp. 620-629, 1991

[3] B-J. Kim, J-H. Choi, J-S. Kim and C-H. Choi, "Digital control scheme of UPS inverter to improve the dynamec response", in Conf. Rec. IEEE CCECE /96, pp. 318-321, 1996

[4] S. Inarida, K. Nakamura and Y. Iwaji, "Study on Instantaneous Voltage Control Method for Ausiliary Power Supply Systems Used in Rolling Stocks", IEE Japan, pp. 1132-1139, 1996

[5] B-J. Kim J-H. Choi, "Improved Digital Control Sheme of Three Phase UPS Inverter Using Double Control Strategy", in Conf. Rec IEEE APEC /97, pp. 820-824, 1997