CONTROL STRATEGY OF ACTIVE FILTER USING COORDINATION BETWEEN PROPORTIONAL-INTEGRAL MULTI-RESONANT-TYPE REPETITIVE CONTROL AND COMPOSITE OBSERVER

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ABSTRACT

This paper presents a control strategy to enhance the operation of an active filter (AF). First, the high-order harmonic components of the current are accurately extracted using a composite observer. Then, a proportional-integral multi-resonant-type repetitive control (PIMR-RC) is applied to control the current harmonics generated by the active filter to follow the current harmonics caused by the nonlinear loads. Simulation using PSIM software for the active filter was performed to verify the feasibility of the proposed control strategy.

Keywords: Active power filter, repetitive controller, proportional resonant controller, current harmonics, nonlinear load.

1. INTRODUCTION

Recently, power converters such as thyristor or insulated gate bipolar transistor (IGBT) based-rectifiers, motor speed control drives, and so on have been widely used in industry. This can be one of the main reasons which cause power quality problems in the electric grid.

Power quality problems related to voltage, current and frequency can cause electric equipments to operate abnormally or even lead to fail. Among them, problems such as frequency deviation, voltage swell, voltage sag, voltage fluctuation, unbalanced three-phase voltage, phase failure, and harmonics are the causes of power quality degradation.

Waveforms with frequencies that are multiples of the fundamental frequency (usually 50Hz or 60Hz) are called harmonics. The harmonic generation is caused by the use of nonlinear loads such as welding machines, furnaces, asynchronous motor controllers or DC motors, opening and closing of large power sources, etc. Standards such as IEEE-519 and IEC 61000-3-2 related to harmonics have been published so that electric networks must meet the requirements of harmonic currents within allowable limits [1, 2]. In addition, to satisfy these standards, active filters (AF) are considered as a good solution to improve the quality of power in distribution networks [3].

Several different control methods have been proposed for the active filter. According to [4], a proportional-integral (PI) controller with sinusoidal pulse-width modulation technique has been used to handle high-order harmonic currents with high-frequency signals. However, the PI controller is not a suitable solution for the AF because the bandwidth limit of the PI regulator remains unchanged and there is still a significant error in extracting the high-order harmonic components of the reference current. In addition, the deadbeat control method has been applied and has significantly improved the performance of the AF by eliminating the high-frequency harmonic components. With the reference current prediction technique, the current error can be almost eliminated in the steady state. However, the current error and its overshoot level may increase when there is a sudden change in the load. Another control method using hysteresis control has been applied for the AF [5]. The use of the AF based on this control method has shown that the implementation of the hysteresis controller is simple, robust, and significantly improves the performance of the hysteresis current. However, the disadvantage of this controller is that the resonant problem still exists in the distribution network. In addition, the hysteresis band must be carefully selected so that its value is as small as possible for better performance of the current. For this, the switching frequency increases considerably and causes switching losses for high power electronic components [6, 7].

In this paper, a current compensation control strategy using a proportional-integral multi-resonant-type repetitive control (PIMR-RC) combined with a composite observer for the AF is proposed to significantly reduce the current harmonics flowing into the grid. With this method, the composite observer is firstly used to accurately extract the harmonic components of the current. Then, the proportional-integral multi-resonant-type repetitive control is applied so that the AF control generates current harmonics that are approximately equal to the current harmonics generated by the nonlinear load. The simulation using PSIM for the AF system has been performed to verify the effectiveness of the proposed control strategy.

2. CONTROL OF COMPENSATING SOURCE CURRENT HARMONICS USING ACTIVE FILTER

2.1. System model of active filter

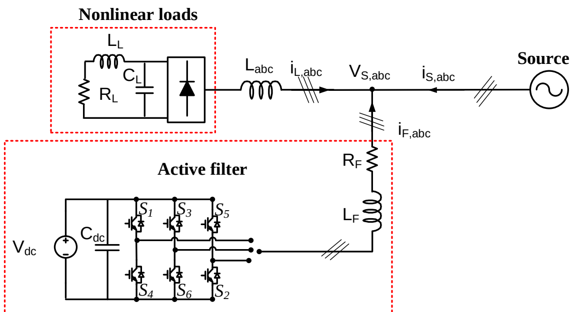

Figure 1. Circuit diagram of active filter

Figure 1 shows the circuit diagram of the AF connected to a three-phase three-wire grid (source) system. As shown, the AF consists of a three-phase voltage inverter using six IGBTs connected in parallel with a nonlinear load at the point of common coupling. The input of the AF is a DC voltage source connected in parallel with a capacitor and the output of the AF is connected in series with an inductance (L_F) and a resistor (R_F). The nonlinear loads consist of a three-phase voltage rectifier using a diode full-bridge connected to an RLC load at the output.

2.2. Existing current control strategies of active filter

The AF is a flexible solution for compensation since it is capable of compensating current harmonics generated by various types of nonlinear loads as well as fast compensation of current harmonics in the case of load changes (Figure 1). The target of the AF is to generate current harmonics ($i_{F,abc}$) that have the similar magnitude and phasor inversion to the current harmonics caused by the nonlinear loads. Thus, the source currents ($i_{S,abc}$) become purely sinusoidal. On the other hand, they only contain the fundamental component.

2.2.1. PI based-current control strategy of active filter

As shown in Figure 2, the reference current in d -axis in the rotating reference frame (i_{de}^*) is the current containing the harmonic components of the compensated currents, after removing the fundamental component using a low-pass filter (LPF). Meanwhile, the reference current in q-axis in the rotating reference frame (i_{qe}^*) is also the current (i_{qe}) that also contains the harmonic components of the compensated currents. These reference current components are compared with the measured current components and their errors are fed into the PI controller, to generate values of the reference voltages (v^*_{Fde} , v^*_{Fqe}) and are used to convert to the abc reference frame for space vector pulse-width modulation (SVPWM) to control the switching of the IGBTs.

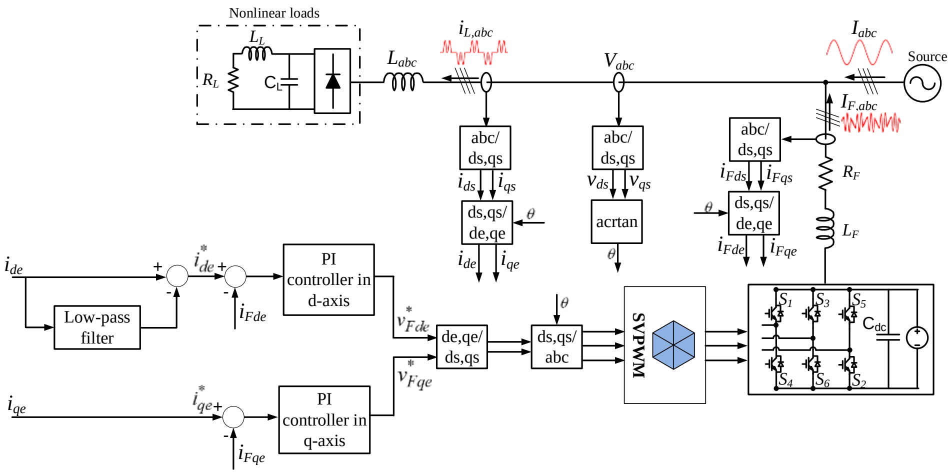

Figure 2. Block diagram of PI based-current control strategy for active filter

The PI controller has been used for current control in the AF. However, this control method does not eliminate source current harmonics perfectly because the extraction of reference harmonics from the low-pass filter is not accurate.

2.2.2. PR based-current control strategy of active filter

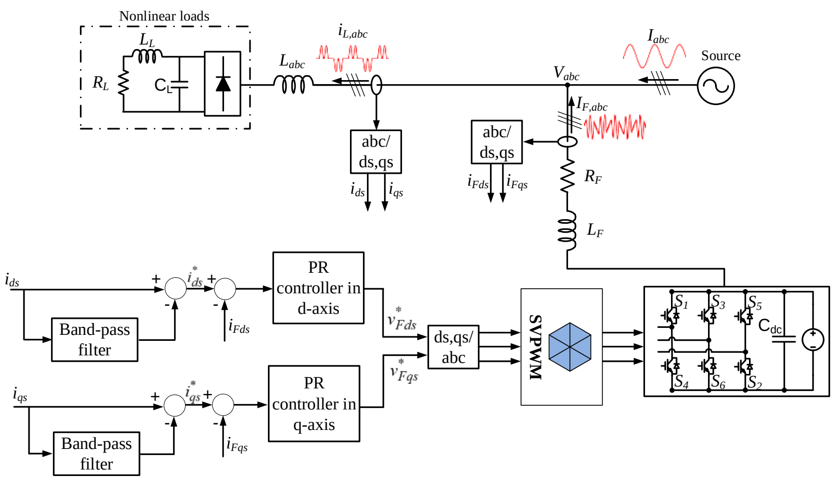

Figure 3. Block diagram of PR based-current control strategy for active filter

As shown in Figure 3, the reference current in d-axis in the stationary reference frame (i^*_{ds}) is the current containing the harmonic components of compensated currents, after removing the fundamental component by using a band-pass filter (BPF). Meanwhile, the reference current in q-axis (i^*_{qs}) in the stationary reference frame also contains the harmonic components of compensated currents. These reference current components are compared with the measured current components and their errors are put into the proportional resonant (PR) controller to produce reference voltages, which is used to generate the pulses using the SVPWM method.

The transfer function of the proportional resonant controller is expressed as:

$$G_{PR}(s) = \sum_{h=3,5,7...} K_{ph} + \frac{2K_{rh}s}{s^2 + \left(h\omega_s\right)^2} \quad (1)$$

Where K_{ph} and K_{rh} are proportional and resonant controller parameters, respectively.

The PR control method is used for controlling the current of the active circuit. However, this control method does not solve the problem completely due to the inaccurate extraction of the reference current harmonics for compensation from the band-pass filter.

2.3. Current control strategy using proportional-integral multi-resonant-type repetitive controller (PIMR-RC) combined with composite observer (CO)

2.3.1. Extraction of currents using a composite observer

The composite observer (CO) is used to extract the current components. The principle of the CO is summarized as follows [8]:

Assume that the periodic signal of y(t) consists of components such as DC signal ($y_0(t)$), fundamental component ($y_1(t)$) and harmonic components ($y_5(t)$, $y_7(t)$),... which are expressed as follows:

$$y(t) = \sum_{m=0,1,5,7} y_m(t) \quad (2)$$

The input signal is written in the discrete domain as follows:

$$y(i) = \sum_{m=0,1,5,7} y_m(i); \quad i = 0,1,2,\ldots,\infty \quad (3)$$

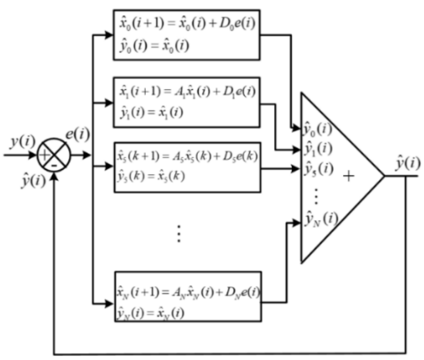

Figure 4. Closed loop diagram using CO

The structure of CO is shown in Figure 4 as follows:

$$\begin{cases} \hat{x}(i+1) = A\hat{x}(i) + De(i) \\ \hat{y}(i) = C\hat{x}(i) \end{cases} \quad (4)$$

Where the index "^" indicates the estimated value, x(i) is the state vector, y(i) is the output vector, A and C are the observer matrices and D is the gain vector, which is as follows:

$$D = [d_0, (d_{11}, d_{12}), (d_{51}, d_{52}), (d_{71}, d_{72}), (d_{111}, d_{112}), (d_{131}, d_{132})]^T \quad (5)$$

and e(i) is the observer error calculated by the following formula: $e(i) = y(i) - \hat{y}(i)$

In this study, the DC, fundamental and harmonic components of the 5th, 7th, 11th, 13th order of the source (grid) current are used as state variables in the CO. To select the gain vector of the CO, the pole-placement technique is often used [8].

2.3.2. Current control strategy using proportional-integral multi-resonant-type repetitive controller (PIMR-RC)

The transfer function of the repetitive controller is expressed as:

$$G_{re}(s) = K_{re}\frac{e^{-sT}}{1-e^{-sT}} \tag{5}$$

Where K_{re} is the coefficient of the repetitive controller and $T = 2\pi/\omega_0$ is the delay time.

Implementing the Taylor series, (5) is rewritten as:

$$G_{re}(s) = -\frac{K_{re}}{2} + \frac{K_{re}}{Ts} + \frac{2K_{re}}{T}\sum_{h=5,7...}\frac{s}{s^2+(h\omega_s)^2} \tag{6}$$

By adding (6) the proportional constant of $K_p > K_{re}/2$, the proportional-integral multi-resonant-type repetitive controller (PIMR-RC) is rewritten as follows:

$$G_c(s) = \left(K_p - \frac{K_{re}}{2}\right) + \frac{K_{re}}{Ts} + \frac{2K_{re}}{T}\sum_{h=5,7...}\frac{s}{s^2+(h\omega_s)^2} \tag{7}$$

Or $$G_c(s) = K_{pc} + \frac{K_{ic}}{s} + K_{rec}\sum_{h=3,5,7...}\frac{s}{s^2+(h\omega_s)^2} \tag{8}$$

Where $K_p = (K_p - K_{re}/2)$, $K_{ic} = K_{re}/T$ và $K_{rec} = 2K_{re}/T$ are the proportional, integral and resonant constants of the proportional-integral multi-resonant-type repetitive controller, respectively.

The higher order harmonic components of the load current are accurately extracted from the load current ($i_{L,abc}$) using the CO. Then, the reference currents in the dq-axis (i^*_{dqs}) are compared with the measured currents from the AF. The errors of their currents are put into the proportional-integral multi-resonant-type repetitive controller (PIMR-RC) to obtain the reference voltages in the dq-axis (v^*_{Fdqs}) and these voltage components are transferred to the abc reference frame which are used for pulse modulation using the SVPWM method (Figure 5).

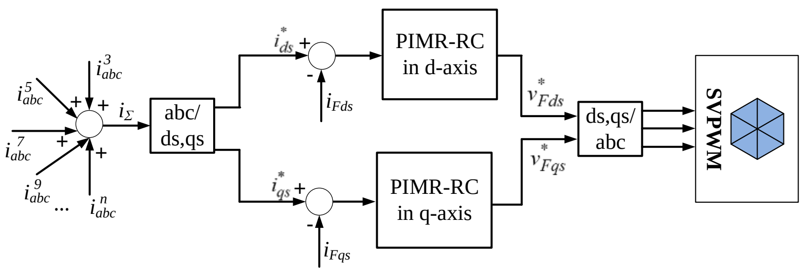

Figure 5. Block diagram of PIMR-RC based-current harmonic compensation control strategy for active filter

1. SIMULATION RESULTS AND DISCUSSION

Simulation using PSIM software has been used to verify the effectiveness of the proposed control strategy (PIMR-RC combined with CO) for the AF. The system parameters for the simulation are listed in Table 1.

Table 1. System parameters for the simulation

Parameters	Values	Parameters	Values
Grid voltage ($V_{ll(rms)}$)	135 V	Filter resistor (R_F)	0.05 Ω
Grid frequency (f_0)	50 Hz	Load resistor (R_L)	15-25 Ω
Rated power (P)	1.5 kVA	Load inductor (L_L)	1 mH
DC voltage (V_{dc})	340 V	Load DC capacitor (C_L)	220 µF
DC capacitor (C_{dc})	1000 µF	PI controller	$k_I = 4$, $k_P = 25$
Switching frequency (f_s)	10 kHz	PIMR-RC controller	$K_{pc} = 26$, $K_{ic} = 1200$, $K_{rec} = 0.5$

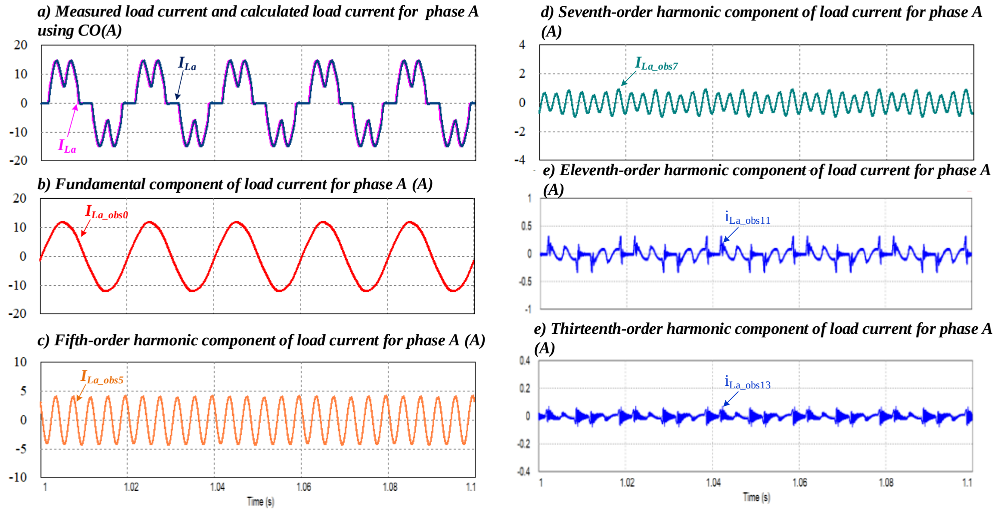

Figure 6. Simulation results for the decomposition of the desired load current harmonic components using CO. (a) Measured and calculated load currents for phase A using CO. (b) Fundamental component of the load current for phase A. (c) 5th order component of the load current for phase A. (d) 7th order component of the load current for phase A. (e) 11th order component of the load current for phase A. (f) 13th order component of the load current for phase A.

The gain vectors of (5) are designed as

$$D = [d_0, (d_{11}, d_{12}), (d_{51}, d_{52}), (d_{71}, d_{72}), (d_{111}, d_{112}), (d_{131}, d_{132})]^T$$

=[0.158413; (0.235203, -0.236894), (0.096, -0.9254); (0.081146, -0.0581);

$(0.04125, -0.0264); (0.0167, -0.00577)]^T$

Figure 6 shows the decomposition results for the harmonic components of the load current for phase A. As shown in Figure 6 (a), the measured load current and the estimated load current from the CO are almost similar. This proves that the CO extracts the desired harmonic components very accurately. By using the CO, the reference currents in dq-axis (i^*_{dqs}) are obtained by summing the harmonic components of the current. The 5th, 7th, 11th, and 13th order harmonic components of the current are shown in Figures 6(c) to 6(f), respectively.

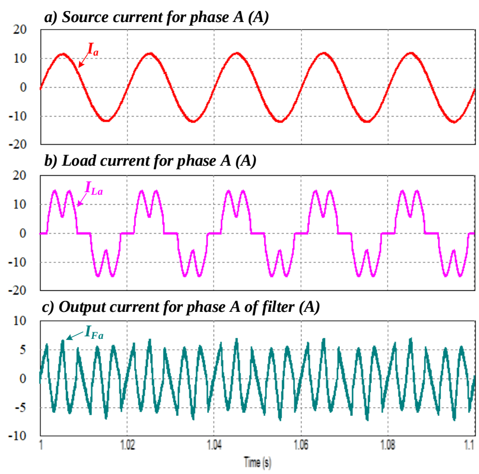

Figure 7. Simulation results of active filter using current control strategy based on PI controller (a) Source current for phase A, (b) Load current for phase A, (c) Filter output current for phase A.

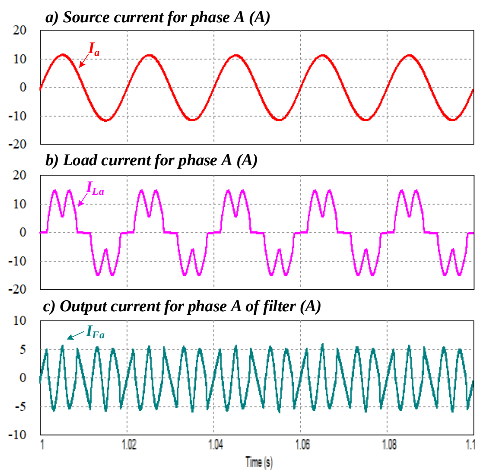

Figure 8. Simulation results of active filter using current control strategy based on proposed controller (a) Source current for phase A, (b) Load current for phase A, (c) Filter output current for phase A.

The simulation results for the AF using the PI controller current control strategy and the proposed controller (PIMR-RC) are shown in Figure (7) and Figure (8), respectively. Each result in Figure 7 and 8 shows the source, load and output currents for phase A of the filter. The FFT (fast Fourier transform) analysis of the source current for phase A using current control strategy based on the PI controller and the proposed controller is shown in Figure 9 and 10, respectively. As shown in Figure 10, the source current for phase A has almost no high-order harmonic components. This proves that the use of the current control strategy based on the proposed controller for the AF gives better performance results than current control strategy based on the PI controller.

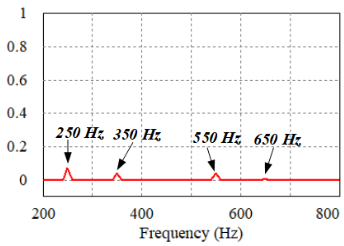

Figure 9. FFT analysis of source current in phase A using current control strategy based on the PI controller.

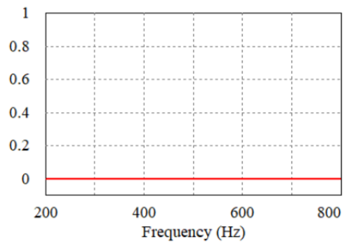

Figure 10. FFT analysis of source current in phase A using current control strategy based on the proposed controller.

Table 2. Total harmonic distortion (THD) of source current

	Without AF	Current control strategy based on PI controller	Current control strategy based on proposed controller
Total harmonic distortion (THD)	39.27%	5.1 %	1.32 %

According to the FFT analysis results of the A-phase source current in Figure 10, the THD index of the source current using the current control strategy based on the proposed controller has been reduced by less than 2%, satisfying the IEEE-519 and IEC-61000-3-2 standards. Therefore, the AF gives good results in the case of using the proposed control strategy.

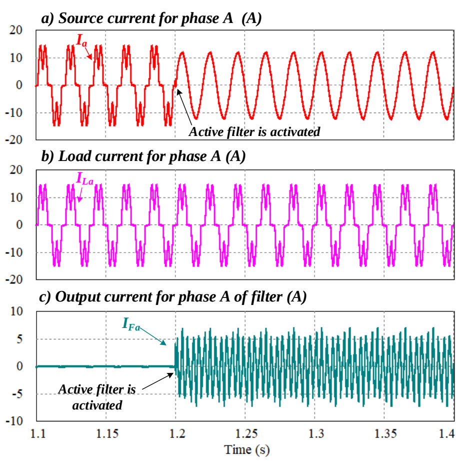

Figure 11. Simulation results of active filter using current control strategy based on PI controller: (a) Source current for phase A, (b) Load current for phase A, (c) Filter output current for phase A

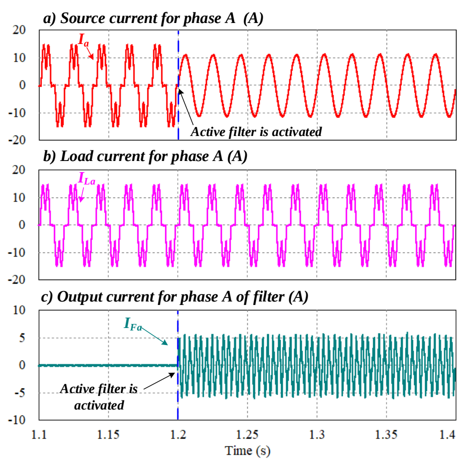

Figure 12. Simulation results of active filter using current control strategy based on proposed controller: (a) Source current for phase A, (b) Load current for phase A, (c) Filter output current for phase A

The performance of the AF using the current control strategy based on the PI controller and the proposed controller are shown in Figures 11 and 12, respectively. During the duration of 1.1 - 1.2 s, the system operates without using the AF. This causes the source current to be distorted, as shown in Figures 11 and 12 (a). At time 1.2 s, the AF is connected to the system, the compensation current is injected into the grid (Figures 11 and 12 (c)), and the source current has a sinusoidal waveform.

4. CONCLUSION

The paper presents a control strategy to improve the performance of the AF. Firstly, a composite observer is used to accurately estimate/extract the high-order harmonic components of the current. Then, a proportional-integral-resonant repetitive controller (PIMR-RC) has been applied to control the compensation of the high-order harmonic components of the current. The simulation of the AF system using PSIM software has been carried out to verify the feasibility of the proposed controller. The simulation results show that both the PI and PIMR-RC controllers for AFs have the ability to compensate the current harmonics, but the proposed controller compensates the current harmonics better than the PI one (THD_L_PI = 5.1%, THD_L_PIMR-RC = 1.32%). In the future, the topic can be extended to apply multi-level inverters to minimize the THD at the source voltage.

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TÓM TẮT

ĐIỀU KHIỂN BỘ LỌC TÍCH CỰC DÙNG BỘ ĐIỀU KHIỂN LẶP ĐA CỘNG HƯỞNG TÍCH PHÂN TỶ LỆ KẾT HỢP VỚI BỘ QUAN SÁT TỔNG HỢP

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Bài báo trình bày chiến lược điều khiển để nâng cao vận hành của bộ lọc tích cực (AF). Trước tiên, các thành phần họa tần bậc cao được trích ra chính xác từ dòng điện tải phi tuyến dùng bộ quan sát tổng hợp (composite observer). Sau đó, bộ điều khiển lặp đa cộng hưởng tích phân tỷ lệ (proportional-integral multi-resonant-type repetitive control-PIMR-RC) được áp dụng để điều khiển bộ lọc tích cực phát ra họa tần bậc cao của dòng điện gần bằng đúng họa tần dòng điện được sinh ra bởi tải phi tuyến. Việc mô phỏng bộ lọc tích cực dùng phần mềm PSIM đã được thực hiện để kiểm chứng tính khả thi của chiến lược điều khiển đề xuất.

Từ khóa: Bộ lọc tích cực, bộ điều khiển lặp, bộ điều khiển cộng hưởng tỷ lệ, họa tần dòng điện, tải phi tuyến.