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Broadband Robust PWM Power Amplifier Using Approximate 2DOF Digital Control

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Abstract

Lately, it is required that the bandwidth of PWM power amplifier is extended. For example, it is in application of the testing power supply of a low ferquency immunity examination, or a class-D ampllifier. In this paper, we show that the bandwidth of PWM power amplifier can be extended by using an Approximate 2DOF Digital Controller. This controller is implemented on a DSP. It is demonstrated from experiments that the bandwidth can be made wider with this controller.

1 Introduction

A PWM power amplifier used as a power supply or amplifier has good power conversion efficiency, small size and lightweight, it is widely used for common apparatus. We apply the PWM power amplifier to an AC power supply apparatus. The AC power supply apparatus output the same AC as the commercial power supply. Since, in the commercial power supply, the voltage may fall and the waveform may not be a precise sine-wave or the noise may be mixed, the AC power supply apparatus is used as a AC regulated power supply. Especially it is needed when performing precise electric measurement etc. And it has a function of frequency conversion or voltage conversion, so it is used when testing and producing of the goods of a foreign country, or when the same power supply specification as the one of a foreign country must be supplied. Furthermore, it is used as the power supply for a low frequency wave immunity test. The low frequency wave immunity test examines whether the electronic devices operate normally in abnormal conditions, such as a fall of voltage and an instantaneous breaking off. Therefore, the AC power supply apparatus in which the transient response characteristics does not deteriorate for the various load characteristics from capacitivity to inductivity is needed. In the low frequency wave immunity test, it is necessary to make various waveforms, such as breaking off wave etc. which have rapid changes. Therefore, it is required that the bandwidth of PWM power amplifier must be very wide in order to follow at high speed to a reference imuunity test signal without overshooting. We proposed[1, 2] previously the different methods from the other methodsd[3, 4] for designing a robust digital controller for PWM power amplifiers which can attain those demands. This method used the idea of an apprximate 2-Degree-of-Freedom(2DOF) sytem. However, the bandwidth is not so wide and is about 2[kHz]. It is necessary to extend the bandwidth to deal with various problems. In this paper we show that the bandwidth can be extended using the approximate 2DOF digital controller by getting more high sampling and switching frequency. This digital controller is actually realized by using a DSP. Some experiments show that the controller can extend the bandwidth.

2 PWM power amplifier

The power amplifier as shown in **Fig.1** is being manufactured. The triangular wave double carrier system is adopted as a PWM switching signal generating part. A power amplification part is a full-bridge type chopper circuit, and the voltage of direct-current power-supply E is 30[V]. The LC circuit is a filter for removing carrier and switching noises. The values of LC circuit are $L_0 = 20[\mu\text{H}]$ and $C_0 = 2.16[\mu\text{F}]$. If the frequency of control signal u is smaller enough than that of the carrier, the state equation of the DC-DC converter at a resistive load in Fig.1 except for the controller in DSP can be expressed from the state equalizing method as follows :

$$\begin{cases} \dot{x} = A_c x + B_c u \\ y = Cx \end{cases} \qquad (1)$$

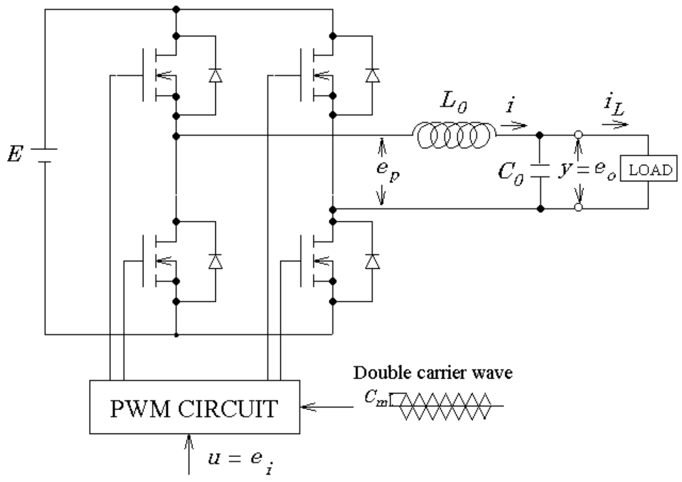

Figure 1: PWM power amplifier

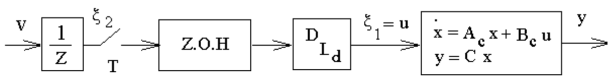

Figure 2: Controlled object with input dead time $L_d(\leq T)$

where

$$x = \begin{bmatrix} e_o \\ i \end{bmatrix} \quad A_c = \begin{bmatrix} -\frac{1}{C_0 R_L} & \frac{1}{C_0} \\ -\frac{1}{L_0} & -\frac{R_0}{L_0} \end{bmatrix} \quad B_c = \begin{bmatrix} 0 \\ \frac{K_p}{L_0} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad u = e_i \quad y = e_0 \quad K_p = -\frac{E}{C_m}$$

and R_0 is the total resistance of coil and ON resistance of FET, etc., and the value is $0.015[\Omega]$. When realizing a digital controller by a DSP, a delay time exists between the starting time of the sampling operation and the outputting time of the control signal due to the calculation and AD/DA conversion times. This delay time is considered to be equivalent to the input dead time which exists in the controlled object as shown in **Fig.2**. Then the state equation of the system in Fig.2 is expressed as follows :

$$\begin{cases} x_{dw}(k+1) = A_{dw}x_{dw}(k) + B_{dw}v(k) \\ y(k) = C_{dw}x_{dw}(k) \end{cases} \quad (2)$$

where

$$x_{dw}(k) = \begin{bmatrix} x_d(k) \\ \xi_2(k) \end{bmatrix} \quad x_d(k) = \begin{bmatrix} x(k) \\ \xi_1(k) \end{bmatrix}$$

$$A_{dw} = \begin{bmatrix} A_d & B_d \\ 0 & 0 \end{bmatrix} \quad B_{dw}(k) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$A_d = \begin{bmatrix} e^{A_cT} & e^{A_c(T-L_d)}\int_0^{L_d} e^{A_c\tau}B_c d\tau \\ 0 & 0 \end{bmatrix}$$

$$B_d = \begin{bmatrix} \int_0^{T-L_d} e^{A_c\tau}B_c d\tau \\ 1 \end{bmatrix}$$

$$C_{dw} = \begin{bmatrix} C_d & 0 \end{bmatrix} \quad C_d = \begin{bmatrix} C & 0 \end{bmatrix} \quad \xi_1(k) = u(k)$$

Now, the power amplifier with the following specifications 1-3 is designed and manufactured by constituting digital control systems to the PWM power amplifier (controlled object) at no load.

1. The band-width of control systems is higher than 20[kHz] to each load , i.e., no load, resistance load, capacitive load, parallel load with resistance and capacitive load and inductive load. The value of such loads is restricted to a certain range.
2. Against all the loads of spec.1, an over-shoot is not allowable in a step response.
3. The specs. 1 and 2 are satisfied also to change of the direct-current power supply of $\pm 10\%$.

The load change for the controlled object and the direct-current power supply change are considered as parameter changes in eq.(2). The parameter changes can be transformed to equivalent disturbances q_v and q_y as shown in **Fig.3**. Moreover, if the saturation in the input arises or the input frequency is not so small in comparison with the carrier frequency, the controlled object will be regarded as a class of nonlinear systems. Such characteristics changes can be also transformed to equivalent disturbances as shown in Fig.3. Therefore, what is necessary is just to constitute the control systems whose the pulse transfer functions from equivalent disturbances q_v and q_y to the output y become as small as possible in their amplitudes, in order to robustize or suppress the influence of these parameter changes, i.e., load change, and direct-current power-supply change. In the next section, an easy designing method which makes it possible to suppress the influence of such disturbances with the target characteristics held will be presented.

3 Design of approximate 2DOF digital controller

First, the transfer function between the reference input r and the output y is specified as follows :
$W_{ry}(z)$

$$= \frac{(1+H_1)(1+H_2)(1+H_3)(z-n_1)(z-n_2)(z+H_4)}{(1-n_1)(1-n_2)(z+H_1)(z+H_2)(z+H_3)(z+H_4)} \quad (3)$$

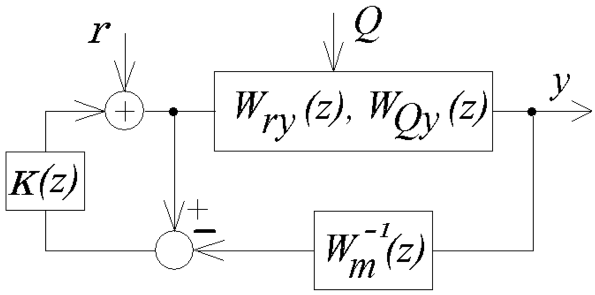

Figure 3: System reconstituted with inverse system and filter

where, n_1 and n_2 are the zeros for the discrete-time control object (2). It shall be specified that the relation of H_1 and H_2, H_3 becomes $|H_1|\gg|Re(H_2)|$, $|H_1|\gg|Re(H_3)|$. Then $W_{ry}(z)$ can be approximated to the following first-order model:

$$W_{ry}(z) \approx W_m(z) = \frac{1+H_1}{z+H_1} \quad (4)$$

This target characteristics $W_{ry}(z) \approx W_m(z)$ is specified so that it satisfies the specs.3 and 4.

Applying a state feedback and a feedforward

$$v = -Fx^* + GH_4 r \quad x^* = [y \;\; x_2 \;\; \xi_1 \;\; \xi_2]^T \quad (5)$$

$$\xi_1(k+1) = Gr \quad (6)$$

to the discrete-time controlled object (2), we determine $F = [F(1,1) \;\; F(1,2) \;\; F(1,3) \;\; F(1,4]$ and G so that $W_{ry}(z)$ becomes eq.(3). If equivalent conversion is carried out at the system which does not use current feedback directly, the control system of only voltage feedback will be obtained. The transfer function $W_{Qy}(z)$ between this equivalent disturbance $Q = [q_v \;\; q_y]^T$ and the output y of the model matching system desfined as

$$W_{Qy}(z) = \left[\; W_{q_v y}(z) \quad W_{q_y y}(z) \;\right] \quad (7)$$

The system added the inverse system and the filter to the system in Fig.3 is constituted as shown in **Fig.4**. In Fig.4, the transfer function $K(z)$ becomes

$$K(z) = \frac{k_z}{z-1+k_z} \quad (8)$$

The transfer functions between $r-y$ and $Q-y$ of the system in Fig.4 are given by

$$y = \frac{1+H_1}{z+H_1}\frac{z-1+k_z}{z-1+k_z W_s(z)}W_s(z)r \quad (9)$$

$$y = \frac{z-1}{z-1+k_z}\frac{z-1+k_z}{z-1+k_z W_s(z)}W_{Qy}(z)Q \quad (10)$$

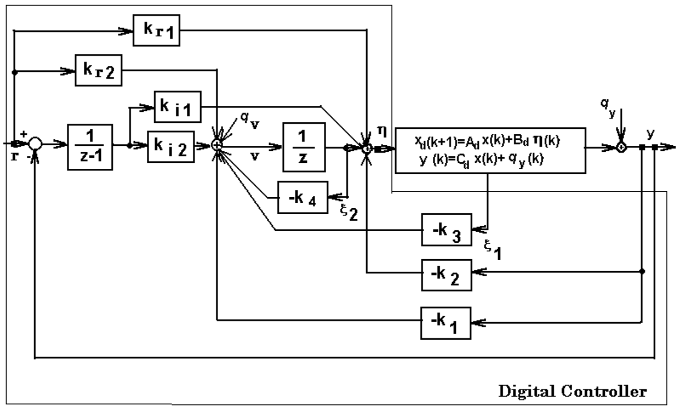

Figure 4: Approximate 2DOF digital integral type control system

where

$$W_s(z) = \frac{(1-H_2)(1+H_3)(z-n_1)(z-n_2)}{(z-H_2)(z+H_3)(1-n_1)(1-n_2)} \quad (11)$$

Here, if $W_s(z) \approx 1$, then Eqs.(9) and (10) become, respectively,

$$y \approx \frac{1+H_1}{z+H_1}r \quad (12)$$

$$y \approx \frac{z-1}{z-1+k_z}W_{Qy}(z)Q \quad (13)$$

From eqs.(12) and (13), it turns out that the characteristics from r to y can be specified with H_1, and the characteristics from Q to y can be independently specified with k_z. That is, the system in Fig.4 is an approximate 2DOF, and its sensitivity against disturbance becomes lower with the increase of k_z.

If an equivalent conversion of the controller in Fig.4 is carried out, the approximate 2DOF digital integral-type control systems will be obtained as shown in **Fig.5**. In Fig.5, the parameters of the controller are as follows :

$$\begin{aligned} k_1 &= F(1,1+F(1,2)FF(1,1)+((-F(1,4) \\ &\quad -F(1,2)FF(1,4))(-F(1,2)/FF(1,2))) \\ &\quad +(GH_4+GF_z)(k_z/(1+H_2)) \\ k_2 &= F(1,2)/FF(1,2)+G(k_z/(1+H_2)) \\ k_3 &= F(1,3)+F(1,2)(FF(1,3)) \quad k_4 = -F_z \\ k_{i1} &= Gk_z \quad k_{i2} = (GH_4+GFz)k_z \\ k_{r1} &= G \quad k_{r2} = GH_4+GF_z \end{aligned} \quad (14)$$

where

$$FF(1,1) = -A_d(1,1)/A_d(1,2)$$

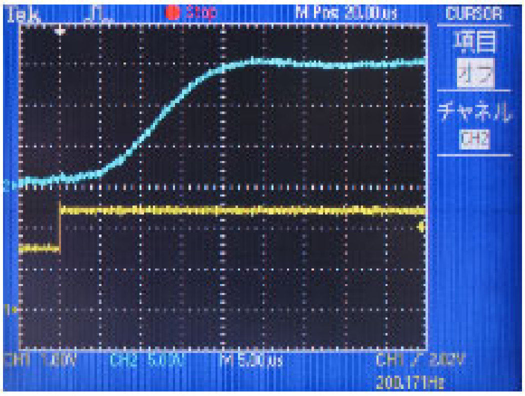

Figure 5: Experimental step response of the output voltage (the upper side : output 5[V/div], the lower side : input 1[V/div], time : 10[μs/div])

$$FF(1,2) = A_d(1,2)$$
$$FF(1,3) = -A_d(1,3)/A_d(1,2)$$
$$FF(1,4) = -B_d(1,1)/A_d(1,2)$$
$$F_z = -F(1,4) - F(1,2)FF(1,4)$$

4 Experimental studies

DSP TMS320LF2801 is used for the digital controller. The sampling frequency is set at 555[kHz] and the design parameters H_1, H_2, H_3 and H_4 are specified as

$$H_1 = -0.825 \quad H_2 = -0.33 - 0.35i \quad H_3 = -0.33 + 0.35i$$
$$H_4 = -0.68 \quad k_z = 0.145 \qquad (15)$$

Then the parameters of controller become as

$$k_1 = -1.4068 \quad k_2 = 2.0296 \quad k_3 = 0.21572$$
$$k_4 = -0.34143 \quad k_{i1} = 0.16316 \quad k_{i2} = -0.05524 \qquad (16)$$

Then experimental result of a step response at no load is shown in **Fig.6**. Here, sine-wave are inputted into the control system with the sampling period $T = 1.8[\mu s]$, and the frequency band width were verified as shown in **Fig.7**. This figure shows that the bandwidth is about 20[kHz] because the output voltage has fallen by about 3 dB at the input frequency 20[kHz]. It turns out that at no load the specification is satisfied.

5 Conclusion

In this paper, it has shown that the bandwidth the PWM power amplifier can be extended using the approximate 2DOF digital controller by getting more

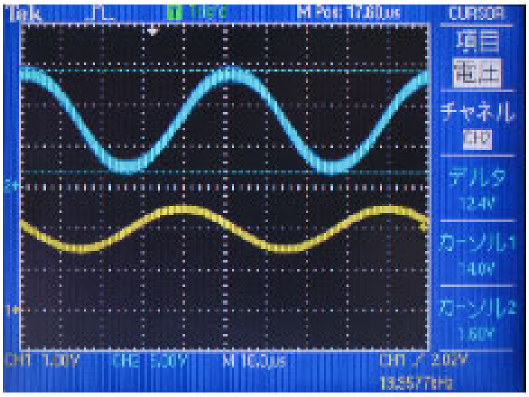

Figure 6: Experimemtal output voltage when the reference input is sine-wave of 20[kHz] (the upper side : output 5[V/div], the lower side : input 1[V/div], time : 10[μs/div])

high sampling and switching frequency. The digital controller was equipmented in DSP, amd it checked by experiment that the sufficient frequency characteristics could be acquired. The bandwidth is about 20[kHz]. As a result, it can use as the examination power supply for many kinds of immunity tests. A future subject is deciding the ranges of all loads and it is checking whether other specifications being satisfied. Furthermore, in order to use for more application, for example the class-D amplifier for audio, it is necessary to acquire more broadband characteristics.

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