*Journal of* ELECTRICAL ENGINEERING, VOL. 55, NO. 3-4, 2004, 64–70

# AN ALGORITHM FOR THE OUTPUT WAVEFORM COMPENSATION OF SPWM INVERTERS BASED ON FUZZY–REPETITIVE CONTROL

**Duan Shan-Xu — Kang Yong — Chen Jian** *

An algorithm based on fuzzy-repetitive control for the output waveform compensation of single-phase CVCF inverters is presented. The performance of CVCF inverters is evaluated in terms of output voltage waveform distortion with linear or nonlinear loads and transient response due to sudden changes in the load. The fuzzy PD controller is used to improve transient performance whenever the system exhibits an oscillatory or overshoot behavior. It preserves the simple linear structure of the conventional PD controller yet enhances its self-tuning control capability. Since fuzzy PD controller cannot provide good small-signal response, repetitive control is applied to generate high-quality sinusoidal output voltage in steady state. Repetitive control can be regarded as a simple learning control because the control input is calculated using the information of the error signal in the preceding periods. The repetitive controller is synthesizing to minimize low-order harmonic distortion. Thus, the fuzzy PD controller and repetitive controller can be combined to take advantage of their positive attributes. The control scheme is implemented based on DSP in a 400 Hz 5.5 kW prototype. Simulation and experimental results prove that the proposed control scheme can achieve not only low THD during steady-state operation but also fast transient response subject to load step change.

K e y w o r d s: fuzzy control, inverter, repetitive control

## 1 INTRODUCTION

In recent years, single-phase constant-voltage constant-frequency (CVCF) inverters have been widely employed in UPS. The output voltage of CVCF inverter is required to follow a sinusoidal command. Its performance is evaluated in terms of output voltage waveform distortion with linear or nonlinear loads and transient response due to sudden changes in the load.

With the availability of high-frequency switching devices and high-performance microprocessors, many digital control schemes with output voltage feedback have been applied to the closed-loop regulation of the CVCF inverters. Deadbeat-controlled PWM inverter has very fast response for load disturbances and nonlinear loads. But in the deadbeat control approach, the control signal depends on a precise PWM inverter load model and the performance of the system is sensitive to parameter and load variations. Sliding mode control of inverter has proved quite useful against parameter variations and external disturbances. However, the well-known chattering problem must be especially taken care in digital realization of the control algorithm. Repetitive control, which modifies the reference command by adding a periodic compensation signal, is applied to generate high-quality sinusoidal output voltage in the inverter whereas its dynamic response is poor [1–4].

In this paper, a hybrid fuzzy-repetitive control scheme for single-phase CVCF inverters is presented. The principle of the proposed control scheme is to use a repetitive controller, which performs satisfactorily in steady state, while a fuzzy PD controller improves transient performance whenever the system exhibits an oscillatory or overshoot behavior. The main improvement of fuzzy PD controller is in endowing the classical PD controller with a certain adaptive control capability. FLC can handle nonlinearity and does not need accurate mathematical model [5–7]. It is represented by if-then rules and thus can provide an understandable knowledge representation.

The control scheme is implemented using a TI TMS320 F240 digital signal processor (DSP). Simulation and experimental results prove that the proposed control scheme can achieve not only low THD during steady-state operation but also fast transient response subject to load step change.

## 2 INVERTER SYSTEM MODEL

The circuit diagram of a single-phase full-bridge voltage-source CVCF inverter is shown in Fig. 1. Since the switching frequency is much higher than the natural frequency and modulation frequency, the dynamics of inverter are mainly determined by its LC filter. Dead-time effect and inevitable loss in every part of the inverter offered a little damping. The damping effect can be summarized as a small resistor connected in series with the filter inductor. Figure 2 shows the circuit model of an inverter. The current source denotes the load current, which can be considered as a disturbance.

* School of Electrical Power & Electronics Engineering, Huazhong University of Science & Technology, Hubei Wuhan, 430074, P.R. China, E-mail: dshanxu@263.net

ISSN 1335-3632 

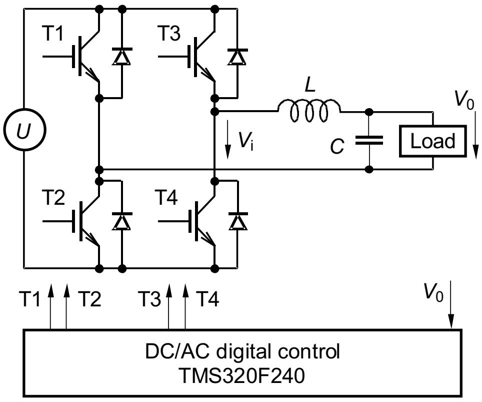



**Fig. 1.** Circuit diagram of an inverter

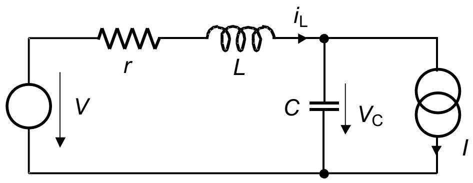



**Fig. 2.** Circuit model of an inverter

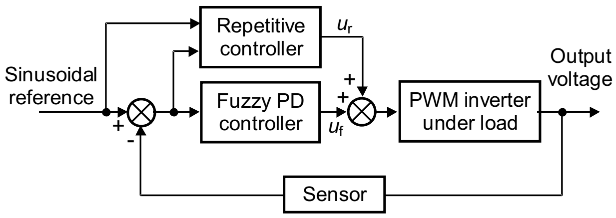



**Fig. 3.** Block diagram of the proposed controller

Based on the state-space averaging and linearization technique, the state equations of the inverter can be obtained as

$$\begin{bmatrix} \dot{v}_c \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} v_c \\ i_L \end{bmatrix} + \begin{bmatrix} 0 & -\frac{1}{C} \\ \frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} U \\ I \end{bmatrix} . \tag{1}$$

However, it is difficult to evaluate the damping resistor through theoretical analysis. In this paper, an experiment is adopted to measure the frequency characteristics of the inverter under no load and determine the natural frequency $\omega_n$ and the damping ratio $\xi$ of the second order model. So the system transfer function of the inverter is given by

$$P(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} . \tag{2}$$

From (2), a discrete transfer function can be obtained using a zero-order hold with an appropriate sampling period $T$,

$$P(z^{-1}) = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} . \tag{3}$$

Conventional control approaches require good knowledge of the system and accurate tuning in order to obtain desired performances. The design of a conventional closed-loop controller becomes difficult because the load connected to the inverter is usually nonlinear and unpredictable. Therefore the FLC may be a good alternative to solve this problem.

## 3 FUZZY–REPETITIVE CONTROL SCHEME

The regulation characteristic of a fuzzy controller is different from the linear controller because the FLC is mostly nonlinear and makes a lot of adjustment possible. The fuzzy controller is able to reduce both the overshoot and extent of oscillations. But it cannot provide a better small-signal response. Thus, repetitive control is applied to generate high-quality sinusoidal output voltage in steady state. It may be possible to take advantage of both controllers to possibly produce a hybrid controller more effective than either one of the two separately.

Figure 3 shows the proposed fuzzy-repetitive control scheme of an inverter. The fuzzy PD controller plays an important role in improving an overshoot and a rise time response during severe perturbations. The repetitive controller [8] can minimize periodic distortions resulting from unknown periodic load disturbances so as to achieve low THD sinusoidal output in steady states. Both of them will be presented in the following subsections.

### 3.1 Fuzzy PD controller

It is well known that PD controller can reduce overshoot and permit the use of a larger gain by adding damping to the system. The transfer function of a PD controller has the following form:

$$u(s) = (k_p + s k_d)\, e(s) . \tag{4}$$

Here $k_p$ and $k_d$ are the proportional and derivative gains respectively. According to the classical control theory, the effects of individual $P/D$ actions of a controller has been summarized as follows: $P$ — speed up response, decrease rise time, and increase overshoot, $D$ — increase the system damping, decrease settling time.

The discrete-time equivalent expression for PD controller is given as

$$u(k) = k_p\, e(k) + \frac{k_d}{T} \left[ e(k) - e(k-1) \right] . \tag{5}$$

The CVCF inverter is demanded to generate constant sinusoidal output voltage, whose period is $T_s = NT$. Thus, equation (5) can be modified to

$$u(k) = k_p\, e(k) + \frac{k_d}{NT} \left[ e(k) - e(k-N) \right] . \tag{6}$$

**Table 1.** Fuzzy Tuning rules

| $e(k)$ \ $ce(k)$ | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | B | B | B | B | B | B | B |
| NM | B | B | B | B | B | S | S |
| NS | B | B | B | B | S | S | S |
| Z | S | S | S | B | S | S | S |
| PS | S | S | S | B | B | B | B |
| PM | S | S | S | B | B | B | B |
| PB | B | B | B | B | B | B | B |

(a) $k_p$

| $e(k)$ \ $ce(k)$ | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | S | S | S | S | S | S | S |
| NM | S | S | S | S | S | B | B |
| NS | B | B | B | S | B | B | B |
| Z | B | B | B | B | B | B | B |
| PS | B | B | B | S | B | B | B |
| PM | B | B | S | S | S | S | S |
| PB | S | S | S | S | S | S | S |

(b) $k_d$

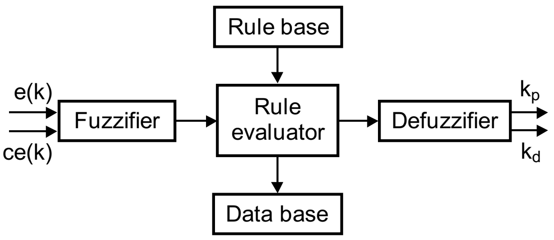



**Fig. 4.** Block diagram of the fuzzy logical controller

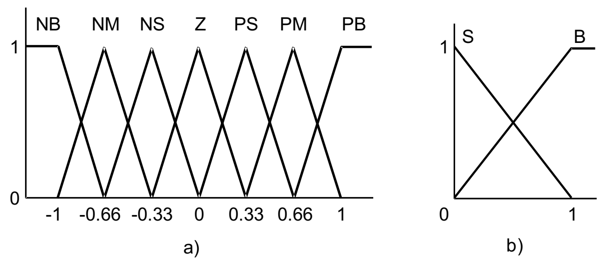



**Fig. 5.** Membership functions of fuzzy variables: (a) $e(k)$ and $ce(k)$, (b) $K_p$ and $K_d$

Obviously, the regulation of equation (6) is realized period-by-period. It makes every sampling output track corresponding constant reference in a period.

However, the PD-type controller cannot yield a good control performance if the controlled object is highly nonlinear and uncertain.

The main improvement of fuzzy PD controller is in endowing the classical PD controller with a certain adaptive control capability. The parameters of the PD controller $k_p$ and $k_d$ are determined based on the error $e(k)$ and the change of error $ce(k) = e(k) - e(k-N)$. The new fuzzy PD controller thus preserves the simple linear structure of the conventional PD controller yet enhances its self-tuning control capability. In this way system stability and a fast large-signal dynamic response with a small overshoot can be achieved with proper handling of the proportional and derivative part as described hereafter.

Figure 4 shows a block diagram of fuzzy logical controller [9, 10]. The fuzzy PD controller is used to compensate for the voltage oscillation of the inverter due to sudden load changes.

Fuzzification converts crisp data into fuzzy sets, making it comfortable with the fuzzy set representation of the state variable in the rule. In the fuzzification process, normalization by reforming a scale transformation is needed at first, which maps the physical values of the state variable into a normalized universe of discourse. The universe of discourse for error and change of error may be adjusted from open loop simulations. In the paper, the membership functions of these fuzzy sets for $e(k)$, $ce(k)$, $k_p$ and $k_d$ are shown in Fig. 5, respectively.

The tuning rules are given in Table 1. The proportional and derivative gains are initially calculated using Ziegler-Nichols tuning formula. For designing the control-rule base for tuning $k_p$ and $k_d$, the following important factors have been taken into account:

(1) For large values of $e(k)$, a larger $k_p$ and a smaller $k_d$ are required.

(2) For small positive/negative values of $e(k)$ and large $ce(k)$ (same sign), the system is diverging away from the equilibrium point. Therefore, a larger $k_p$ and a smaller $k_d$ are required.

(3) For small positive/negative values of $e(k)$ and large $ce(k)$ (different sign), the system is converging toward the equilibrium point. Therefore, a smaller $k_p$ and a larger $k_d$ are required to prevent the system from oscillating further.

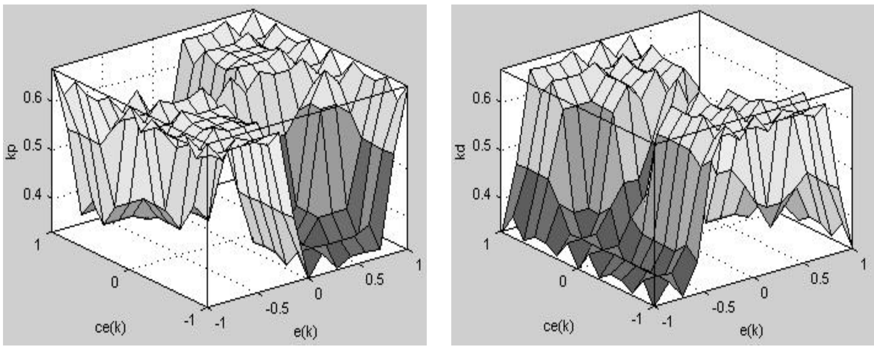
(4) For small/zero values of $e(k)$and large $ce(k)$, the system is near the equilibrium point. Therefore, the controller should operate with the nominal values of the gains. Fig. 6 shows the control surface of fuzzy PD controller.

The inference method employs MAX-MIN method. The output membership function of each rule is given by minimum operator, whereas the combined fuzzy output is given by maximum operator.

The imprecise fuzzy control action generated from the inference must be transformed to a precise control action in real application. The center of mass (COM) method is used to defuzzify the fuzzy variables in the paper.

Output denormalization maps the normalized value of the control output variable into physical domain.

It is well known that fuzzy PD controller cannot provide better small-signal response. Thus, repetitive controller is used to get low THD in the steady state.




(a) (b)

**Fig. 6.** Control surface of fuzzy PD controller: (a) $K_p$, and (b) $K_d$

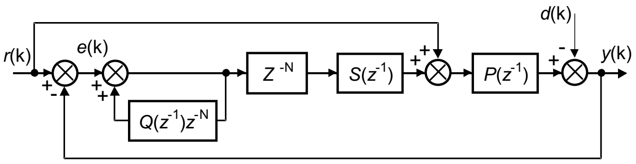



**Fig. 7.** Block diagram of repetitive control system

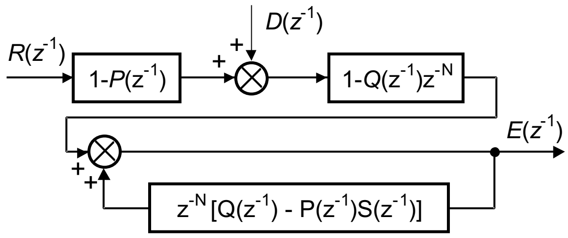



**Fig. 8.** Block diagram representation of the error

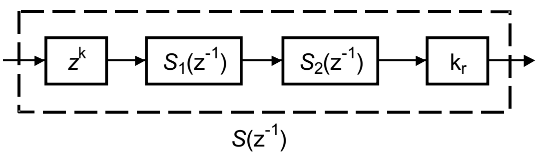



**Fig. 9.** Block diagram of the compensation

### 3.2 Repetitive controller

The main drawback of SPWM inverter is large THD with nonlinear loads such as rectifier and triac loads. The nonlinear load causes a periodic disturbance. Repetitive control provides an alternative to minimize periodic error occurred in a dynamic system.

Repetitive control is based on the internal model principle. The internal model principle means that the controlled output tracks a set of reference commands without a steady-state error if the generator for the references is included in the stable closed-loop system. Repetitive control can be regarded as a simple learning control because the control input is calculated using the information of the error signal in the preceding periods.

Figure 7 shows a block diagram of a plug-in type repetitive control system. The repetitive controller calculates correction component from output voltage error. Then the correction component is added to the original sinusoidal reference to achieve waveform correction.

The transfer function from the disturbance input $d(k)$ to the tracking error $e(k)$ is

$$F\big(z^{-1}\big)= \frac{E(z^{-1})}{D(z^{-1})} = \frac{1-Q(z^{-1})z^{-N}}{1-[Q(z^{-1})-S(z^{-1})P(z^{-1})]z^{-N}} \,. \tag{7}$$

If $Q\big(z^{-1}\big)= 1$ and $P\big(z^{-1}\big)$ is stable, the corresponding frequency function is

$$F\big(e^{j\omega T}\big)= \frac{1-e^{-j\omega NT}}{1-[1-S(e^{j\omega T})P(e^{j\omega T})]e^{-j\omega NT}} \,. \tag{8}$$

The reference command is a sinusoidal signal with period $T_s = NT$. If $d(k)$ is a periodic disturbance with the same period, it can be expressed as Fourier series whose angular frequency is $\omega = 2\pi m/NT$ $(m = 0,1,2,\dots)$. Thus, if $\omega = 2\pi m/NT$ $(m = 0,1,2,\dots,N/2)$,

$$F\big(e^{j\omega T}\big)= \frac{1-e^{-j2\pi m}}{1-[1-S(e^{j\omega T})P(e^{j\omega T})]e^{-j2\pi m}} = 0 \tag{9}$$

It means that no steady-state error is obtained with the repetitive control for any periodic disturbance whose frequency is less than Nyquist frequency $\pi/T$.

The core of the repetitive controller is the modified internal model $1/\big(1-Q(z^{-1})z^{-N}\big)$. Usually $Q\big(z^{-1}\big)$ is a close-to-unit constant, typically $0.95$. It relieves the stringent requirement of the repetitive controller to eliminate periodic error completely.

Applying the small gain theorem to the feedback loop of error system in Fig. 8, a sufficient condition for stability can be obtained,

$$\big|Q\big(e^{j\omega T}\big)-S\big(e^{j\omega T}\big)P\big(e^{j\omega T}\big| < 1\,, \quad \omega \in [0,\pi/T]\,. \tag{10}$$

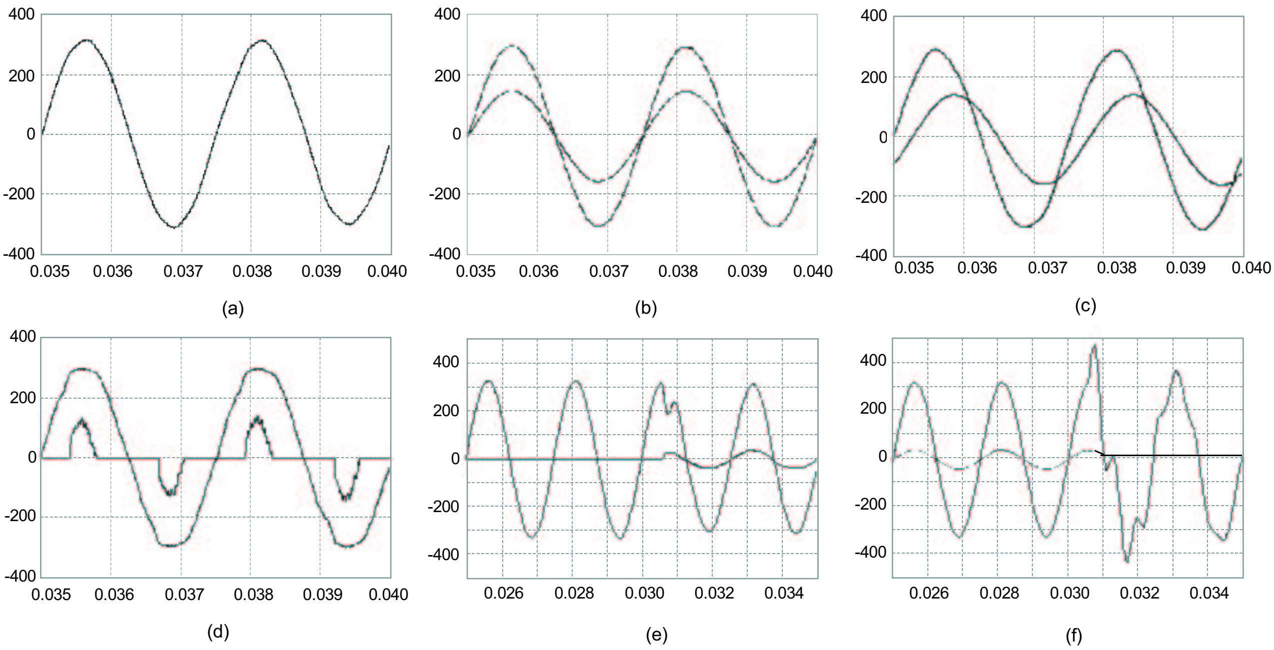


**Fig. 10.** Simulation results of repetitive control inverter, (a) no load, (b) resistive load, (c) inductive load, (d) rectifier load, (e) full load application, (f) full load removal

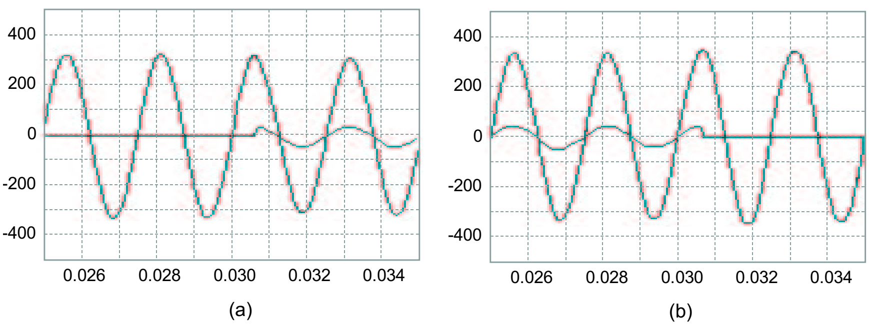


**Fig. 11.** Simulation results of fuzzy-repetitive control inverter, (a) full load application, (b) full load removal

In order to ensure stability and realize satisfactory harmonic rejection $\left|Q\left(e^{j\omega T}\right)-S\left(e^{j\omega T}\right)P\left(e^{j\omega T}\right)\right|$ should be kept close to zero. With the limited system bandwidth, it is impossible to eliminate all harmonics completely. So the repetitive controller is synthesizing to minimize low-order harmonic distortion. Figure 9 shows a block diagram of the compensator $S\left(z^{-1}\right)$.

To ensure stable operation at different load conditions, compensator design must be carried out at no load, when the resonant peak of the inverter is the highest. The moving average filter $S_1\left(z^{-1}\right)$ and second order filter $S_2\left(z^{-1}\right)$ are used to achieve asymptotic stability by attenuating the resonant peak resulting from the inverter.

$$S_1\left(z^{-1}\right) = \frac{\gamma_p(z^{-p}+z^{p})+\gamma_{p-1}(z-(p-1)+z^{p-1})+\cdots+\gamma_0}{2\gamma_p+2\gamma_{p-1}+\cdots+\gamma_0} \quad (\gamma_0>\dots\gamma_{p-1}>\gamma_p) \tag{11}$$

$$S_2\left(z^{-1}\right)=\frac{az^{-1}+bz^{-2}}{1+cz^{-1}+dz^{-2}} \tag{12}$$

**Table 2.** Parameters of the inverter

| Item | Nominal Value |
|---|---|
| DC link voltage | 400 V |
| Output voltage | 230 V |
| Output frequency | 400 Hz |
| Switching frequency | 10 kHz |
| Sampling period | 100 us |
| Filter inductor | 440 uH |
| Filter capacitor | 20 uF |
| Filter natural frequency | 1.7 kHz |

The magnitude of $P\left(z^{-1}\right)S_1\left(z^{-1}\right)S_2\left(z^{-1}\right)$ should be equal to unit at lower frequency and be decreased significantly at higher frequency.

The time advance unit $z^k$ compensates for the corresponding phase delay resulting from $P\left(z^{-1}\right)$ and $S_1\left(z^{-1}\right)S_2\left(z^{-1}\right)$. The period delay unit $z^{-N}$ postpones the error correction by one period so that it is possible to realize the time advance phase cancellation. So the sys-

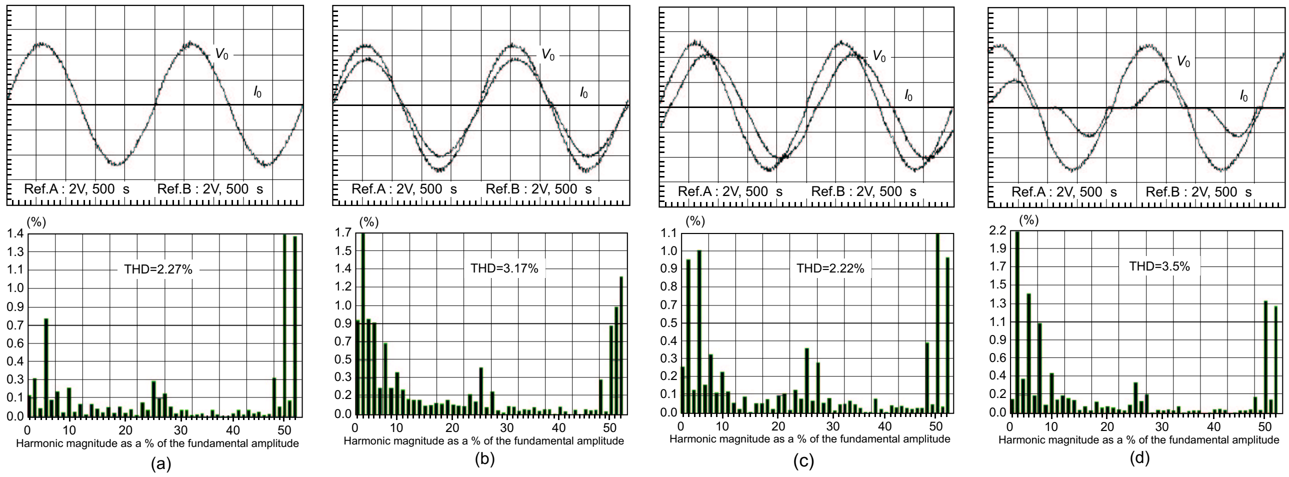


**Fig. 12.** Experimental waveforms of the proposed control inverter, (a) no load, (b) resistive load, (c) inductive load ( $I_0 = 26\,\mathrm{A}$, $cos\phi = 08$ ) (d) rectifier load,

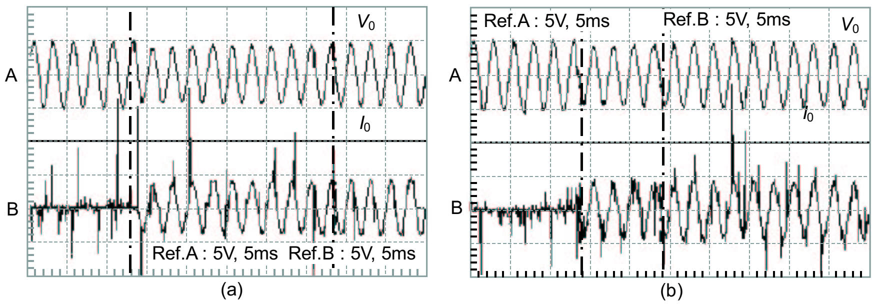


**Fig. 13.** Simulation results of fuzzy-repetitive control inverter, (a) repetitive controll, (b) fuzzy-repetitive controll

tem possesses a nearly zero-phase-shift characteristic in the medium and low frequency range.

The gain $K_r$ is kept below one for stability. A smaller $K_r$ means enlarged stability margin, but a higher $K_r$ brings faster error convergence and smaller steady-state error.

Carefully selecting the controller parameters is a compromise between the convergent rate and relative stability of the repetitive control system.

## 4 SIMULATION AND EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed controller, a 400 Hz, 5.5 kW inverter is constructed and the proposed algorithm is tested. The power circuit parameters of the inverter are shown in Table. 2. Gating signals for the inverter are obtained using the unipolar PWM method, which is the comparison-based method between a single triangular carrier wave and two modulation voltage signals with an opposite phase each other.

The model for the inverter with no load can be obtained as

$$P(z^{-1}) = \frac{0.4801z^{-1} + 0.4438z^{-2}}{1 - 0.8728z^{-1} + 0.7967z^{-2}}\,. \tag{13}$$

Suppose $Q = 0.95$, $N = 25$, every part of the compensator can be designed as

$$S_1(z^{-1}) = \frac{z + 2 + z^{-1}}{4}\,, \tag{14}$$

$$S_2(z^{-1}) = \frac{0.3382z^{-1} + 0.1517z^{-2}}{1 - 0.6016z^{-1} + 0.0915z^{-2}}\,, \tag{15}$$

$$z^k = z^3\,, \tag{16}$$

$$K_r = 0.2\,. \tag{17}$$

The simulation of the inverter under fuzzy-repetitive control is obtained by MATLAB.

Figure 10 shows the simulation results of the repetitive control inverter for various load condition. It is obviously that the repetitive controller has good steady-state characteristics. However, it is not suitable for the applications with sudden load change due to their open-loop manner in the first cycle of load change.

Figure 11 shows the dynamic response of the fuzzy-repetitive control inverter for a 100 % step change in the load. From the simulations, the voltage in the transient response has significant improvement. The figure shows that the system exhibits very fast dynamic response with excellent load voltage regulation, indicating that the control scheme ensures a “stiff” load voltage.

A single-chip DSP TMS320F240 provided by Texas Instruments is used to implement the proposed control scheme. The software approach is adopted to realize fuzzy-repetitive control algorithm. The fuzzy decision table is computed off-line using MATLAB. Then it is stored in the Flash EEPROM of DSP. The fuzzy tuning process is performed on a lookup table. So it can be executed very quickly.

Figure 12 shows the experimental results for various load condition with fuzzy-repetitive control. The nonlinear load was chosen as a bridge rectifier with an output LC filter ($L = 1$ mH, $C = 2200$ uF) and a resistive load ($R = 20\,\Omega$). As in Fig. 10, the distortion of the output voltage is very small.

Figure 13 shows the transient response due to sudden changes in the load. It can be observed that it takes about 10 cycles with conventional repetitive controller, whereas it takes only about 4 cycles with proposed controller for the settling of the step-changed load.

## 5 CONCLUSION

This paper describes a novel fuzzy-repetitive control scheme for CVCF inverter applications. The proposed scheme combines a fuzzy PD controller with a repetitive controller. The control scheme improves both accuracy of steady state response and convergent rate of transient response. It is implemented using a TI TMS320F240 DSP. Simulation and experimental results show that the proposed control scheme is capable of supplying both linear and nonlinear loads with excellent voltage regulation and minimum distortion in the load voltage.

## Acknowledgement

Project Supported by the National Natural Science Foundation of China 50007004, 50237023.

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Received 27 August 2003

**Duan Shanxu** was born in PR China on September 15, 1970. He received the bachelor, master, PhD degrees, all in power electronics and electrical drives, from Huazhong University of Science & Technology, China in 1991, 1994 and 1999, respectively. Since 1999, he has been with the School of Electrical Power & Electronics Engineering, Huazhong University of Science & Technology, where he is currently associate professor. His main research interests include stabilization, nonlinear control with application to power electronic circuit and system, full-digitalized control technique for power electronics apparatus and system, optimal control theory and corresponding applying techniques for high frequency PWM power converters.

**Kang Yong** was born in PR China on October 16, 1965. He received the bachelor, master, PhD degrees, all in power electronics and electrical drives, from the Huazhong University of Science & Technology, China in 1988, 1991 and 1994, respectively. Since 1999, he has been with School of Electrical Power & Electronics Engineering, Huazhong University of Science & Technology, where he is currently professor and tutor of PhD candidates. His main research interests include control theory and application of complex system in power electronics, full-digitalized control technique for power electronics apparatus and system.

**Chen Jian** (Senior member IEEE), was born in Wuhan, China, on August 27, 1935. He received the electrical engineering degree from Zhengzhou Electrical Engineering School, Zhengzhou, China, in 1954 and the BE degree from the Department of Electrical Engineering, Huazhong Institute of Technology, Wuhan, China, in 1958. He has worked in Huazhong Institute of Technology (now Huazhong University of Science and Technology) since 1958. He was promoted to a lecturer in 1963 and to associate professor in 1978. He has studied power electronics, microprocessors, and their applications at the University of Toronto in Canada, as a Visiting Scholar, from 1980 to 1982. In 1985, he became full professor. He is an author of three textbooks and over 120 technical papers. His main research interests include various power electronic converters, ac drives, and power electronics applications in electric power systems.