A Study on commercial frequency source with ZCS type high frequency resonant Inverter

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Abstract - This paper describes a new dc-ac inverter system, which for achieving sinusoidal ac waveform make use of parallel loaded frequency resonant inverter consisting of full bridge. Each one of the pair of switches in the inverter is driven to synchronous output frequency and the other is driven to PWM signal with resonant frequency proportional to magnitude of sine wave. Since current through switches is always zero at its turn-on in proposed inverter, low stress and low switching loss is achieved. The theoretical analysis is proved through the experimental test.

1.INTRODUCTION

In recent years, the UPS(Uninterrupted Power Supply) are used as the power supply of electronics devices, communication equipment and medical treatment electronics systems. It is necessary to have an inverter to convert DC to AC[1][2].

There are a lot of papers introducing how to control the inverter. They have been controlled using phase control and PWM methods up to now [3][4]. The inverter controlled by these methods has some problems such as switching stress and loss, higher order harmonic components. Thus, we usually use ZVS and ZCS techniques to remove them [5][6].

Also, there is an inverter using high frequency resonance that includes VVVF technique. However, the inverter is too complicated because there are two resonant reactors and condensers, respectively.

In addition, there is a disadvantage that is the load assignment between arms in the inverter bridge circuit is unbalance. This paper proposes a simple resonant inverter that is similar to conventional full bridge inverter.

Thus, it is possible to reduce the number of switching devices resonant inductors and condensers in the inverter circuit.

The proposed inverter operates as discontinuous conduction mode and makes the output voltage formed sinusoidal quasi-resonance pulse row by using a high resonant inverter controlled PWM.

The output voltage is become a sinusoidal wave by LPF(Low Pass Filter). In addition, the switching stresses and losses are reduced because the switches are turned on when the current through the inverter circuit is always zeroed.

2.OPERATING PRINCIPLES OF THE PROPOSED INVERTER

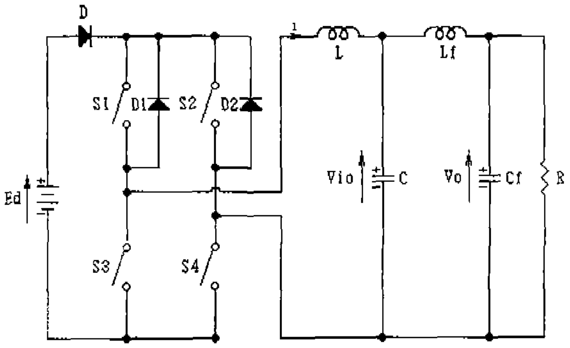


Fig. 1 ZCS type a high frequency resonant inverter.

Fig. 1 shows a high frequency resonant inverter connected in parallel with the load. This is the proposed inverter circuit and similar to the conventional full bridge inverter. In Fig.1, the switches S1, S2, S3, S4 are self turn-off devices for PWM control. L and C are the resonant reactor and the resonant condenser, respectively. Lf and Cf are the filter reactor and the filter condenser, and R is the load resistor. Diodes D1, D2 are for composing high frequency resonant loop, and Diode D is for blocking a resonant current conducting backward. Fig. 2 shows on/off timing diagram of the switches S1, S2, S3, S4 in order to make the output voltage close to the sinusoidal wave.

The proposed circuit shown in Fig. 1 consists of two switch family proportional to (S1, S2) and (S3, S4) as a full bridge type. The S1 and S2 are operated in turn to get the sinusoidal commercial frequency voltage and synchronize with the frequency of the source. The S3 and S4 are operated by the signal of PWM in the frequency of the source.

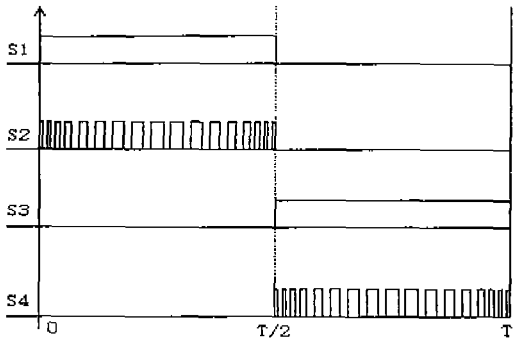


Fig.2 on/off timing diagram of switches S1 – S4

Thus, if the operating frequency of the switches S1, S2 is changed, the frequency of the output voltage will be changed. Also, if the duty ratio of the switches S3, S4 is altered, the amplitude of the output voltage will be altered. Therefore, the proposed circuit can be operated as VVVF(Variable Voltage Variable Frequency).

In the case of without the filters Lf and Cf, the operating mode, as like shown in Table 1, decided by L and C of the proposed circuit during one period can be divided into three modes. According to the states of the S1 and S2, each mode can be divided into two again.

These two modes have the same operation except that the voltage and current is the opposite direction.

Table 1. Operating mode

Operating Mode	Mode 1		Mode 2		Mode 3	
	a	A'	b	b'	c	c'
S1	1	0	1	0	0	0
S2	0	1	0	1	0	0
S3	0	1	0	0	0	0
S4	1	0	0	0	0	0
D	1	1	0	0	0	0
D1	0	0	0	1	0	0
D2	0	0	1	0	0	0

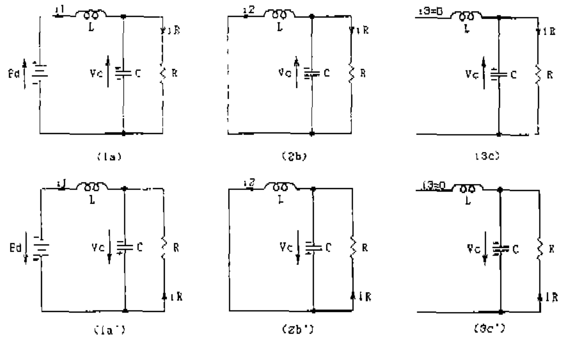


Fig. 3 Equivalent circuit of each mode

In Table 1, 1 and 0 represent the state of turn-on and off of the switching devices, respectively. Fig. 3 shows the equivalent circuit of the each mode.

To simplify the analysis of the circuit, the state equation is represented by per unit, as like shown in Table 2. After this, all values are represented by the per-unit.

Table 2. Reference value of per unit system

Parameter	Reference value
Voltage	$V_b = E_d$
Current	$I_b = V_b / Z_b$
Reactor	$L_b = 44(\mu H)$
Capacitor	$C_b = 1.24(\mu F)$
Impedance	$Z_b = \sqrt{L_b / C_b}$
Time	$t_b = 2\pi\sqrt{L_b C_b}$
Frequency	$f_b = 1/t_b$
Angle Frequency	$\omega_b = 1/\sqrt{L_b C_b}$
Power	$P_b = V_b I_b$

The operation of the circuit at k times switching is as follows:

(1) Mode 1(a, a')

In this mode, the capacitor C is charged by the current i1 flowing from the source. The solutions of the current i1 and the voltage Vc1 can be get by the state equation as follows:

$$\begin{cases} i_1(t_k) = \dfrac{1}{R} + e^{-\alpha t_k}(k_{11}\sin\beta t_k + k_{12}\cos\beta t_k) \\ v_{c1}(t_k) = 1 + e^{-\alpha t_k}(k_{13}\sin\beta t_k + k_{14}\cos\beta t_k) \end{cases} \quad (1)$$

Where $\alpha = \dfrac{1}{2RC}$, $\beta = \sqrt{\omega^2 - \alpha^2}$

$$k_{11} = \{\alpha k_{12} + (1 - v_{01})/L\}/\beta,\ k_{12} = i_{01} - \frac{1}{R}$$

$$k_{13} = \frac{i_{01}}{C} - \frac{\alpha(1 - v_{01})}{\beta},\ k_{14} = v_{01} - 1,\ t_k = t - t_0$$

The v_{01} equals $v_{c3} = (T_r - t_2)$ because the initial value of the v_{01} equals the final value of that. In the case of the mode 1(a), sn is 1. Under the mode 1(a'), sn is −1.

(2) Mode 2(b, b')

In this mode, the source is disconnected, and the energy of the inductor is discharged.

The solutions of the current i2 and the voltage Vc2 can be get by the state equation as follows:

$$\begin{cases} i_2(t_k) = e^{-\alpha t_k}(k_{21}\sin\beta t_k + k_{22}\cos\beta t_k) \\ v_{c2}(t_k) = e^{-\alpha t_k}(k_{23}\sin\beta t_k + k_{24}\cos\beta t_k) \end{cases} \quad (2)$$

Where $k_{21} = \left\{\alpha i_{02} - \frac{v_{02}}{L}\right\}\Big/\beta$, $k_{22} = i_{02}$

$k_{23} = \left\{\frac{i_{02}}{C} - \alpha v_{02}\right\}\Big/\beta$, $k_{24} = v_{02}$, $t_k = t - t_1$

The i_{02} and v_{02} are the initial values of the mode 2. Thus, $i_{02} = i_1(t_1 - t_0)$, $v_{o2} = v_{c1}(t_1 - t_0)$.

(3) Mode 3(c, c')

In this mode, the current i_3 flowing through the inductor L is decreased to zero , the capacitor C starts to discharge through the load. The solutions of the current i3 and the voltage Vc3 can be get by the state equation as follows:

$$\begin{cases} i_3(t_k) = 0 \\ v_{c3}(t_k) = v_{03}e^{-2\alpha t_k} \end{cases} \quad (3)$$

Where $t_k = t - t_2$, $v_{03} = v_{c2}(t_2 - t_1)$

The waveforms of the voltage and the current of the mode 3 during the k times a resonant period Tr are shown in Fig. 4.

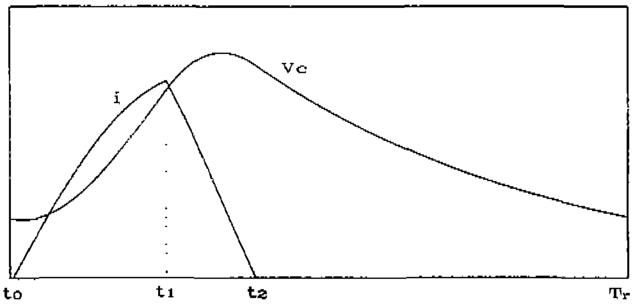


Fig. 4 Operating wave of a high frequency resonant inverter

When the switch S1(S2) is turned on at $t = t_0$, the current flowing through the resonant condenser and the load from the source starts to conduct and the energy of the inductor is stored.

The proposed system is using the high frequency resonant inverter operating as discontinuous conduction mode. The duty ratio of S1 and S2 has to be less than 1/2 in order to keep a time interval that is 50(%) of a switching period.

Thus, under the condition of the duty ratio, the switch is turned off at $t = t_1$, the stored energy of the inductor begins to discharge and the resonant current reduces and becomes zero at $t = t_2$.

The current of the inductor doesn't conduct until next signal and the recharged energy of the condenser starts to discharge through the load.

3. OPERATING CHARACTERISTICS OF THE PROPOSED INVERTER.

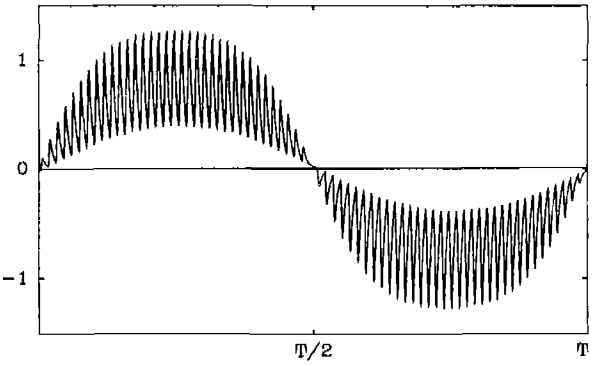
To make the output voltage formed sinusoidal quasi-resonance pulse row like that shown in Fig. 4, the turn-on switching signal width t_{on} should be in proportion to the magnitude of the sinusoidal wave like Eq (4).

$$t_{on} = \frac{1}{2} ma \sin\left(9.28\times10^{-5}\pi f t\right) \quad (4)$$

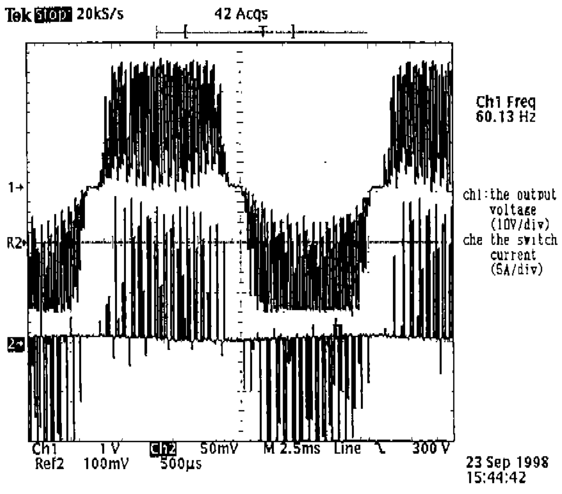
Where ma is the amplitude modulation ratio.

According to the Eq (4), in the case of without the filters, the theoretical and the experimental waveforms of the output voltage are shown in Fig. 5(a), (b), respectively.

In Fig. 5(b), the circuit parameters $E_d, L_r, C_r, L_f, C_f, R$ are $50(V)$, $44[\mu H]$, $1.24[\mu F]$, $730[\mu H]$, $100[\mu F]$, $20[\Omega]$



(a)



(b)

Fig. 5 (a), (b) output voltage of the proposed inverter (without filters)

According as the carrier frequency, that is, the resonant frequency, is modulated the sinusoidal wave of the commercial frequency, the waveform of the output voltage is shown like in Fig. 5.

Thus, as like shown in Fig. 1, since the carrier frequency components included the waveform of the output voltage can be reduced by adding the LPF composed of L_f and C_f, finally, the sinusoidal wave of the output voltage can be obtained.

The state and the output equation including the filter condenser resister r_c, and the inductor resistor r_l, is given by

$$\begin{cases} \dfrac{dx_1}{dt} = A_1 x_1 + B_1 \mathrm{u}_1 \\ y_1 = C_1 x_1 \end{cases} \tag{5}$$

Where $x_1 = \begin{bmatrix} i_f & v_{cf} \end{bmatrix}^t$, $y_1 = v_0$, $u_1 = v_{io}$

$$A_1 = \begin{bmatrix} -\dfrac{r_1 r_c + R(r_1 + r_c)}{L_f(R + r_c)} & -\dfrac{R}{L_f(R + r_c)} \\ \dfrac{R}{C_f(R + r_c)} & -\dfrac{1}{C_f(R + r_c)} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \dfrac{1}{L_f} & 0 \end{bmatrix}^t, \quad C_1 = \begin{bmatrix} \dfrac{r_c R}{R + r_c} & \dfrac{R}{R + r_c} \end{bmatrix}$$

The transfer function of the output voltage v_o with respect to the filter input voltage v_{io} is given by

$$G(s) = \frac{v_o(s)}{v_{io}(s)} = \frac{a_o + a_1 s}{b_0 + b_1 s + b_2 s^2} \tag{6}$$

Where $a_0 = R$, $a_1 = r_c R C_f$, $b_0 = r_1 + R$

$$b_1 = L_f + r_1 R C_f + r_c r_l C_f + r_c R C_f$$

$$b_2 = L_f C_f (R + r_c)$$

The inductor and the capacitor using low pass filter circuit should be chosen by the current flowing the capacitor at no load is less than 5(%) of the rated current. The cut-off frequency is decided by the range of frequency controlled. In this paper, in the case of R=1.5, the cut-off frequency f_c is 0.4. Thus, the filters, L_f and C_f are 70 and 16, respectively. The frequency response of the transfer equation of the equation (6) is shown in Fig. 6.

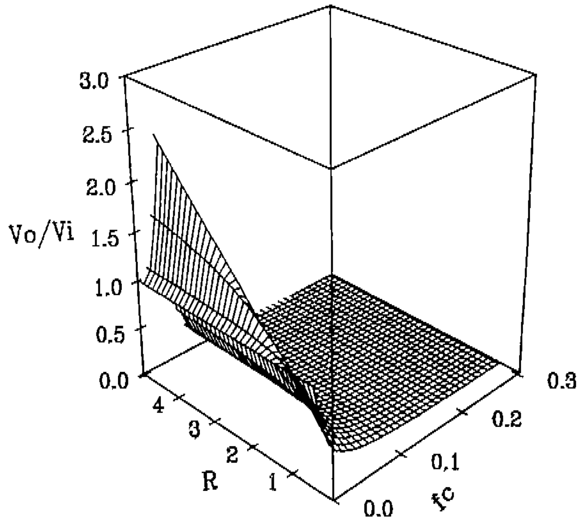


Fig. 6 Frequency characteristics of the transfer function

The state equations and the output equation including the filter are given by

$$\begin{cases} \dfrac{dx}{dt} = Ax + Bu \\ y = Cx \end{cases} \tag{7}$$

Where $x = \begin{bmatrix} i_1 & i_f & v_c & v_{cf} \end{bmatrix}^t$, $u = 1$

$$A=\begin{bmatrix} 0 & 0 & -\dfrac{m_1}{L} & 0 \\ 0 & 0 & \dfrac{1}{L_f} & -\dfrac{1}{L_f} \\ \dfrac{m_2}{C} & -\dfrac{1}{C} & 0 & 0 \\ 0 & \dfrac{1}{C_f} & 0 & -\dfrac{1}{RC_f} \end{bmatrix},\ y=v_o$$

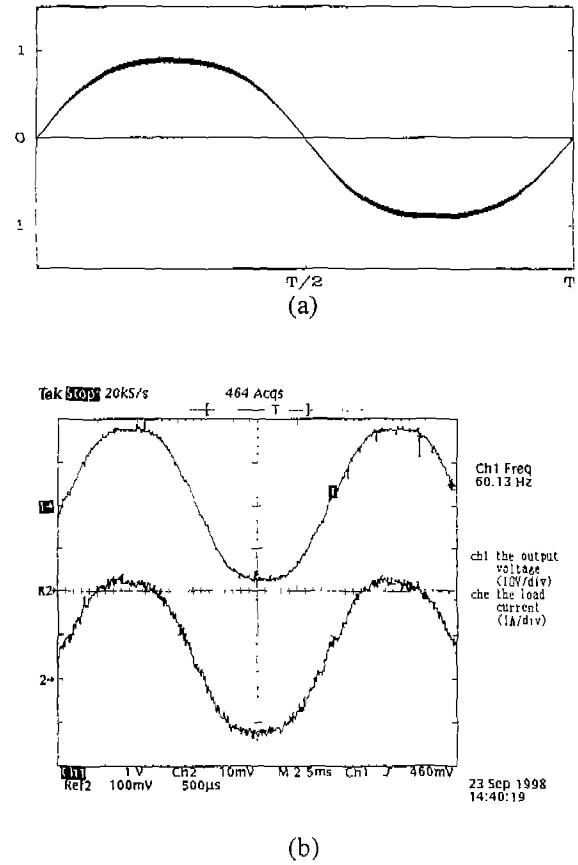
$$B=\begin{bmatrix} \dfrac{m_1 sn}{L} & 0 & 0 & 0 \end{bmatrix}^t,\ C=\begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

Where m1 and m2 are 1 in the mode 1 and 2, in the mode 3 they are 2. sn is 1 in the mode a, b, c, in the mode a', b', c' , it is −1.

The solution of the equation (7) can be obtained by the numerical analysis method.

Fig. 7 (a), (b) show the output voltage waveforms that are obtained by the simulation using the Runge-Kutta method and the experiment, respectively.

The circuit parameters have already represented in Fig. 5(b).



(a)

(b)

Fig. 7 (a), (b) The output voltage of the proposed inverter (with filters)

In order to analyze the harmonic components, the harmonic factor is essential and defined by

$$H.F=\frac{harmonic\ component}{fundamental\ component}=\frac{\sum_{h=2}^{\infty}V_h}{V_1}$$

$$=\sqrt{\frac{V_r^2-V_d^2}{V_1}-1} \tag{8}$$

Fig.8 shows the rms values and the harmonic factors with respect to the amplitude modulation ratios.

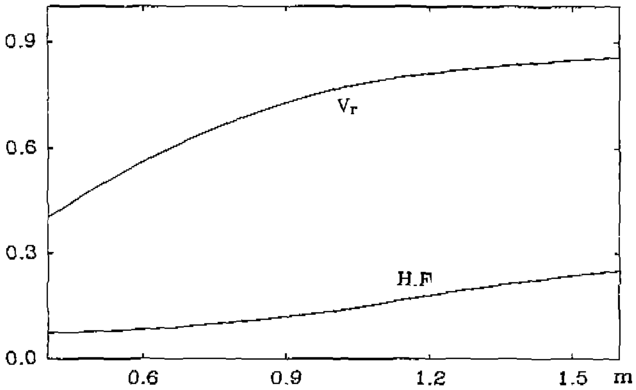


Fig.8 The rms voltage and harmonic factor with amplitude modulation ratio ma

In Fig.8, the amplitude ratio is in proportion to the rms value and harmonic factor. Thus, when the amplitude modulation ratio is increased, the harmonic factor is also increased. Accordingly, the maximum *output power in the harmonic factor permitted can be* decided by Fig. 8

According to the change of the load resistance, the rms voltage of the output and the harmonic factor are altered and shown in Fig. 9.

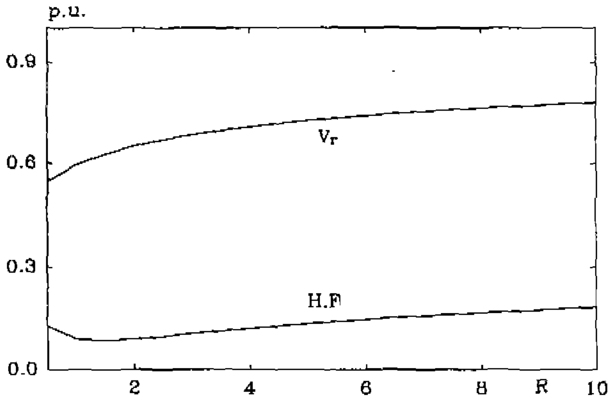


Fig. 9 The rms value and harmonic factor of the output voltage with load resistance.

The load resistance is proportional to the output voltage is shown in Fig.9. In order to keep the output voltage constantly needs a proper control.

4. CONTROL OF THE PROPOSED INVERTER SYSTEM.

In Fig. 8, since the output voltage is changed with the amplitude modulation ratio ma, ma is decided to keep the output voltage constantly using the PI controller to reduce the error between the output voltage and the reference one. The ma is as follows:

$$ma = k_p\left(v_{ref} - v_o\right) + k_i \int\left(v_{ref} - v_o\right)dt \tag{9}$$

Where $v_{ref} = v_{rm}\sin\left(9.28\times10^{-5}\pi ft\right)$

The total control system to control the inverter system proposed in this paper is shown in Fig. 10.

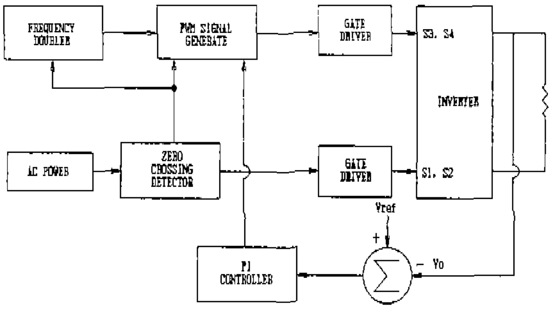


Fig. 10 Control system diagram with ZCS type a high frequency resonant inverter

The dynamic characteristics of the output voltage controlled by this system are shown in the Fig. 11 and 12. Even though the reference voltage and the load are changed, the error is very small, and the output voltage follows the reference voltage well. Thus we can know that the proposed inverter has a good response.

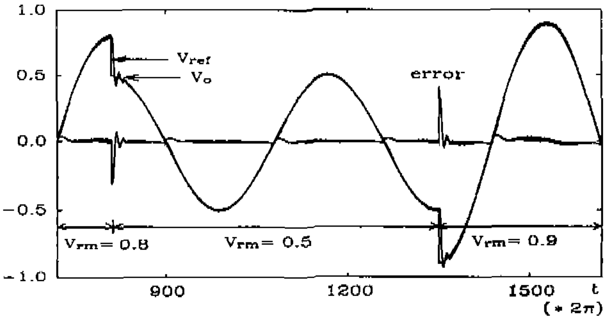


Fig.11 Dynamic characteristic of the output voltage with varying reference voltage

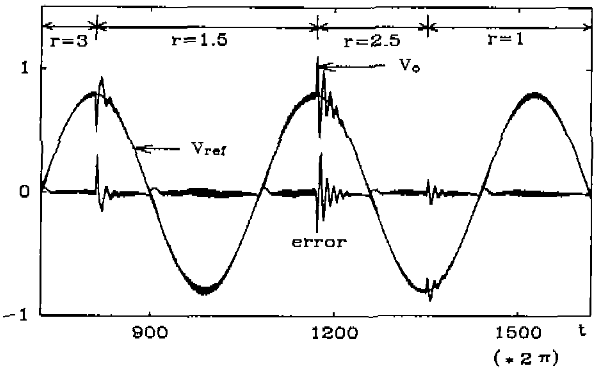


Fig. 12 Dynamic characteristic of the output voltage with varying load.

5. CONCLUSION

This paper proposed the resonant inverter system that could control the amplitude and the frequency of the output voltage using PWM and lessen the problems such as switching stress, loss, and harmonics, of conventional high frequency inverters.

Comparing the theoretical waveforms to the experimental waveforms certified the operating characteristics of the proposed system.

6. REFERENCE

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