Direct Instantaneous Active and Reactive Power Control of PWM Converter

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Abstract — In order to obtain DC power sources, diode rectifiers are generally used in many kinds of electronic components. The circuit configuration of the rectifiers is very simple, and they do not need any control signals to convert AC power to DC. In recent years, however, several problems of the rectifiers have been pointed out, for example low input power factor, harmonics of the input current, no ability of regeneration and so forth. On the other hand, PWM converters have been adopted to the applications which require higher performance instead of the diode rectifiers, because the converters enable the unity input power factor as well as the regenerative operation. The converters are usually constituted by a current controller with current minor loops which regulates the input currents so that the currents can be in phase with the power source voltages. This paper describes a novel control strategy of the PWM converters. The strategy is based on the direct instantaneous active and reactive power control of the converter, and its configuration and operation are quite different from those of conventional methods. In the paper, the control algorithm and several experimental results are presented comparing the new technique with conventional methods.

I. INTRODUCTION

OWING to the spread of power electronic systems, AC to DC power converters have come to play important roles in various kinds of industry applications. There are mainlv two types of the converters. One is a capacitor-input diode rectifier, and the other is a PWM converter. The diode rectifier is extensively used because of its simple circuit configuration, although it has drawbacks of low input power factor, line current harmonics, no ability of regenerative operation and so forth. On the other hand, the PWM converter has more complicated circuit configuration than the diode rectifier, but it has advantages of the unity input power factor, low current harmonics and regenerative operation [1]. Therefore, not a few research studies have been done on the PWM converter, and some of them focuses on simplification of the system configuration [2] and some of them are relevant to the improvement of the

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system performance, especially conversion efficiency and comprehensive input power factor. Almost all the converters which have been investigated ever since are based on the current control, which is employed to make the line currents be in phase with the phase voltages of the power source [3][4]. It seems to be very difficult to achieve both quick current response and optimum PWM waveforms at the same time when the conventional current controller is simply adopted to the converter.

This paper describes a novel control strategy of the PWM converter of which algorithm completely differs from that of the conventional converters, because the strategy never employs the current controller in the system. The algorithm is based on relay control of the instantaneous active and reactive power of the converter, and it enables not only the quick response but also the optimum PWM waveforms by means of the relay elements and an optimum switching table [5]. In the paper, comparing with the conventional techniques, the system configurations and the control algorithms are discussed, and several experimental results are presented to verify the feasibility of the novel strategy.

II. CIRCUIT CONFIGURATIONS OF CONVENTIONAL AND NOVEL TECHNIQUES

A. Conventional PWM Converter with Hysteresis Current Controller

Fig. 1 shows a schematic diagram of a conventional PWM converter. In the figure, the converter is connected to a three-phase power source through interconnecting reactors with inductance L and winding resistance R, and is connected to a resistive load of R_ℓ on the DC bus side. In order to make the unity input power factor possible, line currents i_a, i_b and i_c must be controlled so that the currents can be in phase with the phase voltages v_a, v_b and v_c of the power source. The converter shown in the figure employs a hysteresis current controller to regulate the currents. A command of the current amplitude I^* can be obtained from an error between the detected DC bus voltage V_{dc} and the command $V_{dc}{}^*$, and the

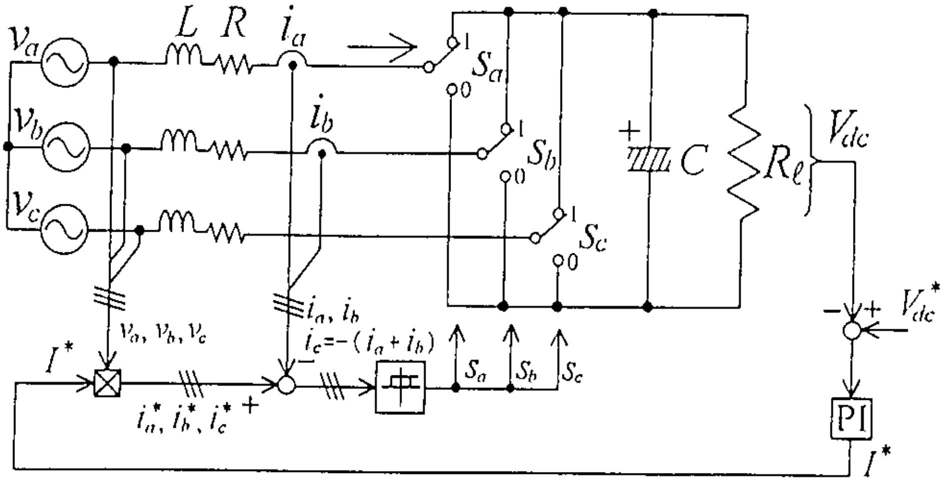


Fig. 1. Conventional PWM converter with hysteresis current controller.

line current commands i_a^*, i_b^* and i_c^* are calculated by multiplying I^* by the detected phase voltages. It should be noted that the phase voltage signals act as phase references or sinusoidal waveform references of which amplitudes are unity; hence the phase current commands can be exactly in phase with the voltages of the power source, which results in the unity power factor operation of the converter. After calculating the current commands, errors between the commands and the detected currents are input to the hysteresis elements respectively in order to restrict the errors to be within the hysteresis bands. The hysteresis elements put out switching signals S_a, S_b and S_c to the converter, and each switching signal is determined to reduce the current error as small as possible. By using the hysteresis current controller described above, relay control is performed to make the actual currents follow the current commands with small errors which correspond to the hysteresis band width. Since the method is based on the relay control, the fastest current response can be achieved of all kinds of control algorithms. However, it is very difficult to obtain optimum PWM waveforms, because the switching signal for a specific phase can not be determined with relation to the switching modes of other phases.

B. Conventional PWM Converter with Sub-harmonic Modulation Current Controller

This converter employs a sub-harmonic PWM technique to regulate the line currents. The schematic diagram of the converter is shown in Fig. 2. The line current commands are obtained in the similar way described in the previous section, but the errors between the commands and the detected currents are magnified by P (Proportional) elements to obtain phase voltage commands v_a^*, v_b^* and v_c^*. The voltage commands are compared with a triangular shaped carrier signal to produce PWM waveforms. When the converter employs the sub-harmonic technique like this, the output PWM waveforms can be nearly optimized because the voltage commands are modulated by the common carrier signal. Since loop gain of the current control is not so high as that of hysteresis control, however, the fast current response can not be expected.

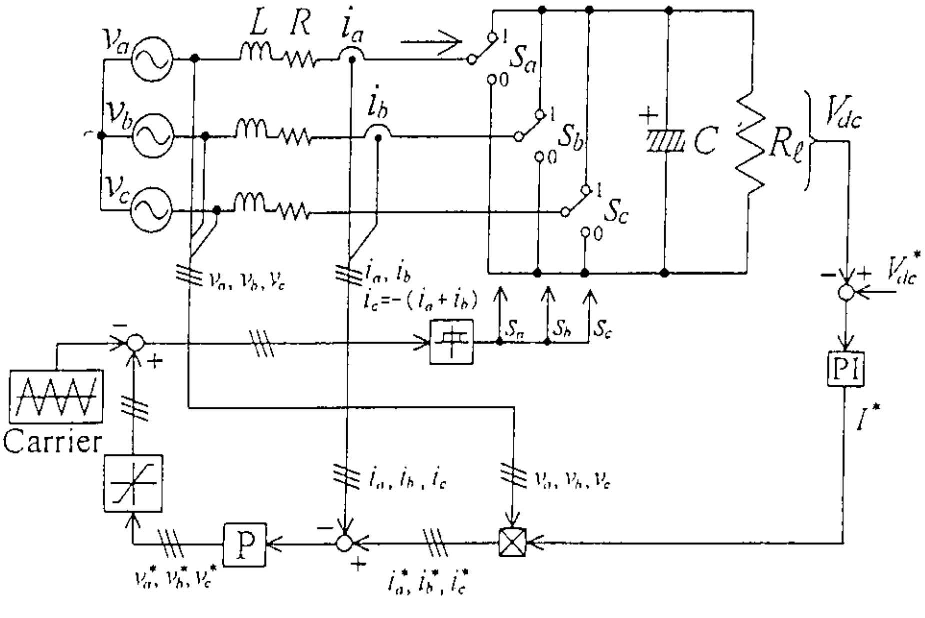


Fig. 2. Conventional PWM converter with sub-harmonic modulation current controller.

C. PWM Converter with Direct Instantaneous Active and Reactive Power Controller

Fig. 3 shows a schematic diagram of the converter which is based on direct instantaneous active and reactive power control. It should be notified that there are no current controllers to regulate the line current. Relay control of the instantaneous active and reactive power is basically performed in the system, and each power is directly controlled by switching modes of the converter. It is possible to achieve the unity input power factor when the reactive power is controlled to be zero.

The active power command p^* is provided from the DC bus voltage control block. When the DC bus voltage is sufficiently smoothed by the capacitor, the active power command can be calculated by multiplying the DC bus voltage and the DC bus current command which is obtained as a result of DC bus voltage control. The reactive power command q^* is directly given from the outside of the controller. On the other hand, the actual instantaneous active and reactive power p and q, can be calculated by the line currents and the phase voltages of the power source as follows :

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_a i_a + v_b i_b + v_c i_c \\ \frac{1}{\sqrt{3}}\left\{(v_b - v_c)i_a + (v_c - v_a)i_b + (v_a - v_b)i_c\right\} \end{bmatrix} \quad \cdots\cdots\cdots\cdots (1)$$

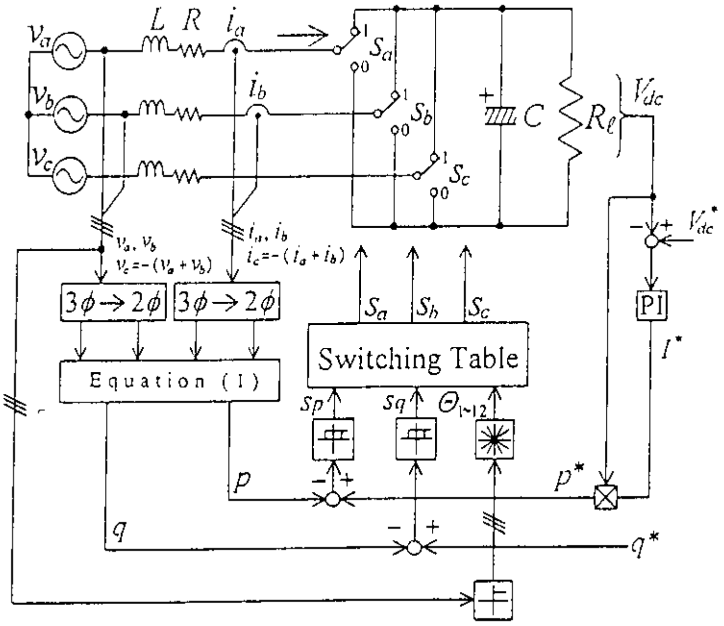


Fig. 3. PWM converter with direct instantaneous active and reactive power controller.

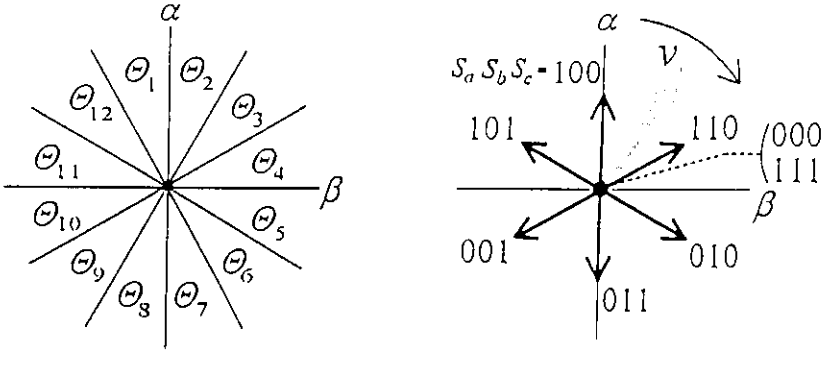


Fig. 4. Voltage vector of converter and quantized plane.

Differences between the commands and the detected values are quantized by the hysteresis elements, and the outputs of the hysteresis elements are represented as S_p and S_q respectively. Also, the voltage phase of the power source is quantized by using several comparators. As shown in Fig. 4, the stationary $\alpha - \beta$ plane is divided into twelve sectors which are represented by (2), and one of the sectors to which the voltage vector of the power source belongs is determined.

$$(n-2)\frac{\pi}{6} \le \Theta_n < (n-1)\frac{\pi}{6} \quad \because n = 1,\ 2,\ \cdots,\ 12 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (2)$$

The quantized signals S_p, S_q and Θ_n are input to a switching table shown in TABLE I, and an optimum switching mode of the converter is uniquely selected according to one of the combinations of the input signals.

III. EXPERIMENTAL RESULTS

A. Comparison of Operating Characteristics between Conventional and Novel Techniques

Several experiments have been conducted to compare the operating characteristics of the direct instantaneous active and reactive power control with those of the conventional techniques. In the experiments, an actual control system for each method has been entirely constituted by analogue circuits, while an identical power circuit of which parameters are shown in TABLE II has been commonly used to evaluate the differences of the operating characteristics. Also, the averaged switching frequency of the converter has been settled at an identical value shown in TABLE II for the purpose of comparison.

Fig. 5 (a) - (c) show the PWM waveforms (line to line voltages) , the line current waveforms and the current frequency spectra of the three methods respectively. From the PWM waveform of the hysteresis

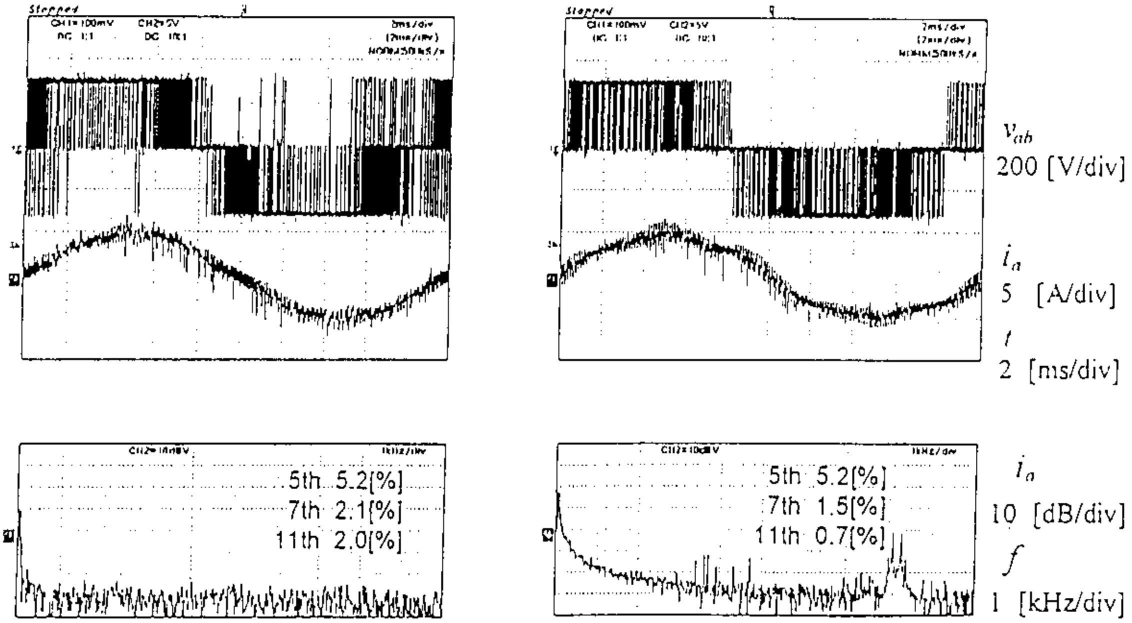
TABLE I Optimum switching table.

S_p	S_q	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6	Θ_7	Θ_8	Θ_9	Θ_{10}	Θ_{11}	Θ_{12}
1	0	101	111	100	000	110	111	010	000	011	111	001	000
	1	111	111	000	000	111	111	000	000	111	111	000	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
	1	100	110	110	010	010	011	011	001	001	101	101	100

TABLE II Parameters of power circuit and operating conditions.

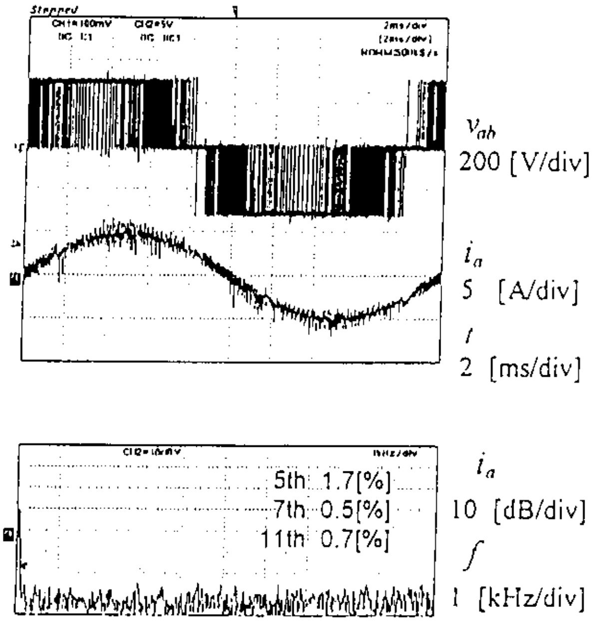
Reactor L	2.5 [mH]
Smoothing capacitor C	4700 [μF]
Load resistor R_l	80 [Ω]
Carrier frequency	8 [kHz]
Power source	200 [V], 50 [Hz]
Dc-bus voltage command	300 [V]

current control shown in Fig 5 (a), it is found that there are terms in which both positive and negative pulses are simultaneously put out. This means that the method is not optimized for selecting a switching mode of the converter, because the switching mode of a specific phase is independently determined with no relation to other phases. On the other hand, in the PWM waveforms of the sub-harmonic current control and the direct instantaneous active and reactive power control shown in Fig 5 (b) and (c), the phenomena of Fig. 5 (a) can not be observed. From the current frequency spectra of Fig. 5 (c), the direct instantaneous active and reactive power control achieved the least current harmonics in lower order components. It should be noted that the frequency spectra of the novel method is similar to those of a white noise, whereas the side band components are remarkable as for the sub-harmonic current control as shown in Fig. 5 (b).



(a) Hysteresis current control.

(b) Sub-harmonic modulation current control.



(c) Direct instantaneous active and reactive power control.

Fig. 5. PWM waveforms and line current waveforms.

Fig. 6 shows comprehensive input power factor characteristics against the load power for the three methods. It is found that every method has achieved more than 99% in maximum input power factor. However, the direct instantaneous active and reactive power control can make the highest power factor possible even in light load conditions. Efficiency characteristics of the three methods are shown in Fig. 7. From the results, it can be found that the highest efficiency has been obtained by the direct instantaneous active and reactive power control over the whole range of the load power. Its maximum efficiency was 96.2%, and was improved by 2.4% from that of the hysteresis control.

B. Discussion on Power Loss

It is important to analytically consider the power loss which has been measured in the direct instantaneous active and reactive control system. Fig. 8 shows the power loss against the load power.

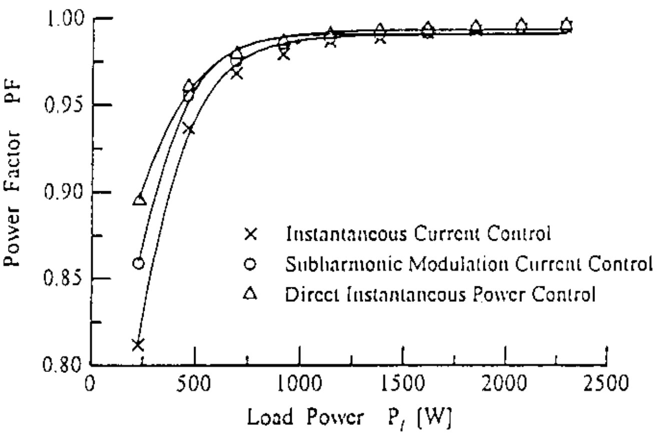


Fig. 6. Comprehensive input power factor.

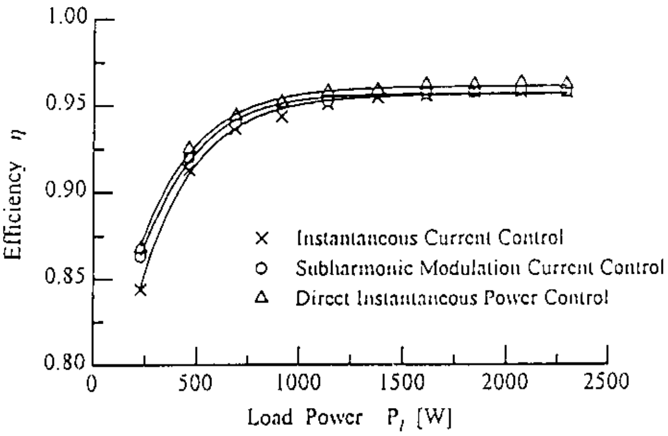


Fig. 7. Efficiency.

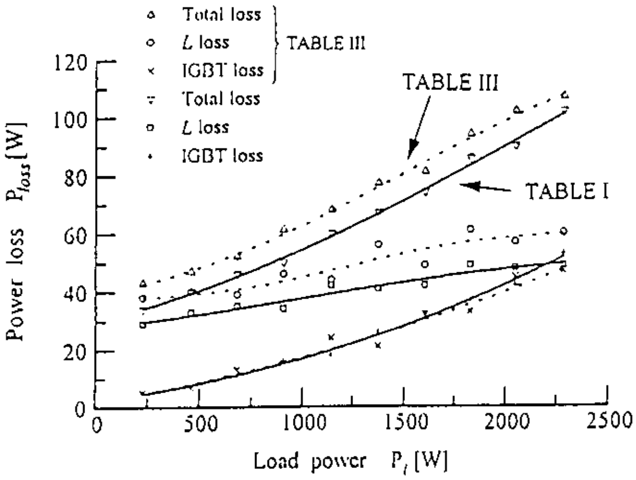


Fig. 8. Analysis of power loss in novel system.

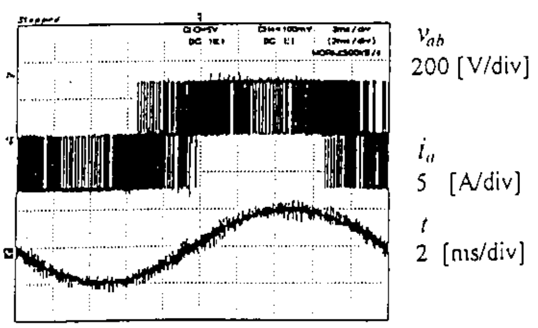


Fig. 9. PWM waveform which has not been intentionally optimized.

The power loss can be divided into two components, which are loss in IGBT modules and loss in the reactors. From the figure, it can be stated that IGBT loss and the reactor loss linearly increase with the load power. The IGBT loss is divided into switching loss and conduction loss, but most of the loss is supposed to be the conduction loss because the switching frequency of the converter was kept constant at any load. The reactor loss slightly increases with the load power and is divided into copper loss and core loss. Component increasing with the load power is regarded as the copper loss, because the core loss can be considered to be almost constant under the condition of the constant power source voltage.

In order to show the influence of the PWM waveforms on the power loss, another set of experimental results have been plotted in Fig. 8. The experiments have been conducted using another switching table which has not been intentionally optimized to select a switching mode of the converter. The switching table is shown in TABLE III, and the PWM waveform obtained by the switching table is shown in Fig. 9. From the power loss characteristics of Fig. 8, it can be found that the reactance loss, especially the core loss, is detrimentally affected by the PWM waveform shown in Fig. 9. Therefore, it is absolutely necessary to optimize the PWM waveforms to reduce the power loss.

IV. CONCLUSION

The paper has described direct instantaneous active and reactive power control of the PWM converter comparing with the conventional techniques with respect to the system configuration and the operating characteristics. The control is based on relay operation of the active and reactive power with the hysteresis elements and an optimum switching table. By employing the relay algorithm to directly regulate the power, the converter makes it possible to achieve as quick response as that of the conventional hysteresis current controlled converter. Also, the PWM waveforms can be improved by the optimum selection of the switching mode as well as the conventional sub-harmonic current controlled converter. Since the novel control can reduce the harmonics in the line currents with dispersed frequency spectra, power losses caused by the harmonics can be effectively reduced. The experimental results of a prototype system have proven that the maximum total power factor was more than 99%, and the maximum efficiency was 96.2%.

TABLE III Switching table which has not been intentionally optimized.

S_p	S_q	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6	Θ_7	Θ_8	Θ_9	Θ_{10}	Θ_{11}	Θ_{12}
1	0	101	101	100	100	110	110	010	010	011	011	001	001
	1	110	111	010	000	011	111	001	000	101	111	100	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
	1	100	110	110	010	010	011	011	001	001	101	101	100

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