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무정전 전원공급장치 적용을 위한 PWM 인버터의 Digital 실시간 제어

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Real Time Digital Control of PWM Inverter for Uninterruptible Power Supply(UPS) application

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Abstract - This paper presents the high performance real time control system of PWM inverter for uninterruptible power supply(UPS). This system is based on a digital control scheme which calculates the pulse widths of the inverter switches for the next sampling time in digital signal processor(DSP). A PI compensator is used to eliminate the voltage error caused by the difference between the actual values of LC filter and those designed. Double regulation loops which are the inner current loop and the outer voltage loop are used to make the transient response time reduce in load disturbance and nonlinear load. This method makes it possible to obtain better response in comparison to conventional digital control system. The proposed scheme provides good performance such as stable operation, low THD of the output voltage, and good dynamic response for load variations and nonlinear load.

1. INTRODUCTION

The uninterruptible power supply(UPS) has been widely used as the emergency power system for the critical load such as computer system. This system consists of a rectifier which supplies the storage energy to the battery tank and an inverter with LC filter which converts a DC source to the sinusoidal AC output. The output performances of the UPS are determined according to the characteristics of the inverter. Nowadays, the harmonic components of the output voltage of an inverter which has nonlinear loads and the dynamic response in case of sudden load change are important factors to estimate the performance of the inverter. From these view points, the PWM techniques are preferred to suppress the harmonic components and to improve the dynamic response.

The sinusoidal PWM or the optimal PWM[1-2] techniques are used to control the fundamental component and to suppress the harmonic components of the output voltage. They are simple and have good characteristics under the steady state. But they operates with poor transient response and the total harmonic distortion factor(THD) of the output voltage increases as the nonlinear load is added. To overcome these problems, the instantaneous feedback control techniques such as hysteresis control[3] or dead-beat control[4-6] were presented. These techniques improve the several drawbacks of the conventional control schemes. Nevertheless, they can not eliminate the steady state errors completely, and their THD are still serious to make trouble in case of nonlinear loads. And also, the digital control approaches offer some problems like that the available maximum pulse width should be guaranteed to some wider value caused by the computation time delay in microprocessor. The difference between the LC filter values used in actual system and the designed values deteriorates the performance of the controller.

In this paper, a new real time digital control technique of the PWM inverter for UPS is presented. This proposed scheme has two variables to control the output voltage. One is the output voltage of the filter capacitor, and the other is the capacitor current. These are formed to double control loop as like as the DC motor controller to get the fast dynamic response of the capacitor output voltage control. They are measured at every sampling time, and used to calculate the on/off time of the PWM pulse at the next sampling time in digital signal processor(DSP). So the PWM pulse patterns are determined one step ahead. Specifically, this system uses a PI compensator to eliminate the output voltage errors caused by the sudden change of load or the deviation of the actual values of LC filter from those designed. The system configuration of the power circuit and control circuit, the digital system modeling, and the results of simulations and experiments are described in this paper.

From the simulation and experimental results, the proposed control scheme well provides the low THD of the output voltage and excellent

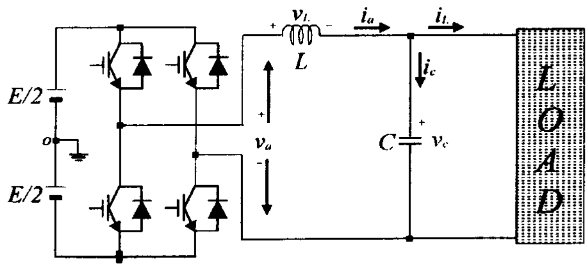

Fig. 1 Circuit diagram of the single phase inverter.

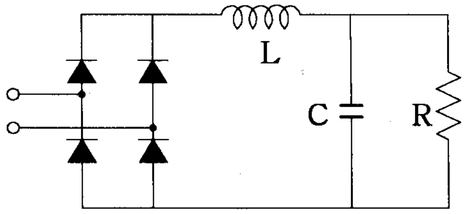

Fig. 2 Power circuit of nonlinear load.

dynamic response in case of sudden load change or nonlinear. The experimental implementation of the system is established using the TMS320C25 DSP.

2. SCHEME OF THE PROPOSED CONTROLLER

2.1 Plant Modeling

Fig. 1 shows the configuration of the power circuit of the single phase PWM inverter for UPS. The power circuit consists of the full bridge inverter and LC filter. Fig. 2 shows the typical nonlinear load such as diode rectifier. From the Fig. 1, the state equation of the system can be drived as follows:

$$X=\begin{bmatrix} V_c \\ I_c \end{bmatrix} \quad \dot{X}=AX+BU \qquad (1)$$

where,

$$A=\begin{bmatrix} 0 & 1 \\ w^2 & -2w\xi \end{bmatrix}$$

$$B=\begin{bmatrix} 0 \\ w^2 \end{bmatrix}$$

$$w=\frac{1}{\sqrt{LC}}$$

$$\xi=\frac{1}{2R}\sqrt{\frac{L}{C}}$$

$$U=V_{in}$$

The sampling interval of the control system, T, is 50[us]. So one period of 60[Hz] reference sine wave is divided into 334 equidistant intervals. The switches are turned on and off once every interval. The inverter output voltage, Vin, takes the value of E, -E, or 0 as the switching state of the devices. Accordingly, the state variables of the output voltage, V_c, and the capacitor current, I_c, at the next sampling instant, t=(k+1)T, is,

$$X(k+1)=\exp(AT)X(k)+\int_{(\tau-u)/2}^{(\tau+u)/2}\exp[A(T-\tau)]BEd\tau \qquad (2)$$

From Eq. (2), the sampled data state equation of the plant is presented as the following Eq. (3). The terms which are higher order than pulse width $U(k)$ in Eq. (3) is neglected, as the magnitude of the pulse width $U(k)$ is smaller than the sampling interval. The sampled data state equation of plant is obtained as follows:

$$X(k+1)=\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}X(k)+\begin{bmatrix} b_1 \\ b_2 \end{bmatrix}U(k) \qquad (3)$$

where

$$a_{11}=\exp(\alpha T)(\cos\beta T-\frac{\alpha}{\beta}\sin\beta T)$$

$$a_{12}=\exp(\alpha T)\frac{\sin\beta T}{\beta}$$

$$a_{21}=-w^2\exp(\alpha T)\frac{\sin\beta T}{\beta}$$

$$a_{22}=\exp(\alpha T)(\cos\beta T+\frac{\alpha}{\beta}\sin\beta T)$$

$$b_1=Ew^2\exp(\frac{\alpha T}{2})\frac{1}{\beta}\sin\frac{\beta T}{2}$$

$$b_2=Ew^2\exp(\frac{\alpha T}{2})(\cos\frac{\beta T}{2}+\frac{\alpha}{\beta}\sin\frac{\beta T}{2})$$

$$\alpha=-\zeta w, \qquad \beta=w\sqrt{1-w^2}$$

2.2 Digital control Algorithm

The power circuit is considered as the plant of a closed-loop digital feedback system with a sinusoidal reference. And the controller has only two measuring datas of the output voltage, V_c, and the capacitor current, I_c. The basic idea consists in predicting the current, I_c flowing through the filter capacitor in order to regulate the output voltage, given the linear dependance between the two quantities.

From Eq. (3), the sampled data state equations of the output voltage and the capacitor current are expressed as Eq. (4) and Eq. (5).

$$V_c(k+1)=a_{11}V_c(k)+a_{12}I_c(k)+b_1U(k) \qquad (4)$$

$$I_c(k+1)=a_{21}V_c(k)+a_{22}I_c(k)+b_2U(k) \qquad (5)$$

Combining Eq. (4) and Eq. (5), and replacing the output voltages $V_c(k+1)$and $V_c(k+2)$by the reference voltages $V_{cref}(k+1)$and $V_{cref}(k+2)$ respectively, the appropriate state of the inverter output voltage is represented,

$$\begin{aligned} U(k+1) &= T_1V_{c_{ref}}(k+2)-T_2V_{c_{ref}}(k+1) \\ &- T_3V_c(k)-T_4I_c(k)-T_5U(k) \end{aligned} \qquad (6)$$

where

$$T_1=\frac{1}{b_1},\ T_2=\frac{a_{11}}{b_{11}},\ T_3=a_{12}\cdot\frac{a_{21}}{b_1},$$

$$T_4=a_{12}\cdot\frac{a_{22}}{b_1},\ T_5=a_{12}\cdot\frac{b_2}{b_1}$$

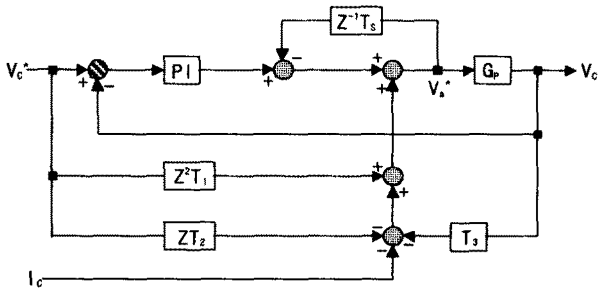

Fig. 3 Configuration of real time output voltage controller.

If the system parameters are not designed exactly, then some errors are generated between the actual output voltage, $V_c(k)$, and the reference voltage, $V_{cref}(k)$. That is, if Eq.(6) is used to determine the inverter output voltage at the next sampling instant, $U(k+1)$, then the control of the system may be unstable.

Therefore, Eq. (6) should be modified to get the stable operation and robustness in spite of the parameter variation. Even if some errors are generated caused by the change of DC input voltage and the difference between the actual values of LC filter component and designed value of them, the compensator should operate to stabilize the output voltage, $V_c(k)$. As a typical compensator, the PI controller is adopted as shown in Fig. 4. The output of the PI controller is calculated as follows:

$$V_{err}(k) = V_{cref}(k) - V_c(k) \tag{7}$$

$$V_{comp} = [K_p V_{err}(k) + K_i \sum_{n=1}^{k} V_{err}(nT)] \tag{8}$$

Combining (6) and (8), the required control variable $U(k+1)$ on next interval can be derived.

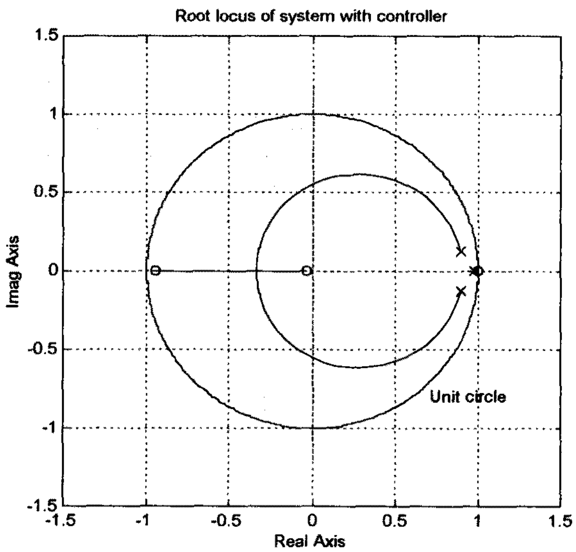

Fig. 4. Root locus with controller.

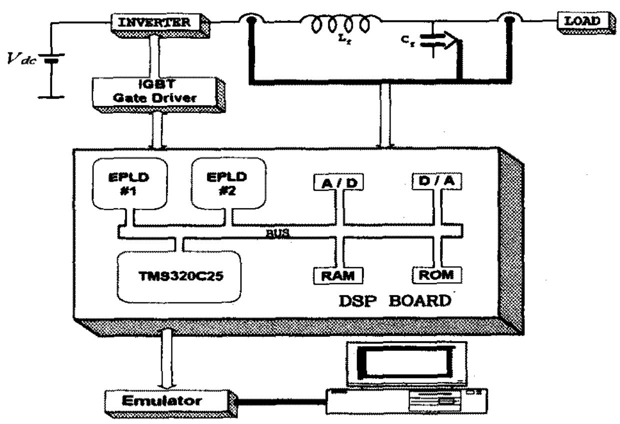

Fig. 5 Configuration of the digital controller hardware.

$$\begin{aligned} U(k+1) &= V_{comp} + T_1 V_{c_{ref}}(k+2) - T_2 V_{c_{ref}}(k) \\ &- T_3 V_c(k) - T_4 I_c(k+1) - T_5 U(k) \end{aligned} \tag{9}$$

Eq. (9) shows that the required control variable $U(k+1)$ at the next sampling interval, (k+1), can be calculated from the measured quantities, $V_c(k)$ and $I_c(k)$, and the known quantities $V_{cref}(k+1)$, $V_{cref}(k+2)$. From Eq. (9), the proposed digital controller is obtained as shown in Fig. 3.

Fig. 4 shows root locus of the proposed system in z-plane. The system stability is validity because the poles are located in unit circle.

3. IMPLEMENTATION OF DIGITAL CONTROLLER

3.1. Hardware Implementation

Fig 5 shows the block diagram of controller hardware using DSP(TMS320C25). DSP performs the real time digital control, the PI compensation and the data acquisition. Hardware of digital controller is largely divided three parts which are data measurement of output voltage V_c and capacitor current I_c at the start of each sampling interval ,operation of calculation equation and digital comparator for PWM generation. Output voltage V_c and capacitor current I_c, which are selected analog multiplexor, are measured at each sampling interval,50[μsec]. Output results of operation values in DSP are compared to 20[kHz] triangle wave which is stored in ROM table. Also IGBT's are used for high switching devices of inverter bridge. From this view point, the higher the switching frequency become, the smaller the filter size and the faster the dynamic response.

3.2 Control procedures

The aforementioned control algorithm can be

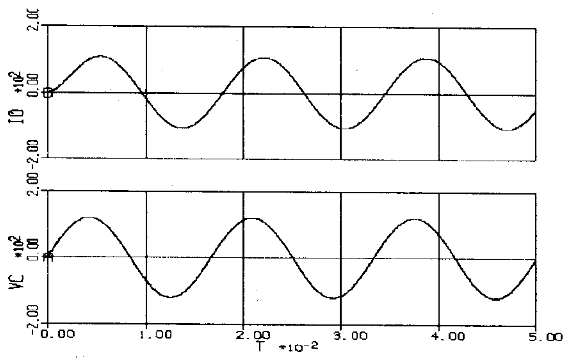

Fig. 6. Simulation result of output waveforms (V_c, I_o) with R-L load.

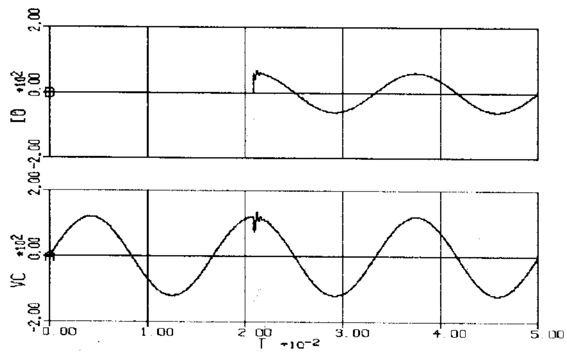

Fig. 7. Simulation result of output waveforms (V_c, I_o) with load change (increasing)

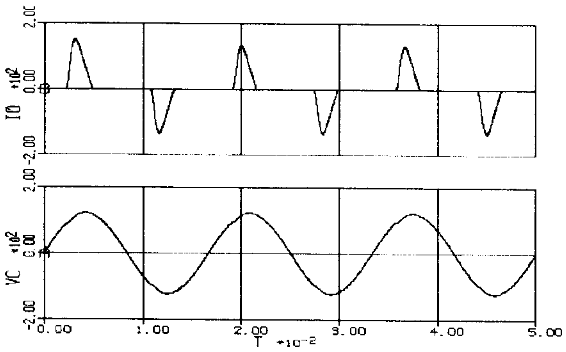

Fig. 8. Simulation result of output waveforms (V_c, I_o) with rectifier load.

shown as follows

[Step 1] Processor initiation and parameter set up.
[Step 2] Set timer interrupt.
[Step 3] Get the k-th reference table(V_c^*).
[Step 4] Measure stable variables ($V_c(k), I_c(k)$).
[Step 5] Calculate Eq. (8) and (9).
[Step 6] Output the operated $U(k+1)$.
[Step 7] Increment k and return [step 3].

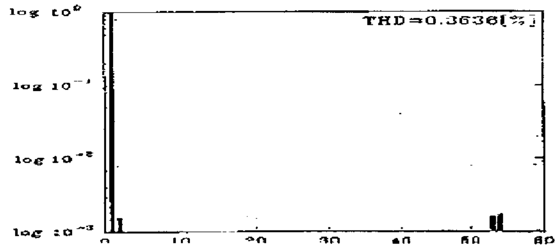

Fig. 9 Simulation spectrum of output voltage(V_c) with R-L load.

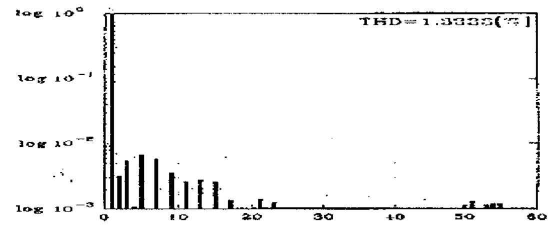

Fig. 10 Simulation spectrum of output voltage(V_c) with rectifier load.

This algorithm from [Step 1] to [Step 7] is carried to every 50[μsec], that is, inverter switching frequency 20[kHz].

4. SIMULATED AND EXPERIMENTAL RESULTS

Characteristics of this new principle of single phase PWM inverter were investigated using digital computer. The proposed digital algorithm was simulated by Advanced Continuos Simulation Language (ACSL) and carried out to study harmonic contents of output voltage under R-L load and rectifier load, respectively. The circuit constants of the system used to simulation are:

Sampling interval	T = 50[μsec]
Switching frequency	20[kHz]
DC link voltage	160[V]
Rated load	5[KVA]
Output frequency	60[Hz]
Output voltage	120[V]
Maximum current	90[A]
Filter inductance	200[μH]
Filter capacitance	100[μF]

In case of R-L load, the simulation result for the output voltage V_c and the load current I_o is shown in Fig. 6. Fig. 7 shows the simulation result for the output voltage V_c and the load current I_o waveforms when the load is changed from the no load to the rated load. From Fig. 7, there are small transient interval and fast response in load variations. Fig. 8 shows the simulated output voltage V_c and the load current I_o waveforms for nonlinear load

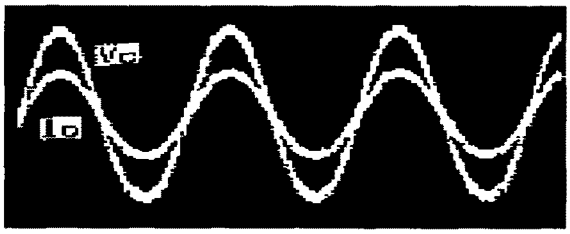

Fig. 11 Experimental result of output waveforms (V_c, I_o)with resister load.(20V/div, 20A/div)

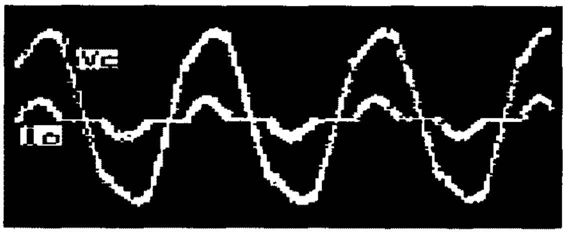

Fig. 12 Experimental result of output waveforms (V_c, I_o)with rectifier load.(20 V/div, 20A/div)

with diode rectifier, respectely. The distortion of output voltage is very small, even feeding high di/dt output current. As shown in Fig. 9, spectrum of output voltage is obtained a very low THD 0.3636[%] in R-L load. In case of rectifier load, Fig. 10 shows very low THD 1.3333[%] in spectrum of output voltage. Consequently, it is easy to understand that the proposed control technique well performs excellent response and robustness for various cases such as sudden load variation and rectifier load.

In order to confirm the validity of the theory, experiments were carried out for two types. Fig. 11 shows the experimental output voltage V_c and the load current I_o waveforms for linear load. Fig. 12 shows the experimental output voltage V_c and the load current I_o waveforms for nonlinear load with diode rectifier. From the experimental results, the output waveforms are nearly close to the sinusoidal waveform such ac nonlinear load.

5. CONCLUSION

This paper describes a new real time digital controller which is used prediction method of capacitor current and a PI compensator for a UPS inverter. Specifically, this system uses a PI compensator to eliminate the output voltage deviation. Output voltage and capacitor current are formed to double control loop as like as the DC motor controller to get the fast dynamic response of the capacitor output voltage control.

From the simulation and experimental results, it is shown that the proposed scheme has good performance such as stable operation, very low THD of the output voltage, and good dynamic response for the nonlinear load such as diode bridge rectifier. The experimental implemen -tation of the system is established by using the TMS320C25 DSP. This type of PWM inverter system is particularly suitable for solar cell and fuel cell energy converters.

[REFERANCES]

[1] G. S. Buja,"Optimum Output Waveform in PWM Inverters", IEEE Trans. Ind. Appl. Vol. IA-16 pp.830-836 , 1980.

[2] P. Zigas,"Delta Modulation Technique in Static PWM Inverters",IEEE Trans. Ind. Appl. ,Vol. IA-17,pp. 289-295, 1981.

[3] A. Kawamura and R.G.Hoft, "Instantaneous feedback controlled PWM inverter with adapitive hystereses", IEEE Trans. Ind. Appl., Vol. IA-20,pp. 769-775, 1984.

[4] I. Takahashi and M Nunokawa, "Prediction Control for a Cycloconverter of a Power Distortion Compensation System", Conf. Rec. IEEE IAS Ann. Meeting, pp. 766-777, 1987.

[5] A. Kawamura, R. Churayapratip, and T. Haneyoshi, "Deatbeat Controller PWM Inverter with Modified Pulse Patterns for Uninterruptible Power Supply", IEEE Trans. Ind. Elec., Vol.35, No.2 May, pp 295-300, 1988.

[6] T. Kawabata, T.Miyashita, and Y. Yamamoto, "Digital control of three phase PWM inverter with L-C filter", IEEE Trans. Pow . Elec., Vol. 6, No.1, pp229-239, 1991