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Design and Simulation on Improved Repetitive Controller for Inverted Power Supply

Deli Jia*. Bo You**
Fengjing Zhang***

**Harbin University of Science and Technology, Harbin, 150080*
China (Tel: +86-451-86390489; e-mail: jiadeli@ hrbust.edu.cn).
***Harbin University of Science and Technology, Harbin, 150080 China (e-mail:*
youbo@hrbust.edu.cn)
****College of Automation, Harbin University of Science and Technology,*
Harbin, China, (e-mail: zhangfengjing2002@yahoo.com.cn)}

Abstract: Aimed at the inverted power supply control system, an improved repetitive control method has been proposed. It combines repetitive controller with proportion and integral controllers, which improves the inverted power supply's output power performance when the load is nonlinear. Based on this control scheme, a detailed program parameters design for each part of the repetitive controller is proposed and the special Notch function is also introduced. The improved repetitive controller design method was verified by simulation and results showed that improved system has good dynamic and static characteristics, stable voltage accuracy is high; the content of output waveform harmonic dropped to 1.07%, the rate of convergence speed was greatly enhanced.

1. INTRODUCTION

Constant voltage and constant frequency (CVCF) AC inverted power supply is widely applied in the aerospace, UPS and other industrial areas. The output voltage waveform quality is an important index to evaluate the performance of inverted power supply, and it is the also hot topic in the field of inverted power supply study.

Requirements for inverted power supply performance are system stability, rapid dynamic response, small output voltage distortion and high reliability. The general standard targets are as follows: total output voltage harmonic distortion rate is less than 5%; single-harmonic distortion rate is less than 3%. Factors causing output voltage waveform distortion are inverted power supply's self internal asymmetry, deadbeat settings and load disturbance and so on. Nonlinear load is the main source of total harmonic distortion (THD). High output voltage total harmonic content will lead excessive heating of capacitors, increase transmission loss and interfere precise instruments. Therefore appropriate control strategy is needed in order to improve output performance of CVCF. There are some methods to minimize THD by increasing the response speed, such as deadbeat control, sliding mode control and hysteretic control. All of those have a relative nice control results. But they also have some drawbacks like low robustness and large transient overshoot. These systems are also sensitive to parameters and the stability design is difficult. Repetitive control is based on the principle of internal model control. It adopts periodic property of load disturbance to "memorize" the position where disturbance happens, targeting to amend and improve output performance gradually. Excellent output waveform can be obtained under steady-state condition. The structure is simple and easy to implement. The former repetitive controller design was too simplified and can not achieve the desired results.

This paper applies improved repetitive controller to inverted power supply. Repetitive controller is combined with the proportion and integral controllers. This structure has not only realized suppression to the SPWM inverted power supply harmonic interference, but it has also overcome the drawbacks of instruction tracking lag in repetitive control system. System robustness and stability have been greatly enhanced. Simulation has proven that this scheme suppresses harmonic and reduces THD effectively.

2. DESINGN OF IMPROVED REPERITIVE CONTROLLER AND HOW TO SELECT PARAMETERS

2.1 Basic structure of repetitive controller

According to the internal model theory, any feedback control system that can offset external disturbance or track reference input signal must include a dynamic model same as external input signal in its feedback loop. As an internal model principle of control technology, digital repetitive controller adopts a repetitive signal generator whose structure is $G_m(z) = 1/(1 - Z^{-N})$ as internal mode. Input signal is accumulated by period to implement accurate tracking of orders. Even if the input signal attenuates to zero, the output of the internal model is still the same with that of last periodic signal, which can eliminate non-linear load and other periodic waveform distortion caused by interference effectively.

As shown in Figure 1, repetitive controller is within the dashed line, $y(z)$ is system output; $u(z)$ is reference signal;

$e(z)$ is the error signal; Z^{-N} is periodic delay positive feedback links; N is the output signal sampling times to each fundamental period; $Q(z)$ is assistance compensator to enhance the robustness of the system; $S(z)$ is the compensation aimed at controlled object; $P(z)$ is the transfer function for the controlled object; $u_c(z)$ is the reference signal after compensation; $d(z)$ is periodic disturbance signal. The output of repetitive controller is accumulated when $e(z)$ appears periodically. When $e(z)$ is zero, the output of repetitive controller stays the same as last waveform. Using this structure, repetitive controller is embedded to conventional control loop, which is also known as embedded repetitive controller. The scheme can effectively compensate periodic instructions and disturbance, making the system have a small phase error and static error. But in practical applications, there are two following drawbacks: suppression and regulation time to system load disturbance normally requires several fundamental cycles; assistance compensator $Q(z)$ designed to enhance the robustness of systems allows static error.

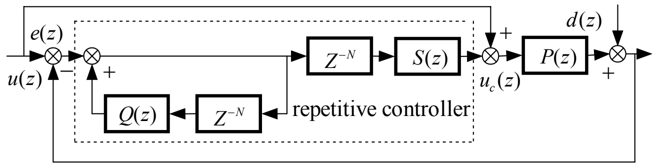


Fig. 1. System block diagram of repetitive controller

2.2 *Design of Improved Repetitive Controller*

To solve the above two issues, this paper presents an improved repetitive control program which will combine proportional, integral links with the repetitive control as a controller system.

Z^L is added to compensate the phase lag of $Q(z)$ filter. Phase ahead L is defined as PH $_{\text{delay}}$ /(2 π /N). PH $_{\text{delay}}$ is the phase lag angle of $Q(z) \cdot R$. N is sampling times for each fundamental period. Z^m is forward channel of repetitive controller, m is PHS $_{\text{delay}}$ /(2 π /N) to compensate $S(z)P(z)$ phase lag, in which PHS delay is the phase lag angle.

A proportion regulator is added parallelly to the repetitive controller in the forward channel of the controller. Then proportion controller and repetitive controller in this system perform different roles. Repetitive controller takes a major adjusting role when system is running stably and the tracking error is very small. When system disturbance is added unexpectedly, sudden change of tracking error happens, at this moment proportion controller play the leading role, which improved the adjustment speed of the system. While repetitive controller will gradually increase its function of regulating until the system comes to a new stable state.

Filter $Q(z)$ is introduced to enhance system stability in traditional repetitive controller, when $Q(z)=1$ and $S(z)=P(z)^{-1}$, the entire system has the best control performance. But in actual system, interference $d_{(Z)}$ not only includes harmonic components, but also includes the non-harmonic frequency components, and interference signals frequency is high. When $Q(z)=1$, non-interference harmonic energy is doubled under repetitive controller. Amplitude of $Q(z)$ is 1 in theory, but the value of $Q(z)$ should be appropriately reduced in high spectrum; the value is often less than or close to some constant or function whose value is one in project. If $Q(z)$ takes α ($\alpha<1$), according to the repetitive control internal model principle, the output will become cumulative. When the input is less than the output up to $1-\alpha$, cumulative process stops and the system is allowed certain static error. Integral controller is introduced based on the proportion control combination with repetitive control, which adjusts the error signal amplitude before the error signal entering repetitive controller.

The final scheme of improved repetitive controller is shown in Figure 2. System error transfer function is shown in Formula (1). The greater K_p is, the smaller tracking error will be, and thus proportion control is very obvious. If K_p is too large, it is easy to cause oscillation and distortion. K_p is taken 0.146 on the basis of the theoretical prediction through simulation. The scheme also eliminates system static error. Through simulation and experiment, K_I is taken 0.862.

$$e(z)=$$
$$\frac{[1-P(z)](1-Z^{-1})[Z^N-Q(z)]}{[K_I K_P P(z)+1-Z^{-1}][Z^N-Q(z)Z^L]+K_I Z^m S(z)P(z)}\cdot u(z)+$$
$$\frac{(1-Z^{-1})[Z^N-Q(z)]}{[K_I K_P P(z)+1-Z^{-1}][Z^N-Q(z)Z^L]+K_I Z^m S(z)P(z)}\cdot d(z)$$

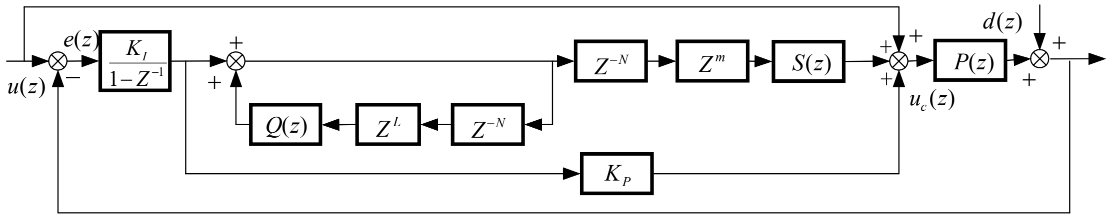


Fig. 2. Block diagram of improved repetitive controller

3. DESIGN OF COMPENSATOR $S(z)$

When $Q(z)=1$ and $S(z)=P(z)^{-1}$, the entire system has the best control performance. M. Tomizok proposed zero phase error track control (ZPETC) design method in 1986. Aiming at controller $P(z)=\frac{Z^{-d}B(z^{-1})}{A(z^{-1})}$, compensator $S(z)=\frac{Z^{d}A(z^{-1})}{B(z^{-1})}$ (d is controlled object self delay) is designed. The method is based on the cancellation concept, which has become a classic design method of repetitive controller. But in application there are two limitations. First, it relies on the accuracy of the object model. Model imprecise can cause system instable. Second, if the zero points of $P(z)$ is out of the unit circle, the controller will have instable poles.

T. Inoue proposed phase reversal method which adopted function fitting concept in 1990, making $S(z)$ be $W_0+\sum_{k=1}^{n}W_kZ^k$ to determine the coefficient W_k and K that the structure $S(z)=P(z^{-1})$ needs. The design solves the difficulty in ZPETC design, that is, $S(z)$ design is irrelevant to the distribution of controlled object zero points. But there are also some restrictions. First, if system parameters are not precise, it is difficult for $S(z)$ to be fitted. Second, complex model fitting or improve fitting precision will increase the order and lead to design difficulty. Aiming at inverted power supply that has strong nonlinear load, model precision is difficult to control and the control effect is difficult to ensure.

Through theoretical analysis and experiments, the low and medium frequency bands of inverted power supply system model can be described by two order low-pass filter accurately. Through the voltage waveform spectrum analysis, we can conclude that harmonic caused by nonlinear load concentrates in the low frequency band. Using a two order low-pass filter in the low frequency band, excellent controlled effect can be obtained. But this model tends to oscillate in the high-frequency band. After cut-off frequency, attenuation rate is -40dB/10 frequency doubling, high-frequency gain becomes larger, and within high-frequency the parameters $P(z)$ distortion gets larger. If high-frequency gain is reduced, the low and medium frequency zero-gain condition will be destroyed, at the expense of system stability accuracy and error convergence speed. In order that bode graph of $S(z)P(z)$ meet the following requirements, the system uses Notch function and a two order low-pass filter superimposing structure $S(z)$. The requirements are that low-frequency band is zero and phase gain is zero, high-frequency amplitude attenuates rapidly and inhibit resonance peak, phase shift approaches zero.

$$F_n(z)=\frac{a_mZ^{m}+a_{m-1}Z^{m-1}+\cdots+a_0+\cdots a_{m-1}Z^{-(m-1)}+a_mZ^{-m}}{2a_m+2a_{m-1}+\cdots+a_0}$$

Notch function has a bigger attenuation to some specific frequency and has a small impact on the neighboring frequency gain. From the above information, we can see that Z^m link is added in the forward channel of repetitive controller to compensate $S(z)P(z)$ phase lag. Using circuit parameter, the model for controlled object $P(z)$ is calculated as follows: $\frac{0.1726Z+0.1527}{Z^2-1.6142Z+0.9354}$, the ultimate form of controller is the product of two-order low-pass filter, Notch function and Z^m. Finally, compensator $S(z)$ is shown as follows: $\frac{Z^5+2+Z^{-5}}{4}\cdot\frac{0.1164Z+0.0788}{Z^2-1.0164Z+0.3116}\cdot Z^5$. The Bode diagram of $S(z)P(z)$ is shown in Figure 3. In the low and medium frequency bands $S(z)P(z)$ gain is zero, phase shift is almost zero, the system has good stability and convergence. In high-frequency band, phase difference exists, but high frequency signal attenuates greatly, without affecting system performance.

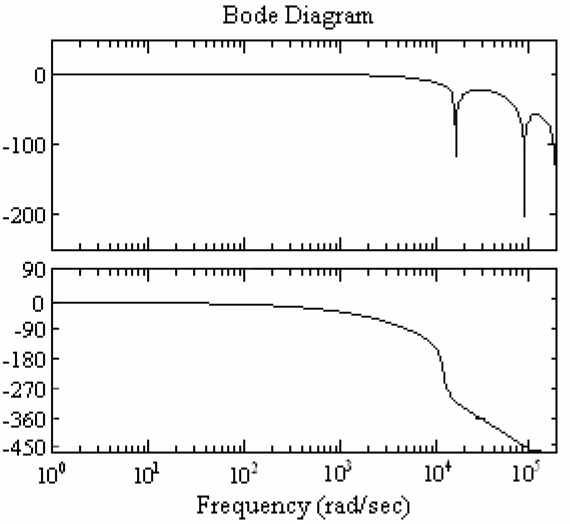


Fig. 3. $S(z)P(z)$ bode graph

4. DESIGN OF COMPENSATOR $Q(z)$

Value of $Q(z)$ is too conservative, and it will lead to sacrifice of system steady precision and convergence speed and other indicators. Through theoretical analysis, $Q(z)$ has a close relationship with the change of $Z^mS(z)P(z)$. $Q(z)$ is a variable tracking of the change of $Z^mS(z)P(z)$. From the amplitude and phase characteristic curve of $S(z)P(z)$ in Figure 4, we can see that the follow difference frequency increase and $S(z)P(z)$ trajectory move to the left in the direction from 1 to 0. Therefore $Q(z)$ is designed to track the trend of $Z^mS(z)P(z)$ change. In the low and medium frequency bands, assuming $Q(z)-Z^mS(z)P(z)\approx 0$, thus on the premise that system stability is ensured, the stability error accuracy of the system is also enhanced In the paper, zero phase shift of Notch function is adopted as the ultimate form of $Q(z)$ expression, $Q(z)$ is $\frac{Z^2+4Z+6+4Z^{-1}+Z^{-2}}{16}$, whose amplitude and phase characteristic curve is shown in Figure 5. Between high frequency band and medium frequency band, the system always has a good stability and convergence.

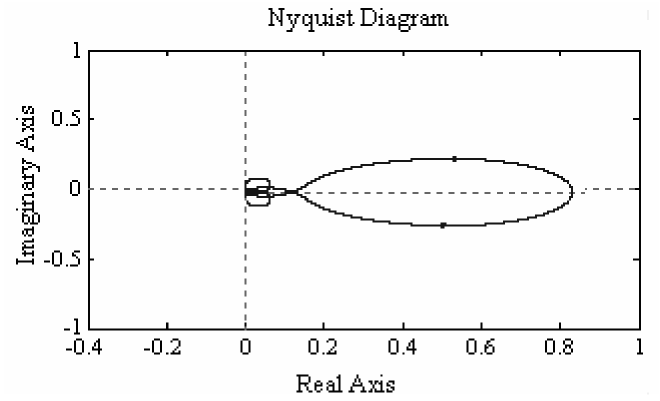


Fig. 4. Amplitude and phase characteristics curve of $S(z)P(z)$

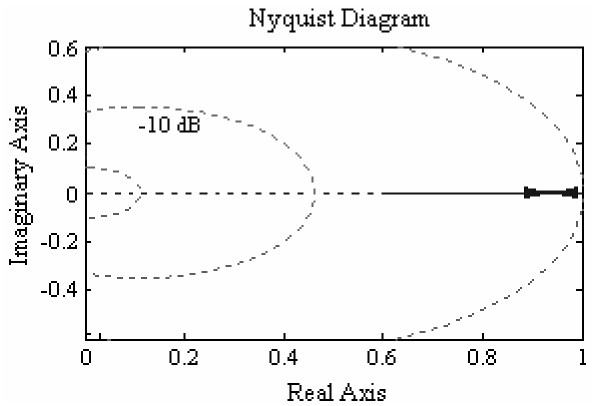


Fig. 5. Amplitude and phase characteristics curve of $Q(z)$

5. SYSTEM SIMULATION RESULTS

Parameters are selected based on the above analysis. In this paper simulation model is established in the MATLAB7.1/SIMOLINK6.3 environment. As shown in Figure 6, the system parameters and performance indexes are verified, the simulation results are shown in Figure 7, 8, 9 and 10. Figure 7 shows the output waveforms under abrupt load comparison before and after improvement. Before the improvement, if sudden load is added to the inverted power supply, it takes 8 cycles for the system to regulate. But after the improvement, only one cycle is needed. The dynamic performance and anti-shock ability of the inverted power supply has enhanced greatly. Besides, there is almost no distortion. Figure 9 shows the error convergence curve under disturbance. System error can converge to a relative small value. After the spectrum analysis to system output, harmonic spectrum analysis shown in Figure 10 is obtained. THD of the output waveform harmonic is only 1.07%. The harmonics whose frequency band is five times of the fundamental frequency account for 0.85%.

6. CONCLUSIONS

This paper proposes an improved repetitive controller scheme, which combines PI control with the traditional repetitive controller to overcome the drawbacks of traditional controller, and the controller is deducted and designed. The simulation results showed that using the control scheme can achieve ideal performance of the output voltage, the system has high dynamic and static characteristics, THD value is low to the nonlinear load, harmonic distortion of the output voltage is small, and the improved repetitive controller is completely as an effective waveform control technique for Inverter Power.

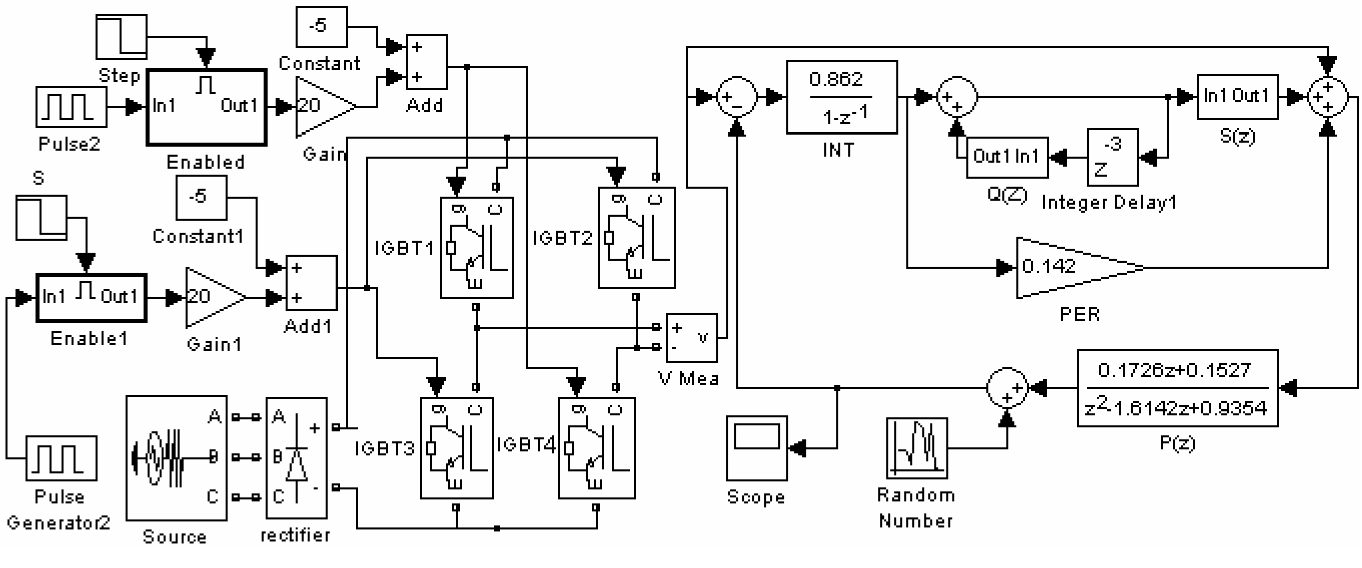
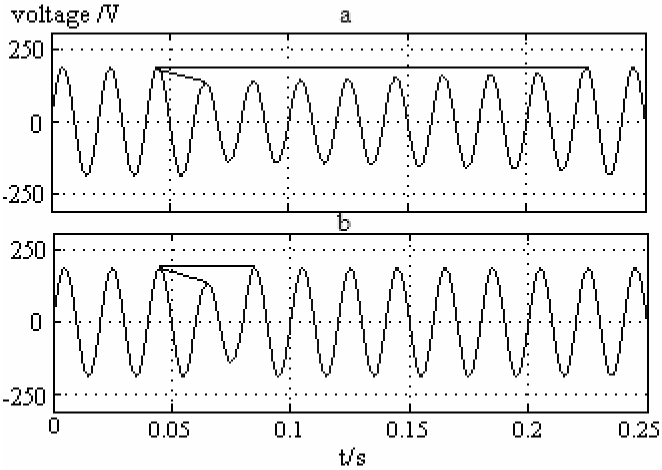


Fig. 6. Simulation model of improved repetitive controller



(a) The output voltage waveform of repetitive controller before suddenly adding load

(b) The output voltage waveform of repetitive controller after suddenly adding load

Fig. 7. The output voltage waveform with load

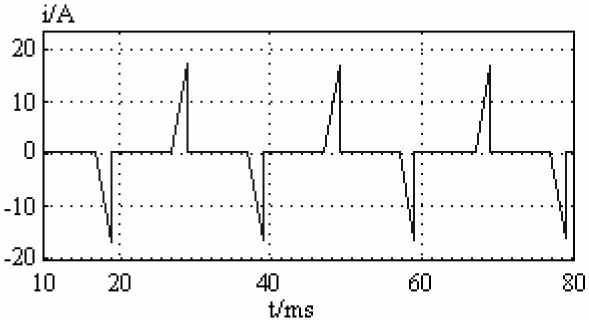


Fig . 8. The current waveform with nonlinear load

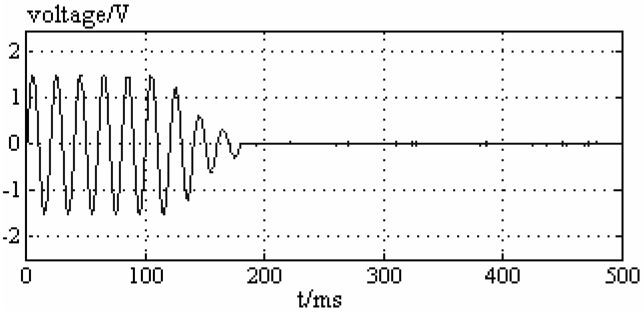


Fig. 9. The convergence curve of error e

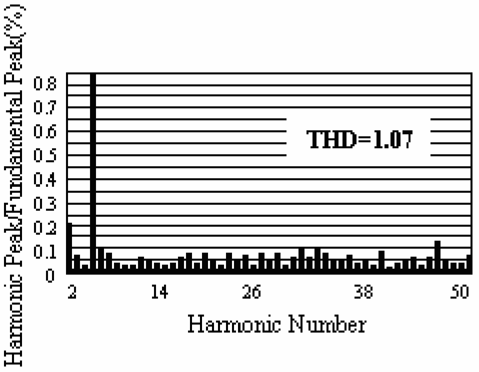


Fig. 10. Harmonic spectrum analysis

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