Performance Improvement of Current-Controlled PWM Inverter by Means of Dithering

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***Abstract* — This paper describes a novel current control strategy of a voltage-source PWM (Pulse Width Modulation) inverter by means of dithering. There have been two principal methods to achieve the current control, i.e. a sinusoidal PWM (sub-harmonic) method by using PI regulators and a triangular wave carrier, and a relay (bang-bang) control method by using hysteresis elements as current regulators. It is inherently impossible to achieve PWM-pattern optimization, quick response and current-error minimization with those conventional methods at the same time. The method proposed in this paper is based on dithering of the hysteresis bands in the current regulators, where thresholds of the hysteresis elements are modulated by a triangular wave with minute amplitude and high frequency. The control characteristics of this system mostly depend on the amplitude of the dither signal and all the drawbacks of the conventional methods can be simultaneously overcome by setting the amplitude as small as the hysteresis bands. This paper presents a basic concept of the proposed method and the operating characteristics compared with the commonly known current control methods. Consequently, remarkable performance improvement by the proposed method has been confirmed through experimental tests as well as computer simulations.**

***Index Terms* — Current control, current regulator, dithering, and PWM inverter.**

I. INTRODUCTION

THIS paper focuses on a current control technique of a voltage-source PWM inverter and proposes a novel control strategy to improve its operating characteristics by means of dithering. There have been two principal approaches to achieve the current control with the inverter [1], [2]. One is a sinusoidal PWM (sub-harmonic) technique by using current regulators, e.g. PI elements and a triangular wave as a carrier and the other is a relay (bang-bang) control technique by using hysteresis elements. The former surpasses the latter with regard to its optimized PWM pattern that is generated by the inverter but is inferior to the latter from the viewpoint of a response and a control error of the currents. The latter has the merits and the demerits vice versa. Therefore, it is basically impossible to achieve the PWM-pattern optimization, the quick response and the current-error minimization at the same time with those conventional methods.

On the other hand, a technique of dithering has been recognized as one of the solutions that can make nonlinear phenomenon and systems linear. Since the current-controlled PWM inverter is regarded as a kind of the nonlinear systems, dithering is a possible choice of the most effective measures to improve the performance of the current control. The technique proposed in this paper is based on dithering of the hysteresis bands in the current regulators, where the thresholds of the hysteresis elements are modulated by a triangular wave with minute amplitude and high frequency. The control characteristics mostly depend on the amplitude of the dither signal and the drawbacks of the conventional methods described above can simultaneously be overcome by setting the amplitude as small as the hysteresis bands. This paper presents a basic concept of the proposed technique and performance evaluation compared with the commonly known conventional methods. Consequently, excellent control characteristics of the proposed method have been confirmed through computer simulations and experimental tests. Also, this paper clarifies optimal conditions to obtain the maximum effects of dithering when this method is applied to the current controller.

II. BASIC CONFIGURATIONS AND OPERATIONS OF CURRENT-CONTROLLED PWM INVERTERS

A. Conventional Current Controllers

A power conversion system to be investigated in this paper is a three-phase voltage-source PWM inverter that is connected to a three-phase balanced reactive load. Fig. 1 shows a schematic

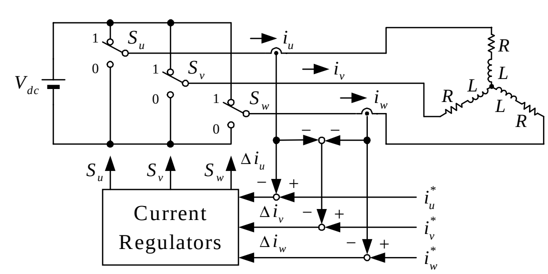

Fig. 1. Current-controlled three-phase PWM inverter.

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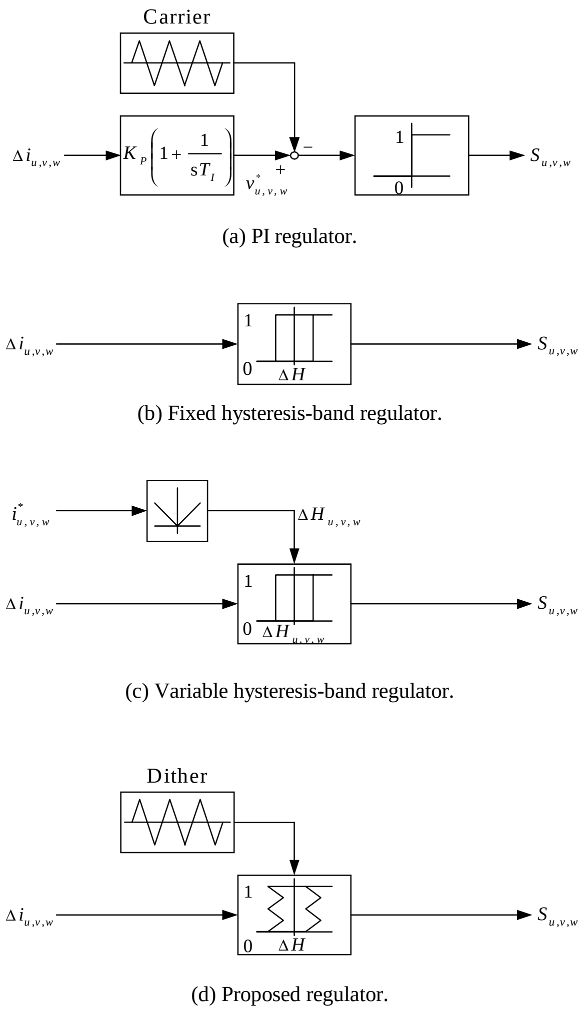


(a) PI regulator.

(b) Fixed hysteresis-band regulator.

(c) Variable hysteresis-band regulator.

(d) Proposed regulator.

Fig. 2. Detailed configurations of various current regulators.

diagram of the system. As shown in this figure, a controller of the inverter has a set of current regulators to control the three-phase load currents i_u, i_v and i_w with current feedback loops. The feedback currents are detected by two Hall-effect current transducers and are compared with three-phase current commands i_u^*, i_v^* and i_w^* to generate current errors Δi_u, Δi_v and Δi_w, respectively. The current commands are basically sinusoidal waves of which amplitude and operating frequency are variable. The current regulators receive the current errors and output switching signals to the inverter legs so that the load currents follow the current commands.

Fig. 2 shows detailed configurations of several current regulators. Fig. 2(a) is the most extensively used PI regulator with PWM. As can be seen in this diagram, the current error of each phase is an input of the PI element and its output is a voltage command to a corresponding phase of the inverter. To generate PWM patterns, i.e. switching signals S_u, S_v and S_w, the three-phase voltage commands v_u^*, v_v^* and v_w^* are compared with a common triangular wave. In this system, an open-loop transfer function of the current control loop can be expressed by the following equation:

$$G_o(s) = K_P\left(1+\frac{1}{sT_I}\right)\frac{1}{sL+R} = \frac{K_P(sT_I+1)}{sT_I(sL+R)}. \tag{1}$$

Assuming that the crossover frequency ω_c is given as a design specification of the current controller, open-loop gain at ω_c can be approximated as

$$\left|G_o(s)\right| = \frac{K_P\sqrt{\omega_c^2 T_I^2+1}}{\omega_c T_I\sqrt{\omega_c^2 L^2+R^2}} \approx \frac{K_P}{\omega_c L} = 1. \tag{2}$$

Therefore, the proportional gain K_P of the PI element can be determined from the above equation. Particularly, if the integral time constant T_I of the PI element is adjusted to be $T_I = L/R$, zero-pole cancellation occurs in (1), which results in the following simple open-loop transfer function:

$$G_o(s) = \frac{K_P}{sL}. \tag{3}$$

Since the closed-loop transfer function, in this case, becomes first-order as expressed by (4), no overshoot appears in a step response.

$$G_c(s) = \frac{K_P}{sL+K_P}. \tag{4}$$

The switching signals are generated by comparing the voltage commands with the triangular wave $tr(t)$ as follows:

$$\begin{array}{ll} S_u, S_v, S_w = 0 & \text{if } v_u^*, v_v^*, v_w^* < tr(t) \\ S_u, S_v, S_w = 1 & \text{if } v_u^*, v_v^*, v_w^* \geq tr(t) \end{array}. \tag{5}$$

On the other hand, the relay control is the simplest algorithm to achieve current control with the inverter. Fig. 2(b) shows a fixed hysteresis-band regulator, which is commonly employed as the relay control technique. These regulators receive the current errors and directly output the switching signals to the corresponding inverter legs. The regulator of each phase individually operates to restrict its current error within a specified hysteresis band. The hysteresis bandwidth ΔH is determined on the basis of the average switching frequency of the inverter.

$$\begin{array}{ll} S_u, S_v, S_w = 0 & \text{if } \Delta i_u, \Delta i_v, \Delta i_w > \Delta H/2 \\ S_u, S_v, S_w = 1 & \text{if } \Delta i_u, \Delta i_v, \Delta i_w < -\Delta H/2 \end{array}. \tag{6}$$

Fig. 2(c) is a modified version of the relay controller that features a variable hysteresis bandwidth, which can be found in [3] or [4]. The hysteresis bandwidth of the method described in [4] is changed with respect to time according to the fundamental current amplitude as expressed by (7).

$$\Delta H_u = k\left|i_u^*\right|, \Delta H_v = k\left|i_v^*\right|, \Delta H_w = k\left|i_w^*\right|. \tag{7}$$

The hysteresis bandwidth of each phase becomes wider around current peaks and does narrower around zero-crossing points. Therefore, it is difficult to avoid violent increase of the inverter switching frequency around the zero-current.

B. Proposed Current Control with Dithering

An objective of the proposed technique is to fuse every advantage of the conventional methods without sacrificing simplicity of its configuration and control algorithm, i.e. to

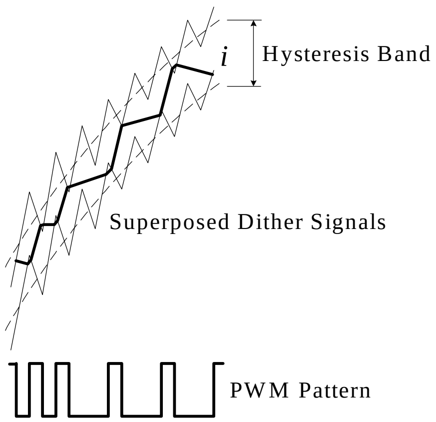


Fig. 3. Operation of proposed method.

achieve the optimized PWM patterns, a quick response of the load currents and the minimized current error at the same time [5]. Fig. 2(d) depicts a schematic diagram of the proposed current regulator and Fig. 3 illustrates the operation of the regulator with hysteresis-band dithering. As shown in Fig. 2(d), the skeletal configuration of the regulator is not changed from that of the original relay current regulator. The only difference from the conventional regulator is time-varying thresholds of the hysteresis elements. The hysteresis bands are dithered by superposing a minute and high-frequency triangular wave onto both the upper and the lower thresholds. The amplitude of the triangular wave is the most important factor to determine the operating characteristics of the proposed control, which is normally chosen to be as small as the hysteresis bands. The frequency of the triangular wave is set at a specific value required by the power devices employed in the inverter.

III. PERFORMANCE EVALUATION OF CURRENT CONTROLLERS

A. *Computer Simulation Results*

Computer simulations and experimental tests have been conducted to examine the operating characteristics of the four methods, i.e. the PI regulator, the fixed hysteresis-band regulator, the variable hysteresis-band regulator and the proposed regulator. Fig. 4 shows computer simulation results of the four methods, where the PWM pattern, the current waveforms, the current vector and the current-error vector loci, and the frequency spectra of the current are depicted for each method.

As shown in Fig. 4(a), the PI regulator demonstrates an excellent PWM pattern in the line-to-line inverter output voltage waveform. However, phase and amplitude errors are observed between the current command and the feedback current although the current ripple is effectively suppressed. As can be seen in the current-error vector locus, the current-error vector distributes in a hexagonal shape with a center hall. The current controllability can be evaluated from the viewpoint of the locus area. Also, it is found that the frequency spectra of this method have conspicuous multiple harmonic components of the carrier frequency.

Fig. 4(b) shows the characteristics of the fixed hysteresis-band regulator. In contrast with those of the PI regulator, less phase and amplitude errors are observed between the current command and the feedback current, which can also be confirmed in the current-error vector locus. As known well, the current-error vector locus of this method indicates a shape of hexagonal star because of independent three-phase relay actions with the fixed hysteresis band. The frequency characteristic of the current is so called spread spectra with no conspicuous components. However, the PWM pattern of the inverter is not optimized and several inappropriate switching operations are observed in the voltage waveform. These merits and demerits are undertaken to the variable hysteresis-band regulator as shown in Fig. 4(c). Even though the hysteresis bandwidth is dynamically changed with current amplitude, the PWM pattern optimization cannot be achieved and current-error vector locus is not reduced. However, this method is scarcely effective to reduce the lower-order harmonic components of the current.

On the other hand, the proposed method demonstrates excellent performance with regard to both current and voltage waveforms. As shown in Fig. 4(d), it is possible to reduce the current-error vector less than that of the fixed hysteresis-band regulator and to optimize the PWM pattern as well as the PI regulator. It is found that the locus shape of the current error is almost circle, which contributes to reduce the rms value of the error. The frequency spectra of the proposed method show a mixed characteristic of the two conventional methods.

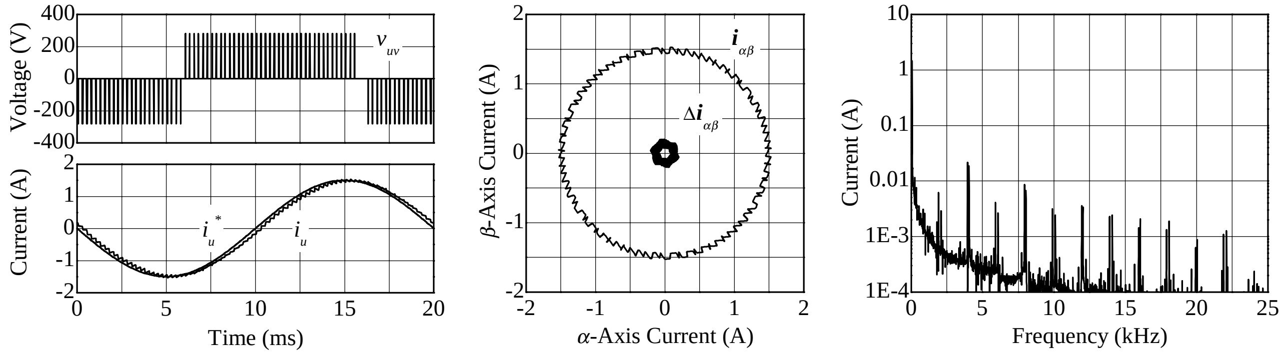
B. *Experimental Results*

An experimental system was setup to verify feasibility of the simulation results and actual control performance. In the system, the current regulators are composed with digital-and-analog hybrid hardware and one of the four methods can be digitally selected on the unified circuit. Also, exactly identical electric components, for example main power circuits, current sensors and so forth, are employed to make performance evaluations fair. The 50-Hz sinusoidal current commands are given to the control circuits by a synthesized function generator. The DC bus voltage is kept constant at 280 (V) and the inverter switching frequency is set at 2 (kHz) for every method. Also, a lockout circuit of which dead time is 2 (μs) is implemented on every controller to prevent short-circuit across the DC bus.

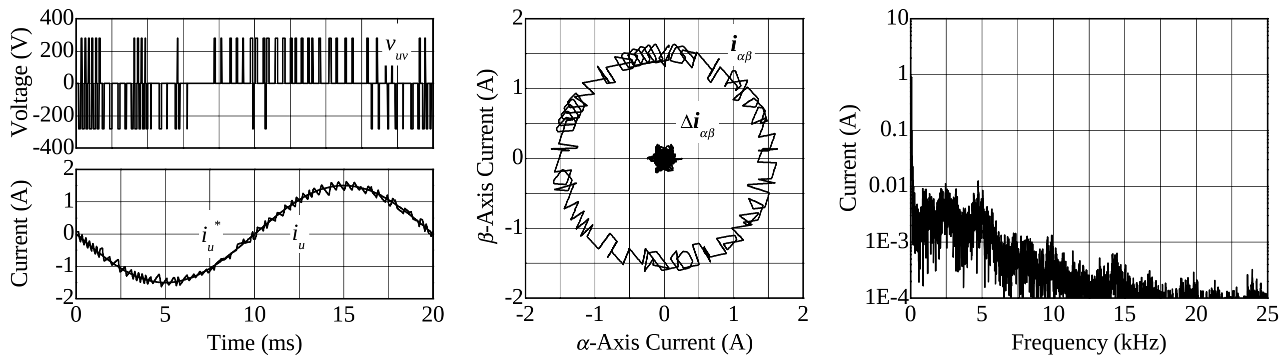
Fig. 5(a)-(d) depict experimental results of the four methods, where the test conditions are identical to those of the simulations. All of the experimental data were measured with a digital oscilloscope that can store the data on a floppy disk in ASCII format. As shown in these results, every operating characteristic agrees with that of the simulations very well. It can be seen that the proposed method is capable to optimize the PWM pattern, to minimize the current ripple and to reduce the current error at the same time.

IV. OPERATING CHARACTERISTICS OF DITHER BASED CURRENT CONTROLLER UNDER VARIOUS CONDITIONS

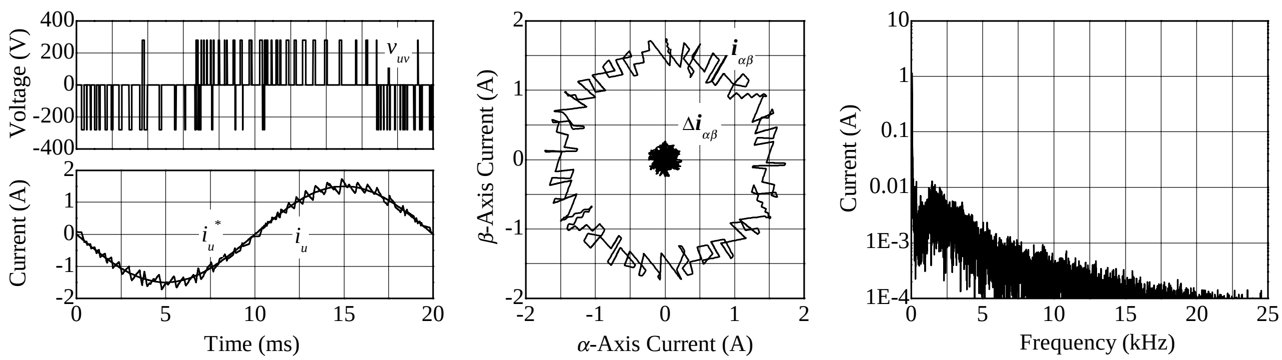
The operating characteristics of the proposed method strongly depend on the dither signal superposed onto the hysteresis thresholds; hence dependency of the amplitude has



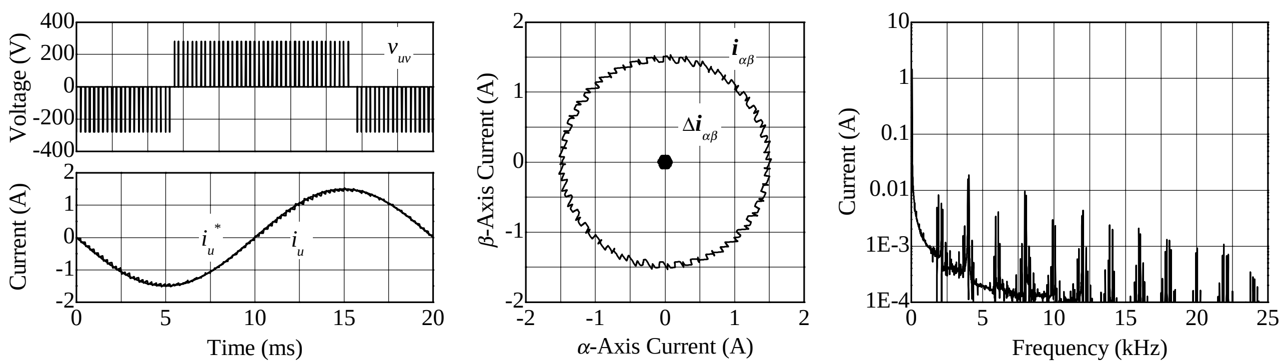
(a) PI plus PWM method.



(b) Fixed hysteresis-band method.

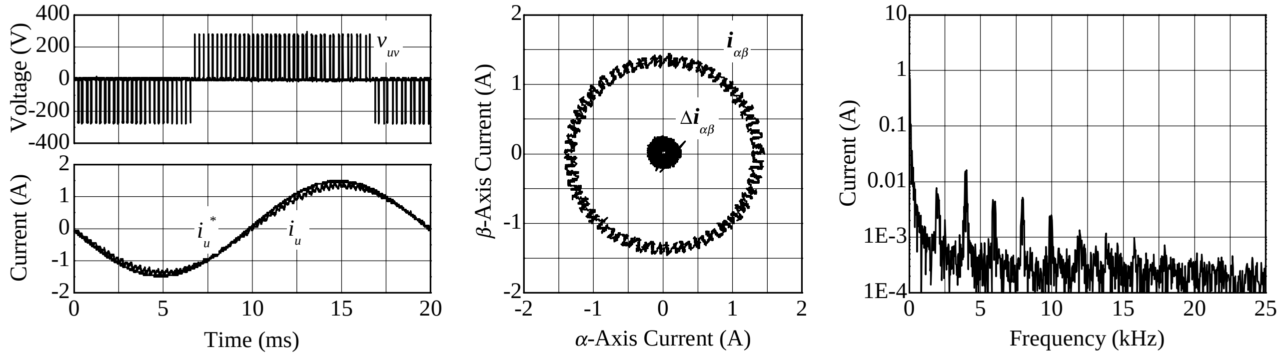


(c) Variable hysteresis-band method.

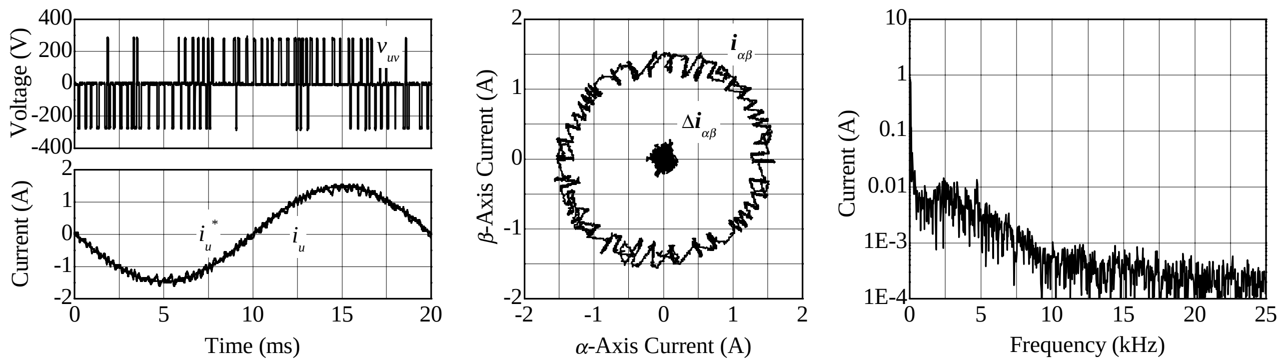


(d) Proposed method.

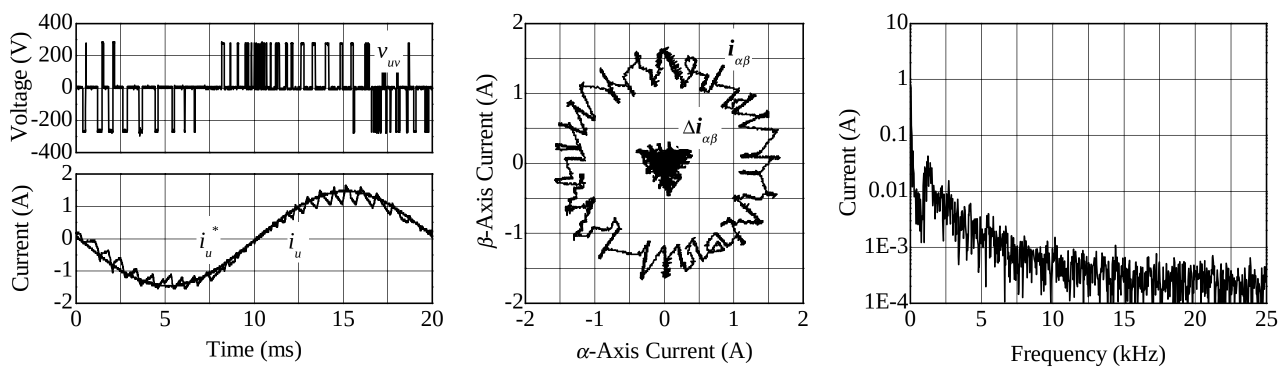
Fig. 4. Current control characteristics (simulation results).



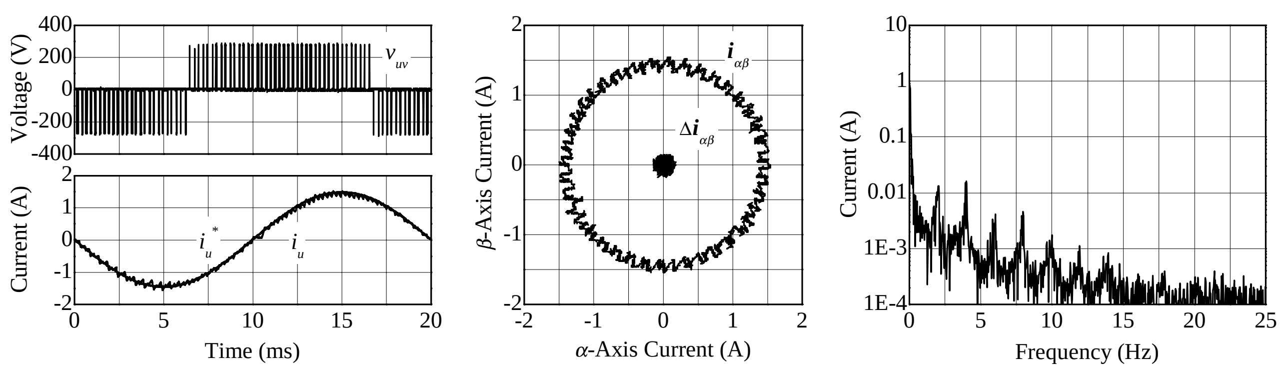
(a) PI plus PWM method.



(b) Fixed hysteresis-band method.

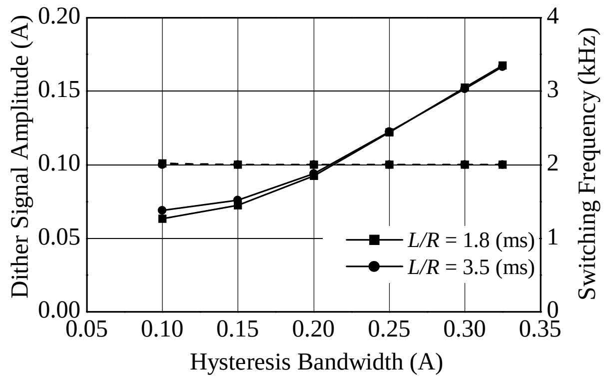


(c) Variable hysteresis-band method.

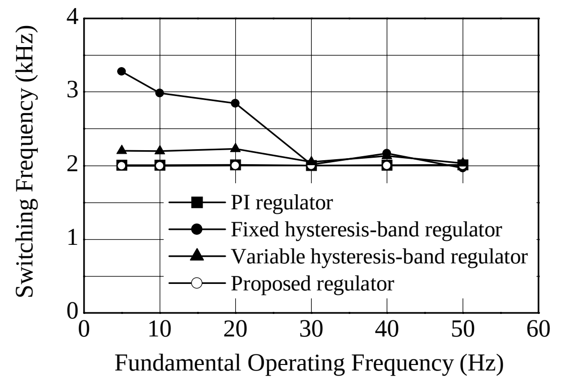


(d) Proposed method.

Fig. 5. Current control characteristics (experimental results).

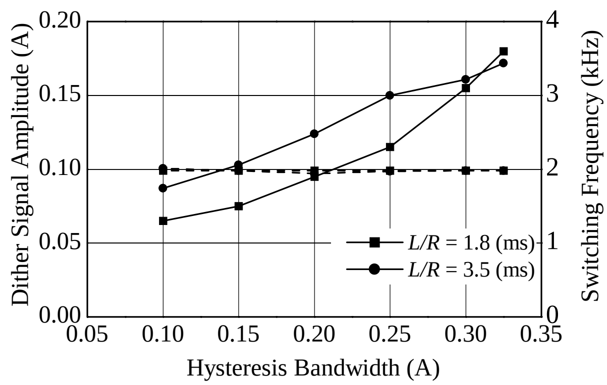


(a) Transition boundaries and average switching frequency with respect to hysteresis bandwidth.

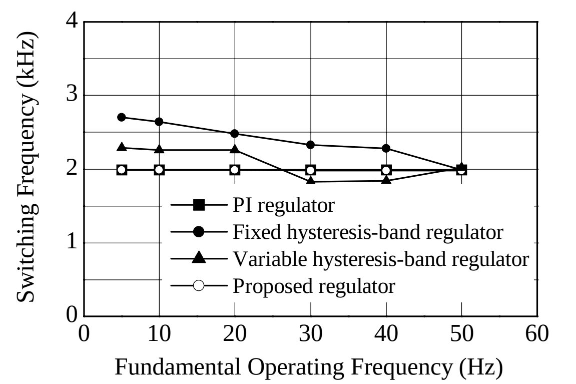


(b) Average switching frequency with respect to operating frequency.

Fig. 6. Operating characteristics of proposed method (simulation results).



(a) Transition boundaries and average switching frequency with respect to hysteresis bandwidth.



(b) Average switching frequency with respect to operating frequency.

Fig. 7. Operating characteristics of proposed method (experimental results).

been examined for various values of the hysteresis bandwidth and the amplitude. Fig. 6(a) and Fig. 7(a) are the simulation and experimental results, respectively, which show the transitional boundaries between the two control characteristics of the PI regulator and the fixed hysteresis-band regulator. Also, average inverter switching frequencies at the transitional boundaries are depicted in these figures. The operating characteristics change from one of the two conventional methods to the other as the dither signal amplitude is consecutively changed. As verified in the previous section, such optimum operating characteristics as Fig 4(d) and Fig. 5(d) can be obtained if the dither signal amplitude is set around these transitional boundaries. Fig. 6(b) and Fig. 7(b) show the average switching frequencies of the inverter. As can be seen in the figures, the switching frequencies of the PI regulator and the proposed regulator are kept at a constant value, which is determined by the carrier or the dither signal. However, the switching frequencies of the hysteresis regulators vary widely depending on the fundamental operating frequency, which is another drawback of the hysteresis regulators.

V. Conclusion

This paper proposed a novel control strategy of the current-controlled PWM inverter by means of dithering. Dithering is a powerful and effective means to solve the drawbacks of the conventional current regulators without sacrificing inherent simplicity of their configurations. Feasibility of the proposed technique has been examined through the experimental tests as well as the computer simulations and every result obtained in this investigation proved advantages of the dither based approach.

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