New Repetitive Current Controller for PWM Rectifier

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Abstract: This paper analyzed and designed a new Repetitive Current Controller (New RCC), performing a comparison with a traditional RCC. Based on the tracking performance by the original PI controller, the New RCC uses another PI controller to replace the compensator to achieve better control performance. That is the novel approach of the proposed method. And it has been proved in this paper that the controller is not sensitive to the controlled object, therefore it is suitable for use in complex object model scenarios. Simulations and experimental results demonstrate that the new RCC is effective in improving the AC current quality of the three-phase PWM rectifier, which is the right method of control, with high practical application value.

Keywords: Repetitive control, PI controller, PWM rectifier, Object sensitivity

1. INTRODUCTION

Theoretically, the current loop utilizing the PI controller can perform an unmistakable current regulation for PWM rectifier, in steady state and grid voltage is the same phase sinusoidal, etc Taha (2018) and Trinh (2017). However, traditional PI controllers have many limitations in overcoming the dead-time effect of power switches, so it is difficult to make the AC side current of PWM rectifier get a good steady state precision. Moreover, AC currents are not sinusoidal waveforms, and the harmonic components are relatively large. To achieve better AC performance, it is necessary to make improvements to the traditional PI controller. Derived from the dead-time cycle, using the intrinsic principle of overlap control in the alternating current control of a three-phase PWM rectifier can partially overcome the problem mentioned above.

In order to achieve better alternating current, there is a need to improve the PI controller. In order to limit the composition of the harmonics, a special method is used to eliminate or reduce the harmonic component, such as a PR controller with notch filter, Joris (2013); a repetitive-plus-PI control scheme, Zhang et al. (2013); a Model Predictive Control, Wang et al. (2013); and a frequency adaptive selective harmonic control scheme, Yang et al. (2015). But with a three-phase PWM rectifier, the harmonic component has a variety of frequencies, so it is difficult to eliminate. In recent years, many scientists have opted for a repetitive controller in parallel with the PI controller to improve the quality of the current control. For instance, Li et al. (2013) presented an improved repetitive control method using Fourier analyses and signal reconstruction; Nazir (2015) addressed a fractional order repetitive control scheme to adapt grid frequency variations; Ramos (2016) designed an Odd Harmonic High Order Repetitive Controller for increasing the robustness when the signal frequency varies; Gao et al. (2018) proposed a novel dual closed-loop repetitive control strategy based on grid current feedback.

However, the traditional repetitive current controllers (RCC) have a relatively complex compensator, requiring precise controlled object models, but the precise controlled object model is not easily identifiable, and it is also difficult to calculate control parameters with coupling properties.

Based on the drawbacks of the traditional RCC, this paper proposes a new RCC to limit harmonics for three-phase PWM rectifiers. The new RCC using a PI controller to replace the compensator of the object model, which makes its parameters easy to choose.

The paper is organized as follows: Section 2 shows the traditional current control strategies. Section 3 addresses the proposed control strategy. Section 4 presents the calculation of its parameters. And Section 5 indicates the robustness of the proposed method. In Section 6, simulations and experiment results are analysed. Finally, in Section 7, the conclusions are presented.

2. THE CURRENT CONTROL STRATEGIES OF PWM RECTIFIER

To realize static error free tracking control of AC current, PI controllers and a feedforward decoupling strategy, with CLARK-PARK transform, are widely used in the current control of the three-phase voltage source PWM rectifier. Current loop control block diagram with feedforward decoupling of the three-phase voltage source PWM rectifier is shown in Fig. 1, where ω is the angular frequency of grid-side voltage; u_d , u_q and i_d , i_q are the components of the d axis and the q axis after the CLARK-PARK transformation of the three-phase grid-side voltage and current respectively; i_d^* , i_q^* are the references of the d-axis and q-axis current; L is the filter inductance in the grid side; and R is the sum of the switching loss resistance and the equivalent resistance of the filter inductance.

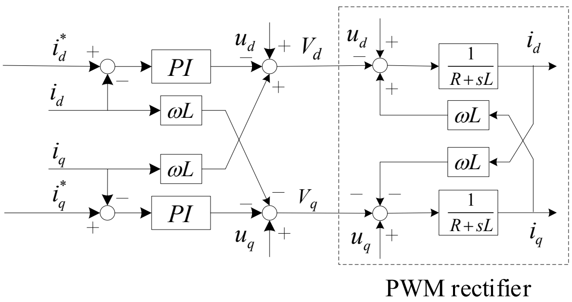


Fig. 1. Current loop control block diagram with feedforward decoupling of the three-phase voltage source PWM rectifier

Considering the impact of data sampling, according to the design principle of a typical type I system, the parameters of the PI controller in Fig. 1 can be set as

$$K_p = \frac{L}{2T_s} \tag{1}$$

$$K_i = \frac{R}{2T_s} \tag{2}$$

where, T_s is the sampling time; K_p is the scale factor; and K_i is the integral coefficient.

Using the PI controller can achieve well tracking of the reference current with zero steady-state error, but it cannot solve the harmonic problem, especially the harmonic caused by the dead time. The traditional repetitive controller is commonly used to solve that problem, in parallel with the PI controllers. The traditional repetitive current controller is often structured as shown in Fig. 2. It is composed of two parts, an internal model and a compensator.

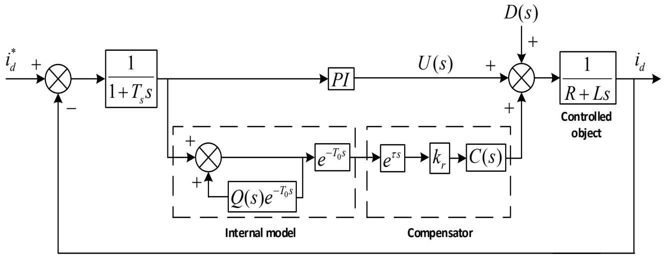


Fig. 2. Current control block diagram with the traditional RCC

In Fig. 2, *D(s)* is the harmonic disturbance; T_s is the sampling time; T_0 is the period of the fundamental current; k_r and $e^{\tau s}$ are the gain compensation and phase-lag compensation, respectively; *Q(s)* is a constant generally for improving the stability of the internal model; and *C(s)* is set as the inverse of the controlled object model to compensate its characteristics.

3. NEW REPETITIVE CURRENT CONTROLLER

3.1 Improved ideas

For the traditional RCC, *C(s)* is always selected as (*Ls*+*R*), the inverse of the controlled object model of current loop. And a small inertia link is added to ensure *C(s)* is physically implemented, then it can be described as

$$C(s) = \frac{Ls+R}{Ts+1} \tag{3}$$

where, *T* is a very small constant that can be adjusted.

It is obvious that, in the traditional RCC, *C(s)* of the compensator is related to the controlled object, requiring high accuracy. And the added inertia link will also affect its performance, in parallel with the original PI controller. Therefore, based on the internal model of the traditional RCC, a new repetitive current controller (New RCC) is proposed in this paper. The novel approach is utilizing another PI controller to replace *C(s)* as the compensation part, as shown in Fig. 3.

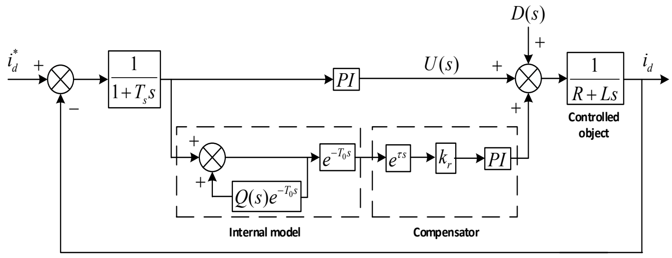


Fig. 3. Current loop control block diagram with the New RCC

The basis of this improved idea is as follows:

1) Less than the cut-off frequency, the integral element of a PI controller has a better suppression of low-frequency harmonics in *D(s)*, compared with the inertia link in *C(s)*.

2) The gain compensation k_r can be considered as a part of the PI controller, which make it easier to adjust in the practical engineering applications.

3.2 Superiority

Similar to (3), the proposed PI controller in the compensator can be selected as

$$C'(s) = PI = \frac{Ls+R}{s} \tag{4}$$

Let

$$P(s) = \frac{1}{Ls+R} \tag{5}$$

Then we have the closed-loop transfer function between the harmonic disturbance *D(s)* and the output current $i_d(s)$

$$\frac{i_d(s)}{D(s)}=\frac{P(s)\cdot(1+T_s s)\cdot(1-Q(s)e^{-T_0 s})}{1+P(s)\cdot PI+T_s s+\left[P(s)\cdot(G-Q(s)\cdot PI)-Q(s)\cdot(1+T_s s)\right]e^{-T_0 s}} \quad (6)$$

where, PI is the transfer function of the original PI controller, its parameters are shown in (1), (2); and *G* represents the transfer function of the compensator.

To make a fair comparison, we keep the same cut-off frequency of the two compensators in Fig. 2 and Fig. 3. Thus, the gain compensation k_r in Fig. 3 is much larger than that in Fig. 2, and the phase-lag compensations are the same.

Table 1. The system parameters

Filter Inductance (*L*)	5mH
Equivalent Resistance (*R*)	0.05Ω
Period of Fundamental Current (T_0)	0.02s
Sampling Time (T_s)	0.0001s
Internal model Coefficient *Q(s)*	0.96

With the close-loop transfer function (6) and the system parameters shown in Table 1, we can plot the Bode diagram shown in Fig. 4.

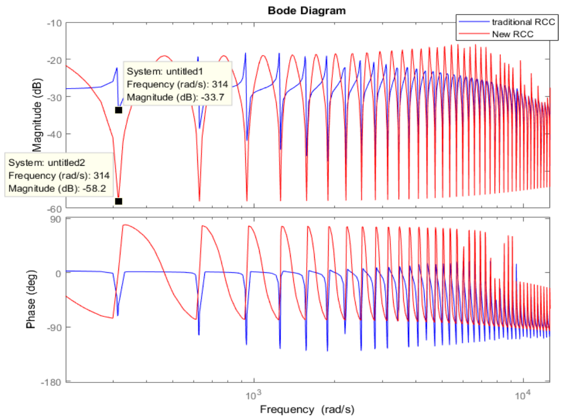


Fig. 4. The closed-loop Bode diagram of the traditional RCC and the new RCC

It can be seen from Fig. 4 that the suppression of lower harmonics is much better, with New RCC. As the proportion of the lower harmonics is larger in the actual system, the proposed method works better.

4. CALCULATE THE PARAMETERS OF THE NEW REPETITIVE CONTROLLER

In the application of digital control system, the New RCC method needs to be discretized. The discretization of the new RCC can be seen in Fig. 5.

The sinusoidal signal with different frequency components is used as the excitation signal *D(z)* of the interference closed-loop system, and the integral of the absolute value of the output signal i_d is taken as the performance index *J*. By minimizing *J*, the optimal controller parameters of the RCC and the New RCC are obtained respectively.

$$J=\int_0^t\left|i_d(\tau)\right|d\tau \quad (7)$$

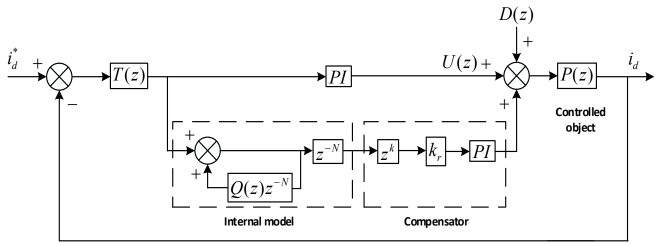


Fig. 5. Discrete control block diagram of New RCC

Here, the parameters of traditional RCC are: *Q(z)*=0.96, *k*=1, k_r=2.27; and the new RCC: *Q(z)*=0.96, *k*=2, k_r=7310. The closed-loop characteristics of the two controllers is shown in Fig. 6.

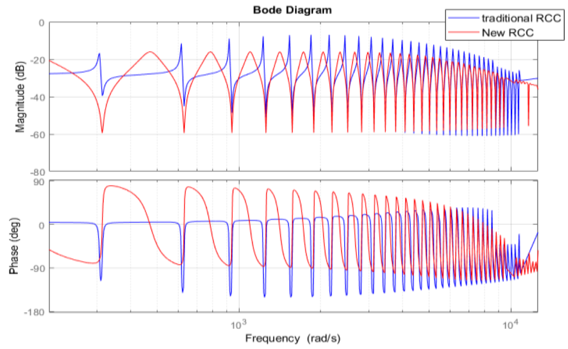


Fig. 6. The closed-loop characteristics of the traditional RCC and the new RCC with the optimal parameters

In Fig. 6, for the low-frequency components below the 13th harmonic, the amplitude of the new RCC is smaller, accordingly the harmonic suppression effect is better than that of the traditional RCC. But in more than 13 harmonic components, the traditional RCC can obtain better notch characteristics. As the actual harmonic components are mainly distributed in the low frequency range below 2500Hz and the integral multiple of the switching frequency, using the new RCC can achieve very good control effect.

5. ANALYSIS OF THE METHOD THAT IS NOT SENSITIVE TO THE CONTROLLED OBJECT

As the conventional PI controller is robust to the controlled object and the New RCC has a PI controller inside, this paper will analyse its sensitiveness to the controlled object.

Keep the parameters obtained in Section 4 and change the parameters of the controlled object in a certain range (considering the heat generation of electronic components and deviations in measurements etc). Similarly, the sinusoidal signal with different frequency components is used as the excitation signal, set i_d^*=0 and then observed the effect of inhibiting harmonics, which can be indirectly reflected by *J*. Chose L∈[0.004,0.006], R∈[0.004,0.006], each time the parameter of the controlled object is changed, the parameters of the original PI controller is again selected to keep the same frequency domain index (cut-off frequency and phase margin). Table 2-4 is the metrics log when the parameters change.

Table 2. Parameters change (L=0.004H)

J (RCC)	0.0087148	0.0087988	0.0088854	0.0089746
J (New RCC)	0.0024480	0.0024471	0.0024463	0.0024455
KP	17.905072	17.905086	17.905101	17.90511
KI	52.528140	74.90930	97.290464	119.671627
L	0.004	0.004	0.004	0.004
R	0.05	0.055	0.06	0.065

Table 3. Parameters change (L=0.005H)

J (RCC)	0.0045112	0.0045233	0.0045354	0.0045477
J (New RCC)	0.0014376	0.0014375	0.0014375	0.0014374
KP	22.381304	22.381319	22.381333	22.381347
KI	9.7072708	32.088432	54.469595	76.850757
L	0.005	0.005	0.005	0.005
R	0.05	0.055	0.06	0.065

Table 4. Parameters change (L=0.006H)

J (RCC)	0.003864	0.003871	0.003877	0.003883
J (New RCC)	0.001278	0.001278	0.001278	0.001278
KP	26.857537	26.857552	26.857566	26.85758
KI	-33.113599	-10.732437	11.648725	34.029887
L	0.006	0.006	0.006	0.006
R	0.05	0.055	0.06	0.065

In order to ensure the tracking performance of the system when the R is relatively small, part of the PI controller's parameter KI<0. That means the system becomes unstable. Thus, the tracking performance must be minimized to ensure system stability.

From Table 2 to Table 4, we find that, in the given range of transformations, the RCC are more effective at inhibiting harmonics than the traditional RCC. Moreover, the proposed method is not relatively sensitive to changes in internal resistance and inductance.

6. SIMULATIONS AND EXPERIMENT RESULTS

Targeted by the effects of grid harmonics and dead-time, the repetitive control method can suppress basic harmonic and multiples of harmonics. Use Matlab–Simulink to perform simulations for the traditional RCC and the New RCC. In three-phase PWM rectifier, the two RCC are added into the current loop control when the current is stable. We add the RCC into the system to further suppress the influence of harmonic current. To show the effectiveness of the RCC, the system dead time is set to 5us. Performed simulations and experiments on the traditional RCC and the new RCC, we obtained the following features.

6.1 Cut-in experiments of the New RCC

After the system is stable, with the original PI controller, the new RCC is cut into the control system. Then, observe the performance of phase-A current on AC side of PWM rectifier to verify the effectiveness of the cut-in method. Meanwhile, in order to validate the control effect of the new RCC in cases of different capacities and the stability during power conversion, the power switching experiment is performed, and the robustness of the new RCC is verified by observing the phase-A current of the PWM rectifier before and after power conversion.

Fig. 7 is the PWM rectifier's current characteristics of phase A before and after the use of a new RCC, which can be seen before and after the introduction of a new RCC, the system is in steady state. Also, the sinusoidal waveform of the current (phase A) after the introduction of the new RCC is significantly improved, which demonstrates that, when using this controller, it is effective in controlling the harmonics.

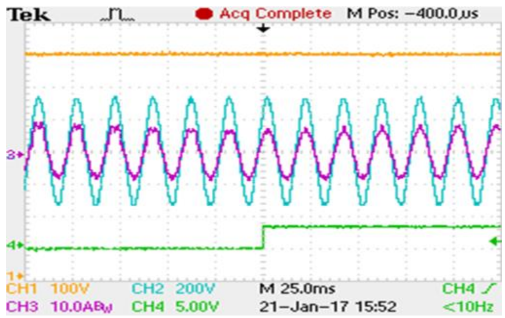


Fig. 7. PWM rectifier's current characteristics of phase A before and after the use of a new RCC

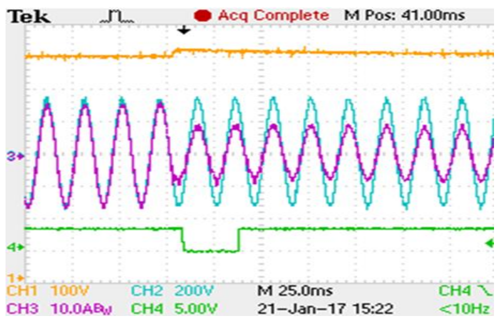


Fig. 8. Current characteristics of phase A when using a new RCC from high power to low power

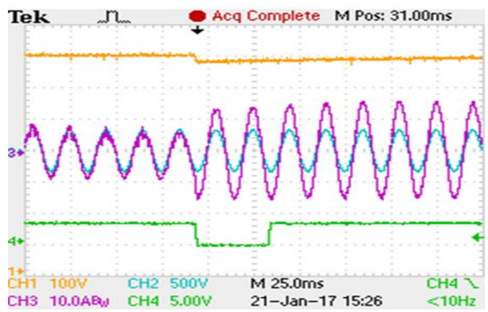


Fig. 9. Current characteristics of phase A when using a new RCC from low power to high power

Fig. 8 and Fig. 9 show that when the system is working steadily it is shifted from 6KW to 3KW and 3KW to 6KW. From the conversion characteristics of the repetitive controller it can be seen that, after switching two basic cycles, repetitive controller can be reconnected and operate stably. Compared to unconnected RCC, the current quality of the phase A is significantly improved.

6.2 Comparisons between the two controllers

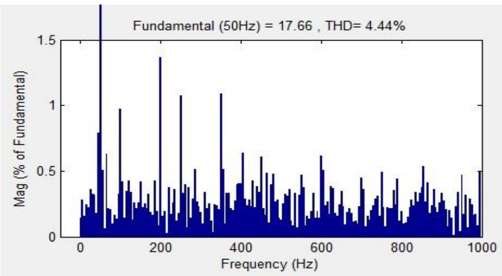


Fig. 10. Current harmonics when using traditional RCC

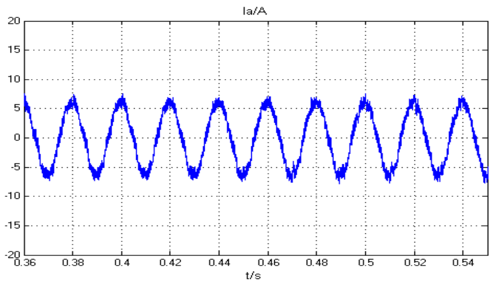


Fig. 11. Alternating current of PWM rectifier of phase A when using traditional RCC

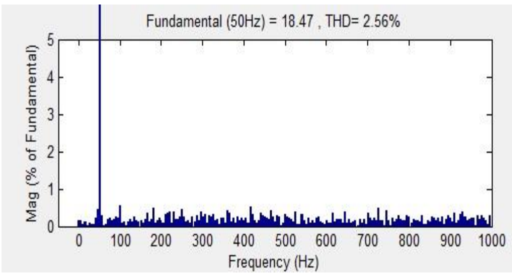


Fig. 12. Current harmonics when using new RCC

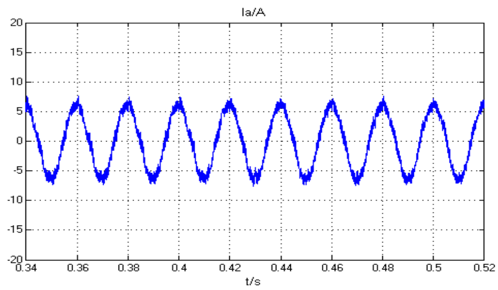
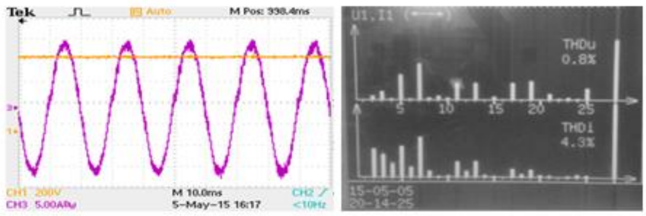
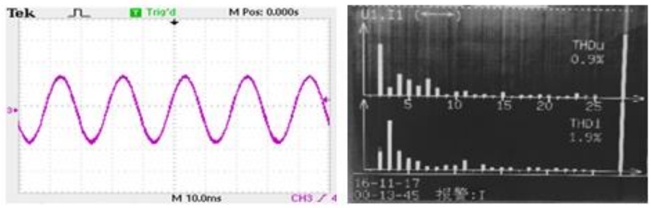


Fig. 13. Alternating current of PWM rectifier of phase A when using new RCC



a)Current and voltage phase-A features b) The experimental data

Fig. 14. Experimental waveform using the traditional RCC



a)Current and voltage phase-A features b) The experimental data

Fig. 15. Experimental waveform using the new RCC

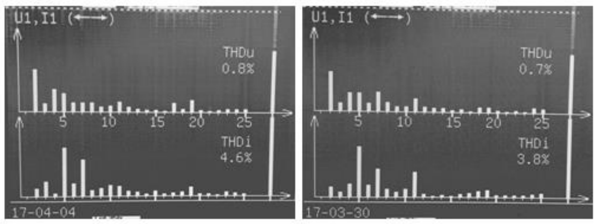
From Fig. 10 and Fig. 11, we see that, when using the traditional RCC, the current of phase A has two relatively high currents, the harmonic coefficient of 4.44%. Fig. 12 and Fig. 13 show that, with the use of a new RCC, the amplitude of the harmonics is small, the harmonic coefficient decreases to 2.56%, the rate to limit harmonics is fast.

The experimental results (Fig. 14, 15) show that When using a new RCC, the current harmonics ratio is relatively small at 1.9%, while for conventional RCC, the result is 4.3%.

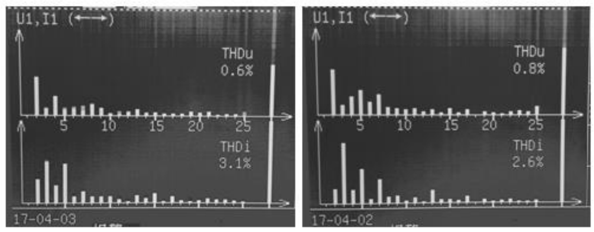
6.3 Object parameter sensitivity experiment

To discuss the susceptibility of two controllers when the object changes, experiments was done with different filter inductances which have values of 4mH, 5mH, 6mH and 7mH. And the output power is 3kW.

From the results of experiments in Fig. 16, 17, we figure out the statistical curve as shown in Fig. 18. When the inductance value increases, the harmonic distortion decreases. With L=4~7mH, using traditional RCC, the harmonic distortion is decreased by 0.6%, 0.5%, 0.3%, and 0.3%, 0.3%, 0.2% for the new RCC. Moreover, when using the same filter inductance value, new RCC has a lower harmonics ratio when using traditional RCC. It can be said that when the inductance is changed in a certain range, the new RCC is less susceptible to changing the parameters of the controlled object, which proves that the design and use of the new RCC is reasonable and effective.

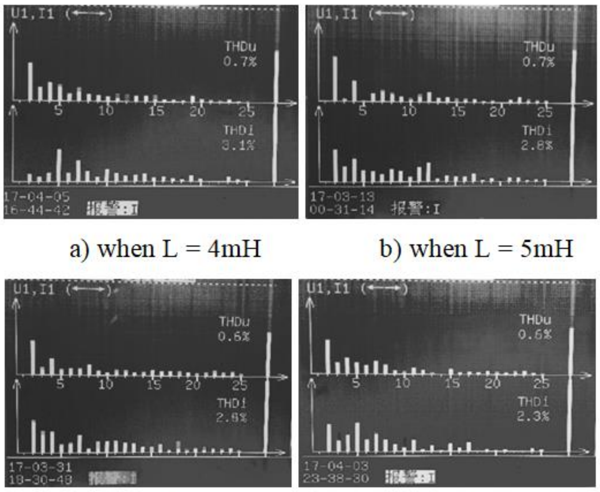


a) when L = 4mH b) when L = 5mH



c) when L = 6mH d) when L = 7mH

Fig. 16. Experimental sensitivity properties when using traditional RCC



a) when L = 4mH b) when L = 5mH

a) when L = 6mH b) when L = 7mH

Fig. 17. Experimental sensitivity properties when using new RCC

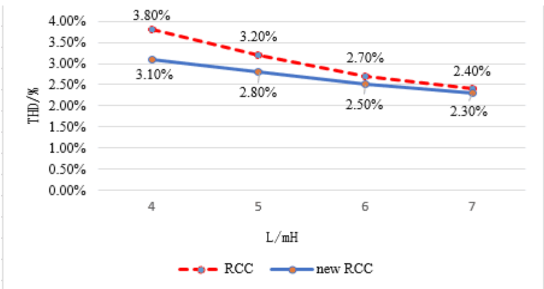


Fig. 18. Trend of change in current harmonics

All of the simulation results and experiments obtained above indicate that the proposed repetitive controller is more capable of high performance than the traditional repetitive controller with better effectiveness and robustness.

7. CONCLUSIONS

When the repetitive controller is applied in a three-phase PWM rectifier system, it will be effective in reducing the current harmonics. The new RCC uses a PI controller to replace the compensator to improve the compensation effect, ensuring the quality of the current loop. This paper uses compound control, a PI controller connected in parallel with a new RCC. Once the system is stable, we put the RCC in place to compensate for harmonics. Perform an analysis of the basic principles of the new RCC and how to define parameters, based on that, performing simulations and experiments to compare the results with the traditional RCC. The results prove that the new RCC is highly effective in improving the quality of alternating current, flexible in wide control range without specific requirements for controlled objects. Basically, it is possible to only change PI parameters of the New RCC to achieve satisfactory control quality. As the New RCC is a simple calculation method and easy to implement, it is suitable for complex situations in which the controlled objects are relatively complex.

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