第26卷 第4期
2007年10月

电工电能新技术
Advanced Technology of Electrical Engineering and Energy

Vol. 26, No. 4
Oct. 2007

# A Robust Deadbeat Control Method for UPS Inverters

WANG Meng (汪 孟)[1], LI Fang-zheng (李方正)[1], HUANG Li-pei (黄立培)[1], SAKANE Makoto[2]

(1. State Key Lab of Power Systems, Dept. of Electrical Engineering, Tsinghua University, Beijing 100084, China;
2. GS Yuasa Power Electronics Ltd., Osaka 569-1115, Japan)

**Abstract**: The traditional deadbeat control for UPS inverters has a robustness problem. The parametric imprecision can greatly harm the stability of the system, which restricts the application. A novel robust deadbeat control method is proposed in this paper to deal with the problem. In the proposed control method, a proportional element is added to the traditional deadbeat control in order to improve the robustness to parametric imprecision. To eliminate the error between output voltage and voltage reference caused by environmental noise and parametric deviation, a model reference adaptive regulator is also added to the control method. A 1kVA prototype is built based on DSP. Theoretical analysis and experimental results show that the robustness for parametric variation of the proposed method is much better than the traditional deadbeat control. The system can remain stable even when the systemic parameters have a large deviation from calculating parameters. The system has small static error and fast dynamic response with the new control method. This method is easy to realize in DSP and is suitable for full digital realization of UPS.

**Key words**: UPS inverter; deadbeat control; robustness; model reference adaptive control

中图分类号: TM464　　文献标识码: A　　文章编号: 1003-3076(2007)04-0031-05

## 1 Introduction

With the rapid growth in the use of UPS (uninterrupted power supply) and the increasing need for high quality UPS, its full digital implementation has been much focused on. To limit the output voltage distortion and improve the performance of UPS inverters, various digital control methods have been proposed[1-5], such as repetitive control, deadbeat control, sliding mode control, and etc.

Deadbeat control, derived from state equations, has fast dynamic response and can eliminate the state variable errors in several control periods. However, its high sensitivity to parametric mismatches, model uncertainties, and noise on the sensed variables still restricts its application[3-5].

This paper proposed a novel robust deadbeat control that is simple and can be easily realized in DSP. A proportional element is added to the traditional deadbeat control. It can effectively improve the robustness of deadbeat control with the expense of a little increased static error and slower dynamic response. A model reference adaptive control regulator is also added to eliminate the output voltage deviation caused by environmental noise and parametric uncertainties. Experiments are carried out on a 1kVA UPS prototype based on DSP TMS320LF2407A. Theoretical analysis and experiments prove the validity and effectiveness of the proposed method.

## 2 Robust Deadbeat Control

The circuit of a single-phase half-bridge UPS inverter is shown in Fig. 1. If the ESR of capacitor is neglected, the capacitor voltage $u_c$ equals to the output voltage $u_o$. The voltage $u_o$ and the inductance current $i_L$ are chosen as state variables, and the load current $i_o$ is

---

收稿日期: 2007-05-08

作者简介: 汪 孟(1983-), 女, 江苏籍, 硕士, 研究方向电力电子与电力传动;
黄立培(1946-), 男, 江苏籍, 教授/博导, 博士, 研究方向为高性能交流电机控制、电力电子变流技术。

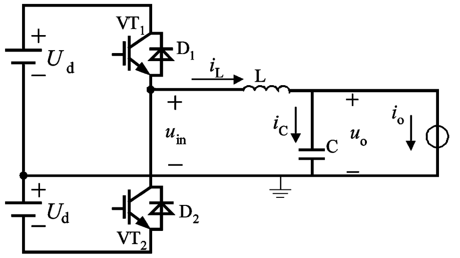


Fig. 1　Diagram of single-phase half-bridge inverter

treated as disturbance. The system state equation is

$$\dot{\boldsymbol{x}} = \boldsymbol{A} \cdot \boldsymbol{x} + \boldsymbol{B} \cdot u_{in} + \boldsymbol{D} \cdot i_o \tag{1}$$

$$y = \boldsymbol{C}^T \cdot x \tag{2}$$

where $x = [u_o \ i_L]^T$, $\boldsymbol{A} = [0 \quad 1/C; -1/L \quad 0]$, $\boldsymbol{B} = [0 \quad 1/L]^T$, $\boldsymbol{D} = [-1/C \quad 0]^T$, $\boldsymbol{C} = [1 \quad 0]^T$ $u_{in}$ is the input voltage of the LC rectifier, and in the two level pattern it is either $+U_d$ or $-U_d$.

The discrete state equation can be expressed as

$$x(k+1) = \Phi x(k) + \mathbf{G}\Delta T(k) + \mathbf{P} i_o(k) + \mathbf{H} \tag{3}$$

where

$$\Phi = e^{AT} = [\Psi_{11} \quad \Psi_{12}; \Psi_{21} \quad \Psi_{22}]^T \tag{4}$$

$$\mathbf{G} = 2U_d e^{(AT/2)} \boldsymbol{B} = [g_1 \quad g_2]^T \tag{5}$$

$$\mathbf{P} = -A^{-1}(I - e^{AT})\boldsymbol{D} = [p_1 \quad p_2]^T \tag{6}$$

$$\mathbf{H} = U_d A^{-1}(I - e^{AT})B = [h_1 \quad h_2]^T \tag{7}$$

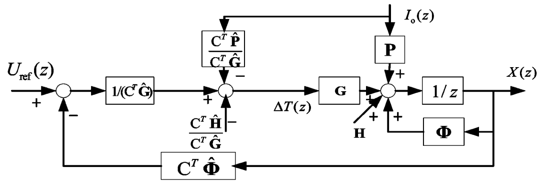
Where $T$ is the control period, $\Delta T(k)$ is the acting time of positive voltage $+U_d$ in the $k$th control period.

In the traditional deadbeat control, the required pulse width $\Delta T(k)$ can be computed by making $u_o(k+1)$ in the first equation in (3) equal to the voltage reference $u_{ref}(k+1)$. It holds

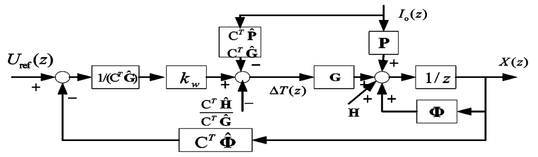
$$\Delta T(k) = \frac{1}{g_1}u_{ref}(k+1) - \frac{\Psi_{11}}{g_1}u_o(k) - \frac{\Psi_{12}}{g_1}i_L(k) - \frac{p_1}{g_1}i_o(k) - \frac{h_1}{g_1} \tag{8}$$

Deadbeat control depends on the precise mathematical models of the controlled object. On ideal conditions, the actual parameters of the inverter are identical with calculating parameters used in equation (8). However, the precise systemic model is difficult to obtain, and the actual parameters may change during operation.

Fig. 2 shows the discrete system block diagrams of the traditional deadbeat control and the deadbeat control part of the proposed method. Symbols with ‘^’ stand for calculating values and symbols without ‘^’ stand for actual values. The difference between Fig. 2(a) and Fig. 2(b) is that a proportional element $k_w$ is added to the new method. Usually $0 < k_w < 1$, and it returns to traditional deadbeat control if $k_w = 1$.



(a)　traditional deadbeat control



(b) deadbeat control part of the proposed method

Fig. 2　Discrete system block diagram

The transfer function from $U_{ref}(z)$ to $X(z)$ in Fig. 2(b) is

$$\frac{X(z)}{U_{ref}(z)} = \left[\frac{C^T\hat{G}}{k_w}(z\boldsymbol{I} - \Phi) + \boldsymbol{G}C^T\hat{\Phi}\right]^{-1}\mathbf{G} \tag{9}$$

The transfer function from voltage reference to output voltage is

$$\begin{aligned} G_i(z) &= \frac{U_o(z)}{U_{ref}(z)} = \frac{C^T X(z)}{U_{ref}(z)} \\ &= C^T\left[\frac{C^T\hat{G}}{k_w}(z\boldsymbol{I} - \Phi) + \boldsymbol{G}C^T\hat{\Phi}\right]^{-1}\mathbf{G} \\ &= \frac{k_w(g_1 z + g_2\Psi_{12} - g_1\Psi_{22})}{q(z)} \end{aligned} \tag{10}$$

where

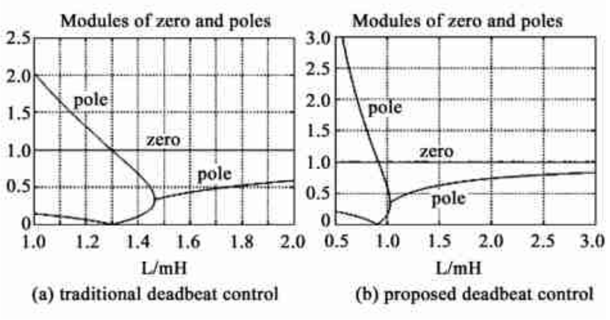
$$\begin{aligned} q(z) = {} & \hat{g}_1 z^2 + [g_1\hat{\Psi}_{11}k_w + g_2\hat{\Psi}_{12}k_w - \hat{g}_1\Psi_{22} \\ & - \hat{g}_1\hat{\Psi}_{11}]z + g_2 k_w(\hat{\Psi}_{11}\Psi_{12} - \Psi_{11}\hat{\Psi}_{12}) + \Psi_{21} \\ & (g_1\hat{\Psi}_{12}k_w - \hat{g}_1\Psi_{12}) + \Psi_{22}(\hat{g}_1\Psi_{11} - g_1\hat{\Psi}_{11}k_w) \end{aligned}$$

If $k_w = 1$, and the calculating values and the actual values are the same, equation (10) can be simplified as

$$G(z) = 1/z \tag{11}$$

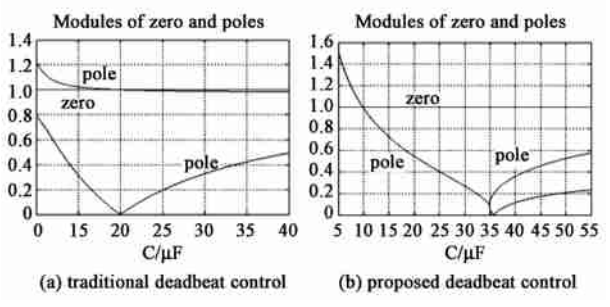
It means that with the traditional deadbeat control, the output voltage follows the reference in one control period in case that there is no parametric mismatch.

However, it is not always the case in practice. A typical UPS inverter main circuit is considered to study the influence of parametric mismatching. The calculating parameters are: $\hat{U}_d = 185\text{V}$, $\hat{L} = 1.3\text{mH}$, $\hat{C} = 20\mu\text{F}$. Fig. 3(a) shows the module tracks of zero and poles of the transfer function in traditional deadbeat control, when $L$ changes, and $U_d$ and $C$ are the same with calculating values. Similarly, Fig. 4(a) and Fig. 5(a) show the module tracks when $C$ and $U_d$ change respectively. According to control therory, the modules of each pole should be less than 1 to ensure the system stable. When actual parameters match calculating values, the zero counteracts one pole, and we get equation (11). However, when there is parametric mismatch, the system can easily become unstable. As shown in Fig. 3(a), Fig. 4(a) and Fig. 5(a), when the actual inductance $L$ is smaller than $\hat{L}$, or the actual capacitor $C$ is smaller than $\hat{C}$, or the actual DC link voltage $U_d$ is bigger than $\hat{U}_d$, the system has a pole outside the unit circle in Z-plane and becomes unstable. The poor robustness makes the traditional deadbeat control almost impracticable in UPS application.



(a) traditional deadbeat control　(b) proposed deadbeat control

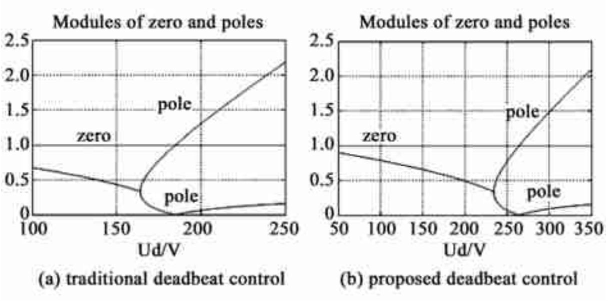
Fig. 3　Modules of zero and poles when $L$ changes



(a) traditional deadbeat control　(b) proposed deadbeat control

Fig. 4　Modules of zero and poles when $C$ changes

The proposed deadbeat control with a proportional element has better robustness compared with the traditional method. Fig. 3(b), Fig. 4(b) and Fig. 5(b) show the module tracks of equation (10) ($k_w = 0.7$) when $L$, $C$, and $U_d$ change respectively. We can see that in this case the system can remain stable as long as $L$ is larger than 0.913mH (70.23% $\hat{L}$), $C$ is larger than 9.82μF (49.1% $\hat{C}$), and $U_d$ is smaller than 264.5V (146.94% $\hat{U}_d$).



(a) traditional deadbeat control　(b) proposed deadbeat control

Fig. 5　Modules of zero and poles when $U_d$ changes

Tab. 1 lists the constraints for actual parameters in traditional and the proposed deadbeat control to make the system stable. It is obvious that constraints in the proposed method are much less strict, and the control method has better robustness when actual parameters deviate from calculating parameters.

**Tab. 1　Constraints for systemic parameters**

| Parameters / Constraints | $L$(mH) | $C$(μF) | $U_d$(V) |
|---|---|---|---|
| Traditional deadbeat | $\geqslant \hat{L}$ | $\geqslant \hat{C}$ | $\leqslant \hat{U}_d$ |
| Proposed deadbeat ($k_w = 0.7$) | $> 70.23\%\hat{L}$ | $> 49.1\%\hat{C}$ | $< 146.94\%\hat{U}_d$ |

The proportional element improves the robustness of the deadbeat control, while it causes a little increased static error. From equation (10) we can get the frequency response by substituting z with $e^{j\omega T}$

$$\dot{G}_i(j\omega) = \frac{\dot{U}_o(j\omega)}{\dot{U}_{ref}(j\omega)} = \frac{k_w(g_1 e^{j\omega T} + g_2\Psi_{12} - g_1\Psi_{22})}{q(e^{j\omega T})} \tag{12}$$

where $\dot{U}_{ref}(j\omega)$ and $\dot{U}_o(j\omega)$ are voltage reference phasor and output voltage phasor respectively. In UPS inverters, the voltage reference $u_{ref}$ is a sine wave with the frequency of 50 Hz, and $\omega_{ac}$ is 314 rad/s. The control frequency is 20 kHz in experiment, and the corresponding control period $T$ is 50 μs. Suppose that the actual parameters match the calculating parameters, Fig. 6 shows the module and phase of $\dot{G}_i(\mathrm{j}\omega_{ac})$ when $k_w$ changes. The steady state error between output voltage and voltage reference increases corresponding to the decrease of the value of $k_w$. When $k_w = 0.7$, the amplitude error is 2%, and the phase error is $-0.891°$. The system still has good steady state performance.

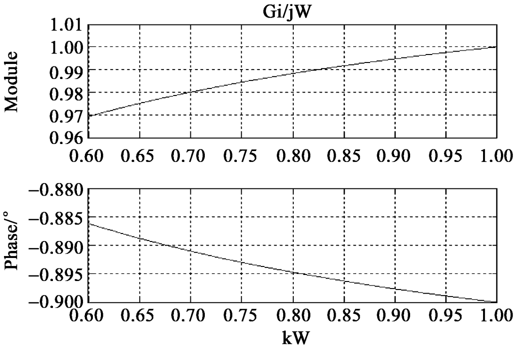


Fig. 6 Influence of $k_w$ on steady state performance

## 3 Model Reference Adaptive Regulator

Because of the actual parametric variance, the sampling noise of state variables and etc, the output voltage may deviate from voltage reference. Besides, the proportional element increases the static error as stated above. Since the phase error can be neglected, we use a model reference adaptive regulator with adjustable amplifying coefficient to eliminate the error between output voltage and voltage reference. Fig. 7 shows the control diagram. The ideal deadbeat control is used as the reference model, which is a delay element with the continuous time transfer function $e^{-Ts}$. The continuous time transfer function of the proposed deadbeat controlled system is $K_v e^{-Ts}$. $K_v$ is the gain of the actual system influenced by environmental conditions. The voltage reference $u_{ref}$ does not act on the controlled system directly as in usual cases. Instead, an adjustable amplifying coefficient $k_c$ is added between $u_{ref}$ and the controlled system. $u_{om}$ and $u_o$ are the output voltages of reference model and actual system respectively, and $e$ stands for the error between them. $k_c$ is adjusted based on the model reference adaptive control law. According to M. I. T. rule[6], in order to minimize

$$J = \frac{1}{2}\int e(\tau)^2 \mathrm{d}\tau = \frac{1}{2}\int (u_{om}(\tau) - u_o(\tau))^2 \mathrm{d}\tau \tag{13}$$

the gradient of $k_c$ should be

$$\dot{k}_c = -\lambda \frac{\partial J}{\partial k_c} = -\lambda e \frac{\partial e}{\partial k_c} = -\lambda e \left( \frac{\partial u_{om}}{\partial k_c} - \frac{\partial u_o}{\partial k_c} \right) = \lambda e \frac{\partial u_o}{\partial k_c} \tag{14}$$

where $\lambda > 0$

After deduction, we can get that

$$\frac{\partial u_o}{\partial k_c} = K_v u_{on} \tag{15}$$

Combining formula (14) and formula (15), it holds

$$\dot{k}_c = \lambda K_v e u_{om} \tag{16}$$

The initial value of $k_c$ is $k_{c0}$. The coefficient $k_c$ is adjusted according to the product of voltage error signal $e$ and reference model output $u_{om}$ to reduce the error between $u_{om}$ and $u_o$, as shown by formula (16). Formula (16) is the adaptive law to make sure error $e(t)$ converges to zero or a certain allowable value.

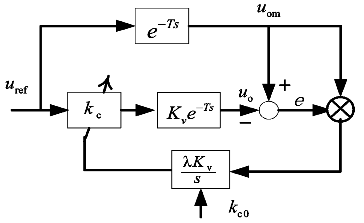


Fig. 7 Model reference adaptive control with M. I. T rule

## 4 Experimental Results

Experiments using the proposed robust deadbeat control method are carried out on a half-bridge inverter system. DSP TMS320LF2407A is used to achieve the control scheme. The experimental parameters:

Sampling frequency: 20 kHz
Rated capacity: 1 kVA/700 W
Output voltage reference: 50 Hz, 100 V(RMS)
DC bus voltage: 185 V
Output filter: $L$ 1.3 mH, C 20μF

Fig. 8, Fig. 9 and Fig. 10 show the waveform of output voltage and output current with resistant load, no load and rectifier load respectively. The RMS values of voltage are 99.5V, 101.7 V and 99.8 V. The THD values are 1.09%, 1.06% and 1.08%.

Fig. 11 shows the dynamic process of output voltage and output current when the load changes from rated load

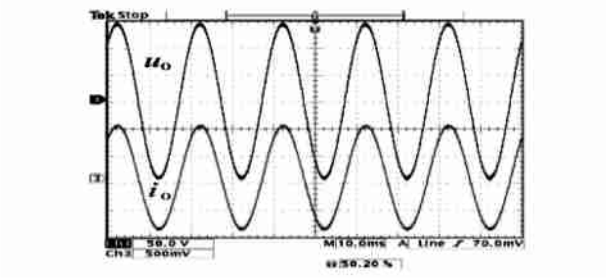


Fig. 8 Output voltage and current with resistance load ( $u_o$ 50 V/div, $i_o$ 5 A/div)

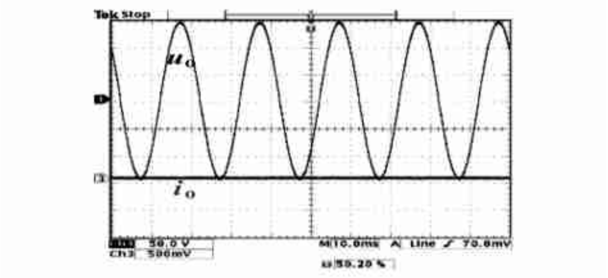


Fig. 9 Output voltage and current with no load ( $u_o$ 50 V/div, $i_o$ 5 A/div)

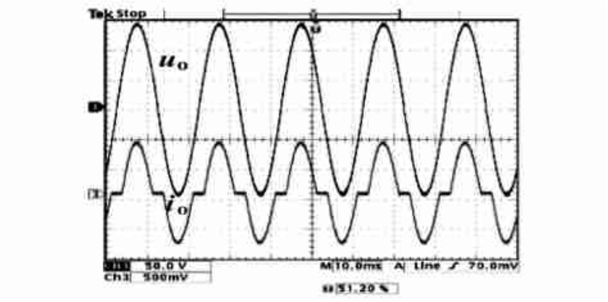


Fig. 10 Output voltage and current with rectifier load ( $u_o$ 50 V/div, $i_o$ 5 A/div)

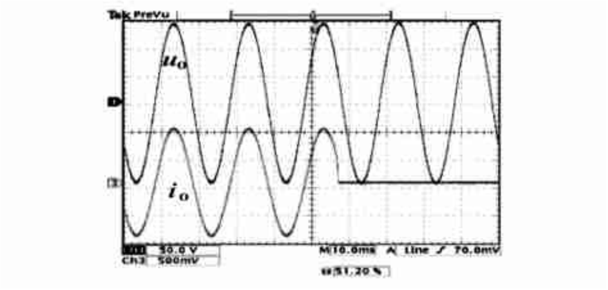


Fig. 11 Output voltage and current with step load( R to ∞) ( $u_o$ 50 V/div, $i_o$ 5 A/div)

to no load. The RMS values of voltage in one period before and after the load change is 99.6 V and 100.6 V respectively, and the voltage change ratio is 1%.

Tab. 2 shows the static performance of the output voltage when the actual parameters of output filter deviate from the calculating parameters ( $\hat{L}$ = 1.3 mH, $\hat{C}$ = 20μF). $L$ changes from 0.5mH to 2.0mH ( 38.5% ~ 153.8% $\hat{L}$ ), and $C$ changes from 10μF to 30μF( 50% ~ 150% $\hat{C}$ ). The prototype still has good performance when the deviation is within a certain range. The RMS value deviation of voltage is less than 2% under rated load, and less than 4% under no load, and the THD of voltage is less than 1.5%. Only when $L$ is reduced to 38.5% $\hat{L}$ ( 0.5mH) and $C$ is reduced to 50% ( 30μF), the system becomes unstable.

**Tab. 2 Static performance with parametric deviation**

| Output Filter | | Rated Load | | No Load | |
|---|---|---|---|---|---|
| $L$( mH) | $C$ (μF) | $U_o$( V) | THD( %) | $U_o$( V) | THD( %) |
| 2.0 | 30 | 100.3 | 1.09 | 101.5 | 1.07 |
| 1.5 | 30 | 100.0 | 1.11 | 102.1 | 1.07 |
| 1.0 | 30 | 100.5 | 1.12 | 102.4 | 1.07 |
| 0.5 | 30 | 100.9 | 1.19 | 102.9 | 1.20 |
| 2.0 | 20 | 100.3 | 1.10 | 102.3 | 1.05 |
| 1.5 | 20 | 100.5 | 1.10 | 101.4 | 1.11 |
| 1.0 | 20 | 100.6 | 1.13 | 101.8 | 1.13 |
| 0.5 | 20 | 101.0 | 1.30 | 103.3 | 1.34 |
| 2.0 | 10 | 100.1 | 1.12 | 101.5 | 1.14 |
| 1.5 | 10 | 101.2 | 1.15 | 101.9 | 1.17 |
| 1.0 | 10 | 101.4 | 1.27 | 103.1 | 1.30 |
| 0.5 | 10 | Unstable | | | |

The prototype has desirable static performance under different kinds of load. Load change causes little disturbance to the output voltage during dynamic process. The system can remain stable when actual parameters deviate from calculating parameters. Experimental results prove that with the proposed control method, the inverter has both small static error and fast dynamic response, and has robustness for parametric deviation.

## 5 Conclusion

A novel deadbeat control method for UPS converters is proposed in this paper. A proportional element is added in this method to improve the robust performance to systemic parameters. Besides, an adaptive regulator is applied to eliminate the error between output voltage and voltage reference. The method does not require much

( 下转第 64 页, cont. on p. 64)

基于PID控制和重复控制的正弦波逆变电源研究(Study on sine wave inverters with PID control and repetitive control) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2002, 21(1): 1-4.

[6] Aleksandar Prodic, Dragan Maksimovic, Robert W Erickson. Design and implementation of a digital PWM controller for a high-frequency switching DC-DC power converter [A]. IECON' 2001 [C]. Denver, CO, USA, 2001. 893-898.

[7] T W Martin, S S Ang. Digital control for switching converters [A]. ISIE' 95 [C]. Athens, Greece, 1995. 480-484.

[8] 舒为亮, 张昌盛, 段善旭, 等 (Shu Weiliang, Zhang changsheng, Duan Shanxu, Kang Yong). 逆变电源PI双环数字控制技术研究 (Research on PI dual-loop digital control technology for inverter supply) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2005, 24(2): 52-54.

# Two level inverter controlled by single DSP

WANG Feng-yan[1,2], ZHAO Wei-gang[1], XU Jian-ping[2]
(1. National EW Laboratory, CETC No.29 Research Institute, Chengdu 610036, China;
2. College of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, China)

**Abstract**: The paper studied "DC/DC converter + DC/AC inverter" two level converter which is controlled by single DSP controller. The principle of the circuit is introduced. The transfer functions of DC/DC converter and DC/AC inverter are designed based on a more accurate model proposed. The influence of digital controller's control delay is analyzed and simulated. The validity of circuits and control transfer function is verified by the experiment on a 500VA 28VDC/115V 400Hz inverter prototype.

**Key words**: inverter; converter; digital control; DSP

---

(上接第35页, cont. from p.35)

computation and can be easily realized in DSP. Systemic analysis and experiments prove that it greatly improves the robustness of deadbeat control, and has good steady state performance and fast dynamic response. It is quite suitable for the full digital implementation of UPS.

**References**:

[1] Liviu Mihalache. DSP control method of single-phase inverters for UPS applications [A]. Proc. IEEE APEC 2002 [C]. Dallas, US, 2002. 590-596.

[2] 熊健, 周亮, 张凯, 等 (Xiong Jian, Zhou Liang, Zhang Kai, et al.). 一种高性能的单相逆变器多环控制方案 (A high precision multi-loop control strategy for single-phase PWM inverters) [J]. 电工技术学报 (Trans. China Electrotechnical Society), 2006, 21(12): 79-83.

[3] Paolo Mattavelli. An improved deadbeat control for UPS using disturbance observers [J]. IEEE Trans. on Industrial Electronics, 2005, 52(1): 206-212.

[4] 汪孟, 刘亚东, 李方正, 等 (Wang Meng, Liu Yadong, Li Fangzheng, et al.). UPS逆变器的渐近收敛无差拍控制 (Progressively converging deadbeat control for UPS inverter) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2007, 26(1): 47-50.

[5] 李俊林, 熊健, 康勇 (Li Junlin, Xiongjian, Kang Yong). 逆变器数字多环控制技术研究 (Study on digital multiple-loop control technology of inverters) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2004, 23(4): 57-59.

[6] Whitaker H P, Yamron J, Kezer A. Design of model reference adaptive control systems for aircraft [R]. Report No. R- 164, Instrumentation Lab. MIT, 1958.

[7] 熊健, 史鹏飞, 张凯, 等 (Xiong Jian, Shi Pengfei, Zhang Kai, et al.). 基于电压微分反馈控制和重复控制的逆变电源控制技术 (Voltage-differential-feedback control plus repetitive control for PWM inverters) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2006, 25(3): 46-49.

[8] 梁斌, 瞿文龙 (Liang Bin, Qu Wenlong). 一种新型单相DC/AC逆变器的并联控制方法 (A new control method for parallel single-phase DC/AC inverter) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2006, 25(4): 58-62.

[9] 马学军, 陈息坤, 康勇 (Ma Xuejun, Chen Xikun, Kang Yong). 一种新的基于DSP的高精度UPS锁相技术 (A novel high precision phase-locked method for UPS based on DSP) [J]. 电工电能新技术 (Adv. Tech. of Elec. Eng. & Energy), 2005, 24(4): 59-62.

[10] 汪孟 (Wang Meng). 单相在线式UPS的数字控制和并联运行 (Digital control and parallel operation for single-phase on-line UPS) [D]. 北京: 清华大学 (Beijing: Tsinghua University), 2007.

[11] Meng Wang, Fangzheng Li, Yadong Liu, et al. Distributed parallel operation of modified deadbeat controlled UPS inverters [A]. The 38th IEEE PESC [C]. Orlando, Florida, USA, 2007. 1727-1732.