Analysis and Design of Repetitive Controlled Power Electronic Load Simulator with High Dynamic Performance

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***Abstract*-In this paper, a digital repetitive control strategy is proposed to achieve zero tracking error for Power Electronic Load Simulator (PELS). The proposed control scheme is of "plug-in" structure: a plug-in digital repetitive controller plus a conventional controller (e.g., P or PD controller). The design of the plug-in repetitive learning controller is systematically developed. The stability analysis of overall system is discussed. A repetitive controlled PELS is given as an application example. Desired current can be ensured under parameter uncertainties and disturbances. Simulation results are provided to testify the effectiveness of the proposed control scheme.**

I. Introduction

Before new power electronic equipments come into use, a burn-in test is used to verify the stability of them. A resistor bank is generally used as load and all this energy is dissipated in the form of heat. To solve this problem, some methods have been presented [1]-[7]. Power Electronic Load Simulator (PELS) is proposed to replace the conventional load so that the consumed energy can be fed back to the utility. Different types of PELS for testing of AC load have been developed [2]-[3], [7]. However, although some passages said that the PELS proposed can be used for various load testing, the operation principle has not been studied in detail.

This paper gives insight into the application of PELS on voltage sources testing. And a new repetitive control scheme will be applied in order to improve the dynamic performance.

II. System Configrations

The connection diagram between the test unit and the PELS is shown in Fig.1. The structure is based on the Current-Controlled Voltage Source (CCVS) Converter, which makes the system very flexible. The circuit can be used to test both the ac and dc voltage sources. It can simulate linear load and non-linear load such as rectifier load. The power passed through the system is returned to the utility grid by an inverter and an insulation transformer [5].

This paper focused on the operation principle of the input converter, the main circuit of which is shown in Fig.2. When the system is used for testing of dc voltage source, the converter can be viewed as a PWM amplifier [5]; while as a PWM rectifier for ac source. The dc-bus voltage V_{dc} can be regulated by the "Power Recycling Units". For ease of design, the voltage on the capacitor C1 can be viewed as constant.

When it is used for DC source testing, we can turn off T1 and T3, turn on T4, and the input converter is equivalent to a boost circuit as shown in Fig.3.

III. Model Controller

In steady state, the dc source is connected with resistive loads only, and there are three main operation modes: constant resistance mode, constant current mode and constant power mode. While in dynamic state, there are several types of load such as RL load and RLC load. In test of voltage source, the current waveform should be controlled in order to simulate a certain structure of load.

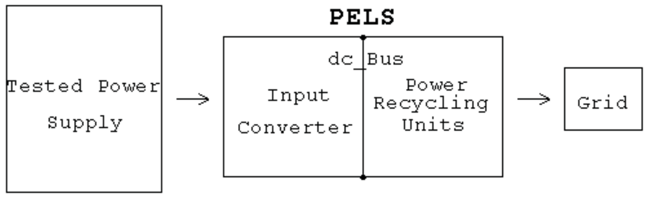

Fig. 1. Block diagram of power electronic load simulator

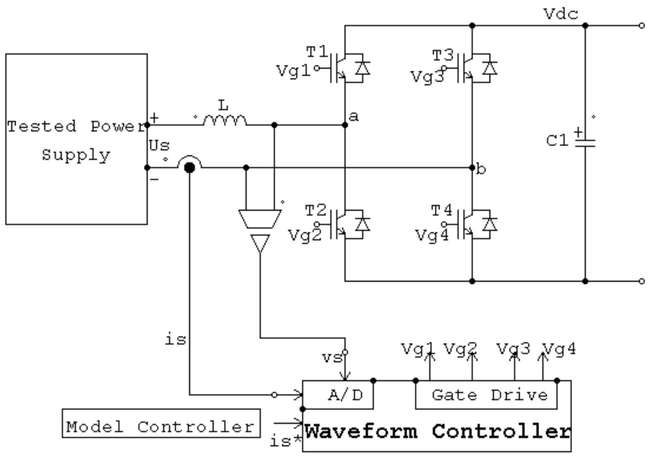

Fig. 2. Main circuit of the Input Converter

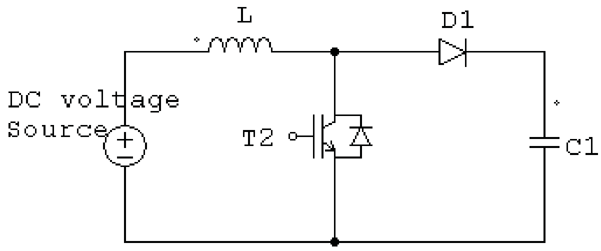

Fig.3. Equivalent circuit of Input Converter under DC source testing

A Model Controller is proposed. It is used to monitor the terminal voltage of the tested voltage source and generate the current reference according to the desired parameter of each component which should be pre-entered using the keyboard. For digital realization of MCU, the discrete-time model should be established. Reference[3], [5] used state-space model, but it is somewhat inconvenient to realize in DSP. As it is a SISO system, directly using the transfer function from current to voltage is proposed here. Taking the load form shown in Fig.4 for example.

Assuming that $i_L(0^-)= v_c(0^-)= 0$, the transfer function of the load can be obtained as

$$\frac{U}{I} = Z = \frac{1+CRs}{LCRs^2 + Ls + R} \tag{1}$$

The discrete-time equation can be achieved by backward-difference method as follow

$$\begin{aligned}&(\frac{LR}{T}+\frac{LCR}{T^2})i(k)-(\frac{2LCR}{T^2}+\frac{L}{T})i(k-1)+\frac{LCR}{T^2}i(k-2)\\&=(1+\frac{CR}{T})u(k)-\frac{CR}{T}u(k-1)\end{aligned} \tag{2}$$

Equation (2) can be expressed as

$$i(k) = ai(k-1) + bi(k-2) + cu(k) + du(k-1) \tag{3}$$

where a, b, c and d are related with the desired parameter of each component.

IV. Modeling of load simulator

The following equation can be obtained, where r is the equivalent resistance of the effect that there is dead-time in the PWM signals and inevitable loss in each part of the converter.

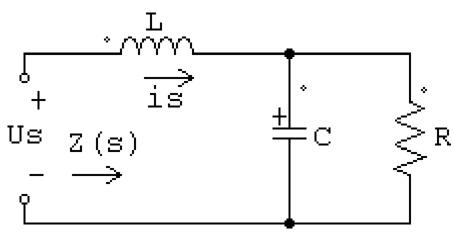

Fig.4. Example of an RLC Load

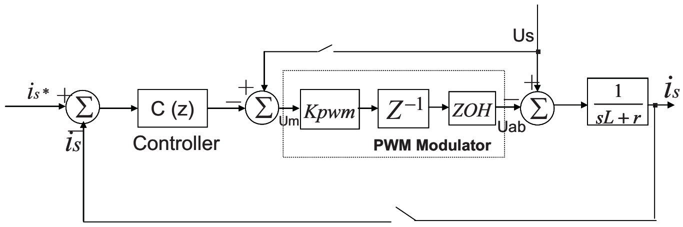

Fig.5. Block diagram of the converter in control scheme

$$u_{ab} = u_s + L\frac{di_s}{dt} + i_s r \tag{4}$$

So the input current transfer function of the plant can be expressed as

$$G(s) = \frac{i_s(s)}{u_s(s) - u_{ab}(s)} = \frac{1}{sL + r} \tag{5}$$

For the digital realization, the above continuous-time transfer function G(s) should be converted into discrete-time.

The control block of the converter is illustrated in Fig.5. Usually, the calculation result of the controller U_m is carried out at the next switching interval. K_{pwm} is a ratio from regulating signal to the output of the PWM modulator and is represented as

$$K_{pwm} = \frac{u_{dc}}{u_{cm}} \tag{6}$$

where u_{cm} means the peak value of the carrier signal and u_{dc} means the value of the dc side voltage. By properly setting the parameters, Kpwm can be set to 1. And in order to decouple the voltage Us, a feedback loop is introduced.

Applying generalized z transform to get a more precise model of the plant G:

$$G(z) = \frac{1 - e^{-\frac{rTs}{L}}}{rz(z - e^{-\frac{rTs}{L}})} \tag{7}$$

where Ts stand as the sampling period.

V. Design of the repetitive controller

The inductor and resistance in the system vary with the temperature, nonlinearity and saturation of magnetic components, so a control scheme is needed which is insensitive to the unknown and immeasurable disturbances.

Since the current error caused by disturbances happens to be periodic, repetitive control scheme can be an effective way to achieve zero steady-state error. Repetitive control theory originates from the internal model principle. A repetitive controller can be viewed as a periodic waveform generator existing within the control loop of a control system. It can eliminate the periodic error. However, as repetitive control needs to use the information of the error of last period, conventional repetitive controller is weak at dynamic responses. The proposed repetitive control scheme can remedy the dynamic performance [4], [8]-[9].

The design principle of the controller will be discussed below. Assuming L=1mH, r=0.5Ω, sampling frequency fs=12500Hz, the control plant transfer function is

$$G(s)=\frac{1}{0.001s+0.5} \tag{8}$$

From (7), we can get the discrete transfer function

$$G(z)=\frac{0.03921}{0.5z^2-0.4804z} \tag{9}$$

The characteristic equation can be obtained as

$$\Delta=(1+K_pG(z))(z^N-(Q(z)-Kr\frac{G(z)}{1+K_pG(z)}z^kS(z))) \tag{10}$$

It can be divided into 2 parts:

$$\Delta=\Delta_1\times\Delta_2 \tag{11}$$

$$\Delta_1=1+K_pG(z) \tag{12}$$

$$\Delta_2=z^N-(Q(z)-K_r\frac{G(z)}{1+K_pG(z)}z^kS(z)) \tag{13}$$

To make the whole system stable, roots of (12) and (13) should be within the unit round. Consequently, the system with only P controller and the system with a plant transfer function of $G(z)/1+K_pG(z)$ under repetitive control should both be stable.

Gz1 represents for control plant when the input inductor decreases by 50% because of saturation or change of environment. We firstly design the P controller. Bode map of the system is shown in Fig.6.

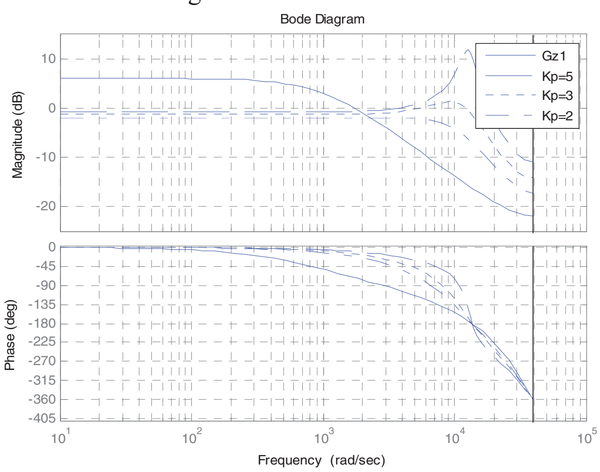

Fig.6. Bode map of the system with P controller

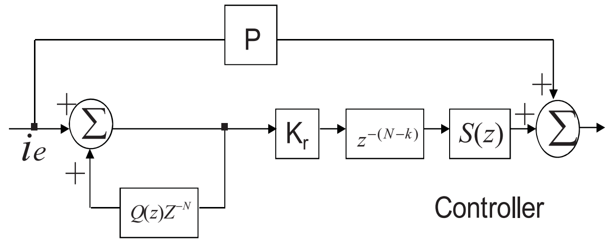

Fig.7. Proposed control scheme

Under condition Kp=5, if the input inductance is reduced by 50%, a resonant peak will appear. So set Kp=2 to assure the stability of the system.

Proposed Control diagram is shown in Fig.7.

$$D(z)=G(z)\Big/(1+KpG(z))=\frac{0.07842}{z^2-0.9608z+0.1568} \tag{14}$$

$$S(z)=\frac{z-0.7523}{0.15(z-0.34)} \tag{15}$$

$$Q(z)=0.95 \tag{16}$$

D(z) means the equivalent plant under repetitive controller.

Bode map of the compensator and plant D(z) is shown in Fig.8. And we use phase compensation unit $z^k = z^3$ to achieve zero phase delay in the low and middle frequency band, as shown in Fig.9.

Kr determines the error-tracking speed and affects the stability of the system. The dynamic response is insured by P controller, so Kr can be set lower to improve stability.

A sufficient condition for stability can be derived with small theorem

$$\left|Q(e^{jwTs})-e^{jwkTs}K_rS(e^{jwTs})D(e^{jwTs})\right|<1,\omega\in[0,\pi/Ts] \tag{17}$$

Equation (17) can be illustrated through a vector map in [8].

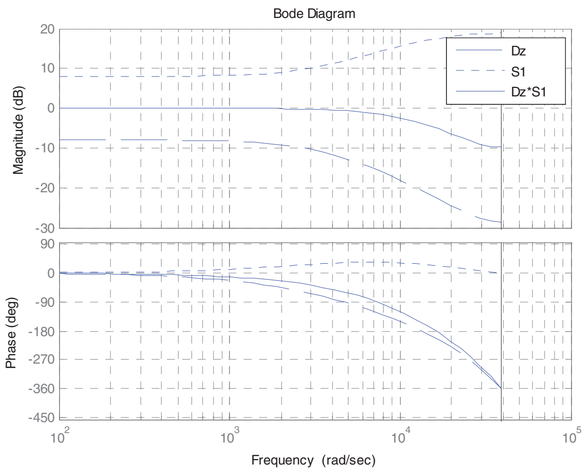

Fig.8. Bode map of the compensator filter and the plant

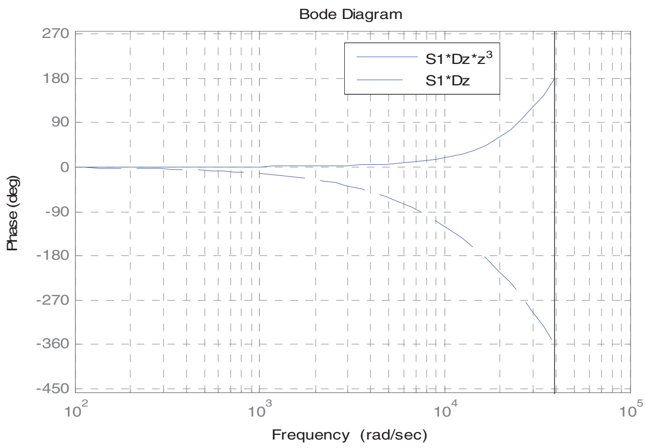

Fig.9. Phase compensation

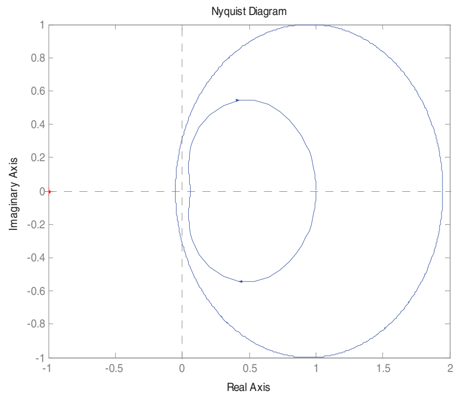

Fig.11. Locus of the vector $e^{jwkTs}K_rS(e^{jwTs})D(e^{jwTs})$

After analysis on the stability, the maximum of Kr is approximately 1.7. Since the error increases with the decreasing of Kr, the steady performance is deteriorated. Fig.10 shows that there is obvious steady-state error， indicating a better compensation is needed. So a second-order filter $S_2(z)$ is added to increase the high-frequency attenuation and designed as the conventional second-order filter. With a damp ratio of 1 and a natural frequency of 3000 Hz, the discrete function of $S_2(z)$ is

$$S_2(z) = \frac{0.4448z + 0.1614}{z^2 - 0.4427z + 0.049} \tag{18}$$

$S_2(z)$ gives a smaller $Z^k S(z)D(z)$ in the high-frequency band. From (17), Kr can be set to a higher value. The sufficient condition of stability is satisfied, as shown in Fig.11. And the waveform is shown in Fig.12. Adding a disturbance signal in the input voltage V_s at t=3.5s, we can see in Fig.13 that the error is eliminated within 3 periods, which indicates a good dynamic performance.

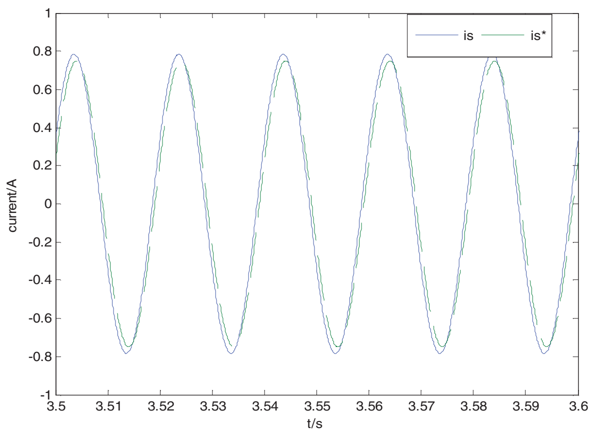

Fig.10. waveform of the current reference and the real current without $S_2(z)$

VI. Conclusion

In this paper, a digital repetitive control scheme is proposed for PELS to achieve zero error tracking. As an example, the proposed digital repetitive control scheme is applied to PELS. Simulation results show that the tracking errors are quickly eliminated by the proposed digital control scheme. The digital repetitive controlled PELS has a constant output voltage under disturbances and parameter uncertainties while maintaining good response characteristics on current tracking. The operating principle of Model Controller is also illustrated in the paper.

The developments and results for a single-phase PELS show that the proposed control scheme is a robust zero tracking error control scheme for PELS. The proposed digital repetitive control scheme provides a simple and high-performance control solution for PELS.

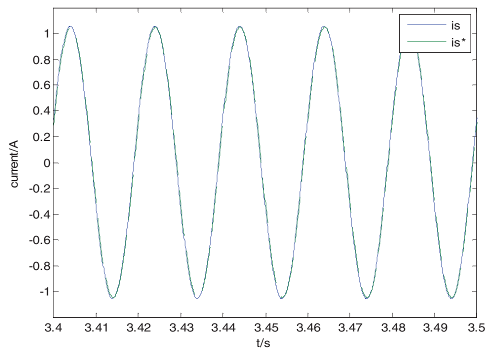

Fig.12 waveform of the current with proposed controller

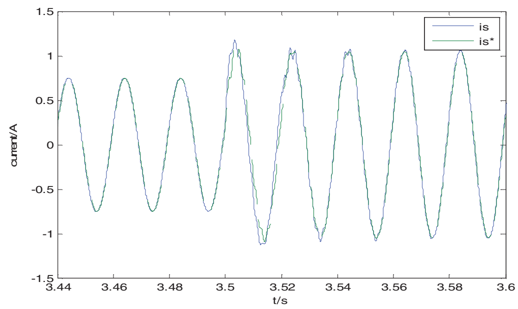

Fig.13 waveform of the current with a disturbance in the reference value

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