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Advanced Three-Phase PFC Power Converters with Three-Phase Diode Rectifier and Four-Switch Boost Chopper

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ABSTRACT

This paper presents an improved three-phase PFC power rectifier with a three-phase diode rectifier cascaded four-switch boost converter. Its operating principle contains the operating principle of two conventional three-phase PFC power rectifiers: one switch boost converter type and a two switch boost converter type. The operating characteristics of the four switch boost converter type three-phase PFC power rectifier are evaluated from a practical point of view, being compared with one switch boost converter type and two switch boost converter topologies.

Keywords: Discontinuous current mode, Three phase PFC converter, Three phase diode rectifier, One switch boost chopper, Two switch boost, chopper, Four switch boost chopper, Harmonic current contents

1. Introduction

In recent years, utility AC and Engine Generator AC connected active three-phase PFC power converters have been widely used for AC UPS, DC UPS Battery and Super capacitor Energy Storage System (BESS). These systems can instantaneously control the AC reactor current so as to track a sine wave line current and unity power factor under high frequency PWM switching scheme. Of these, two feasible switch-mode strategies to control the AC reactor current instantaneously for three-phase PFC converters using MOS gate power transistors, IGBTs, MOS FETs have been basically considered and discussed so far. One method of three-phase PFC converter control is based on a continuous sine wave current tracking mode control procedure which adjusts the AC reactor current in the utility AC power or engine coupled generator AC power source side of three-phase PFC AC/DC power converter so as to follow up instantaneously on the basis of a specified sine wave reference. Another method of PFC rectifier is based on a discontinuous mode control

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procedure which simply modulates the AC reactor current of the input side in a three-phase power PFC converter on the basis of using a series of sine wave-like amplitude modulated discrete pulse currents. In this case, the average value of discrete pulse currents with a sine wave-like amplitude modulation can be simply controlled so as to follow up to a specified sine wave reference.

A precise detection interface processing of AC reactor current in the utility AC power source side or engine coupled generator AC power source of the three-phase PFC power converter and its feedback control strategy has to be required for the continuous mode control scheme, which makes the control circuit more complicated and expensive.

On the other hand, its sine wave-based feedback current tracking control scheme with isolated or non isolated precise current sensor interfacing circuits with wide frequency band performances is not required for the discontinuous mode control strategy. This makes this three-phase PFC power converter simpler and less expensive. The continuous current mode tracking control scheme for a conventional active three-phase PFC power converter is widely employed for DC bus line linked small capacity single-phase active PFC power converters and large capacity three-phase PFC power converters. Discontinuous AC reactor current mode control approach has attracted special interest in several-kW class power conditioning and processing applications in three-phase input AC mains, and some circuit configurations of three-phase active PFC power converter circuits begin to be investigated from an experimental point of view.

Generally, active PFC power converters in 1 or 3 connected power systems are classified into three basic types of topologies; buck type, boost type and buck/boost type. The Boost converter type[1-3] and buck/boost[4]-[5] type have been respectively developed for three-phase active PFC converters operating at a discontinuous current mode control scheme.

In this paper, the operating principle of a novel prototype version of active three-phase PFC AC/DC converters using IGBT power modules which is more acceptable for power conditioning systems such as AC UPS, DC UPS, super capacitors and battery chargers and AC Motor electrical drives is presented as compared with the other two types of three-phase PFC power converters. In addition, the new topological three-phase PFC rectifier using four switch boost converter auxiliary active power switches is demonstrated for power systems in an emergency. Its feasible effectiveness is evaluated and discussed on the basis of the experimental and simulated results as compared with a one switch boost converter type and two switch boost type converter type three-phase PFC power rectifier, in which this three-phase active PFC power converter circuit makes it possible to minimize THD (Total Harmonic Distortion) index in AC currents derived from a three-phase utility grid AC power source side.

2. HARMONIC CURRENT INDEX

The harmonic current suppression values required for the utility AC and engine generator for AC linked power converter supplies for the power system have been regulated and determined by the IEC (Intentional Electromechanical Commission) as the standard of IEC 61000-3-2. But their harmonic current guidelines which are based on this standard regulation are not strict and these can be roughly met in practice by simple harmonic current control implementation.

However, harmonic current suppression levels become much stricter than this standard regulation for input three-phase power conditioning supplies of several-kW class power capacities or more.

3. THREE-PHASE PFC CONVERTER WITH ONE-TRANSISTOR BOOST CHOPPER

3.1 Circuit Description

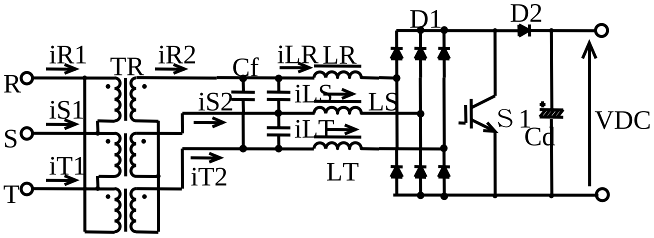

Fig. 1 Conventional circuit configuration of one-switch boost type active three phase PFC converter

Figure 1 shows the schematic circuit configuration of the most basic three-phase active PFC AC/DC power converter operating under a principle of a discontinuous AC reactor current mode control scheme [6-7]. This sort of circuit topology is based upon a principle of a single switch power transistor boost converter type PFC rectifier.

Both operating frequency and the duty ratio of a switching power device, IGBT and S1, are kept at a certain constant value. The AC reactors of each phase; LR, LS, and LT are respectively set to a certain small value so that the currents flowing through those AC reactors can be always kept in a discontinuous current condition. When the boost switch S1 is turned on, the reactor voltage across each phase becomes respective phase voltage. If the conduction state period of S1 switching is t1 and the phase voltage across of phase R is VR, the peak current flowing through AC reactor LR is calculated by eq.(1). Because the switching frequency and duty ratio of the S1 switching pattern of switch S1 are both constant, the conduction state period t1 also keeps constant, As a result i_{LRpeak} changes to a sine wave which is proportional to the amplitude of the phase voltage VR.

$$i_{L_{Rpeak}} = \frac{v_R \cdot t_1}{L_R} \tag{1}$$

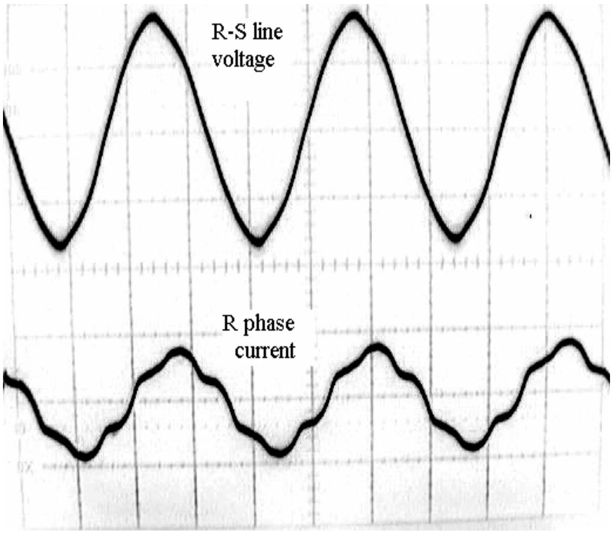

Fig. 2 Input voltage and current waveforms of conventional three phase PFC converter (50V/div.5.0A/div.5.0mS/div)

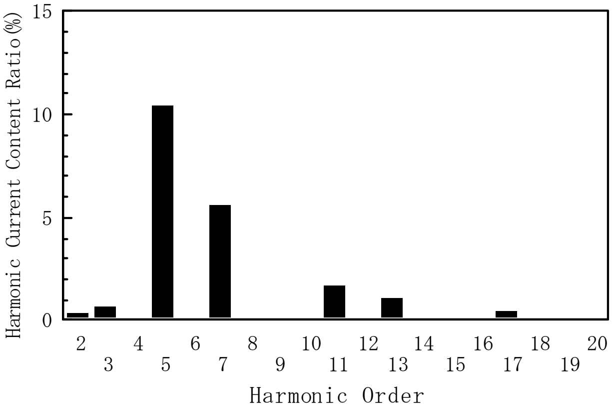

Fig. 3 Spectrum analysis of input current one-switch type three phase PFC active converter

3.2 Circuit Evaluations as Three Phase PFC Converter Circuit Description

Figure 2 shows typical experimental waveforms for the R-S line as line voltage and R phase current in Figure 1. This R phase current leads 30 degrees on R-S line corresponding to line voltage. Thus, R phase voltage and R phase input current become in phase.

Frequency spectrum analysis is illustrated in Figure 3 on the basis of the input current shown in Figure 2. The fifth harmonic current components include 10.4%. The low-harmonic current value of AC input current i_{CS} is the same as that of the low-harmonic component of the AC reactor current.

As mentioned above, three-phase active PFC converter designed for the power capacities of several kW or more has to suppress their input AC reactor harmonic current components so as to be a specified low value under a harmonic guideline. This means the PFC converter circuit in which insufficient harmonic current suppression is not adequate for engine-driven AC generator used emergency power equipment.

4. THREE-PHASE CONVERTER WITH TWO-TRANSISTORS BOOST CHOPPER

4.1 Circuit Description

Figure 4 shows another prototype of three-phase PFC converter employing two switch boost converter topology with a three-phase diode rectifier.

It is an arrangement proposed as a previously developed three-phase PFC rectifier circuit topology a for three-phase active PFC power converter operating under a principle of discontinuous mode AC current control scheme in industrial and telecommunication energy plants including a new energy conditioner as a small scale fuel cell. In this case, the capacitors C R, C S and C T are in a star-connect ion configuration. The potential at N point is greatest where three capacitors are equal to that of the three-phase input neutral point.

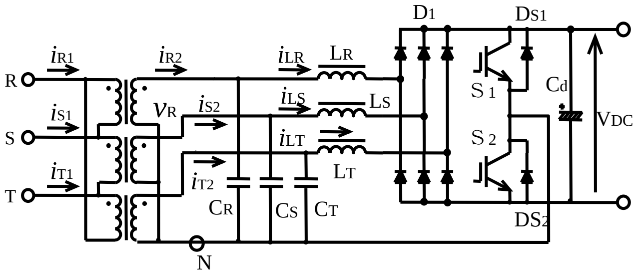

Fig. 4　Conventional three phase PFC converter configuration with two-switches

The capacitor voltage across each phase becomes the phase voltage of phase S1 and S2 which are driven under a condition of opposite phase. The operating frequency and the duty ratio of active power switches of the boost converter are specified at a certain constant value during one cycle period of utility AC voltage in utility mains or engine generator AC voltage.

This three-phase PFC power converter circuit with three-phase diode reactor which is previously considered generates nine operating circuit modes in accordance with the conduction state of each switching power device. It supposes that the voltage across phase R is positive while the other phase voltage S and T are negative.

4.2 Steady-State Circuit Operation

The steady-state operation the of three-phase active PFC converter circuit in Figure 4, which includes the three-phase diode rectifier and two switch boost converter, is described as follows:

Mode 1 When the switch S1 is turned on, the voltage across phase R is applied to boosted AC reactor LR.　As a result, the current i_{LR} increases gradually.

Mode 2 When S1 turns off, the current i_{LR} flowing through AC reactor LR flows through DS2; its energy is delivered to the smoothing capacitor Cd. At the same time, the current starts flowing through LS and LT. The voltage difference between the DC output voltage VDC and the voltage across phase R is applied as the reverse direction for LR, and as a result, i_{LR} begins to decrease.

Mode 3　i_{LR} decreases and is equal to the sum of i_{LRS} and i_{LR}; S2 turns off.

Mode 4 S2 turns on; the voltages for phases S and T are experienced on LS and LT, respectively.

Mode 5 i_{LR} ceases flowing; i_{LS} and i_{LT} continue to increase in the negative direction.

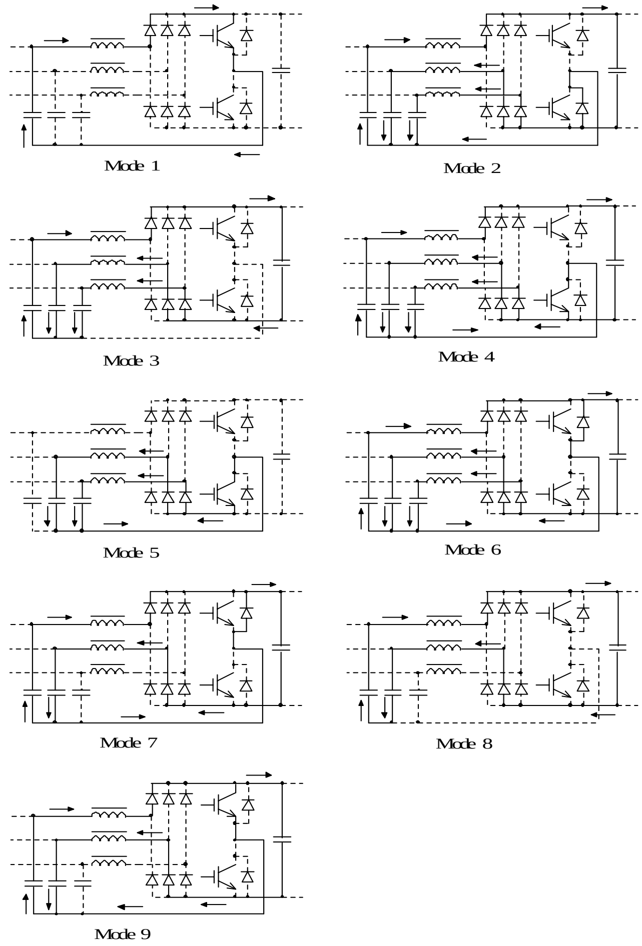

Fig. 5　Equivalent switching mode circuits two switch boost type three phase active PFC converter

Mode 6 When S2 turns off; the total current through LS and LT flows through S1; its power is transferred to the voltage smoothing capacitor Cd. The current begins flowing through LR at the same time. The voltage difference between DC output voltage VDC and phase voltage of each phase is applied as the reverse direction on LS and LT, while i_{LS} and i_{LT} decrease.

Mode 7 The current flowing through phase T ceases flowing.

Mode 8 The current flowing through phase S decreases and is equal to the current flowing through phase R; the switch S1 turns off.

Mode 9 The switch S1 turns on; the voltage across phase R is applied on LR.

According to the voltages being applied to the AC reactors, all the operating modes can be roughly divided into two operating modes as indicated as follows;

(i) The modes in which either phase voltage or the voltage difference between the phase voltage and the DC output voltage is applied to the AC reactors; Mode 1,2,4,5,6,7 and Mode 9.

(ii) The operating modes in which two AC reactors are connected in series, and the voltage difference between the line voltage and DC output voltage is applied to be connected in series with AC reactors; Mode 3 and Mode 8.

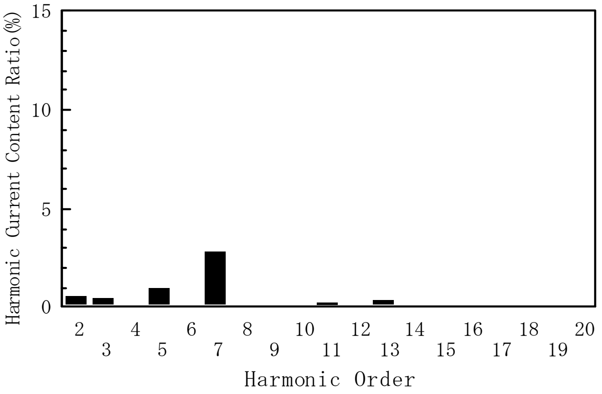

Fig. 6 Spectrum analysis of input current two-switch boost type three phase active PFC converter in case of 46% dutyfactor

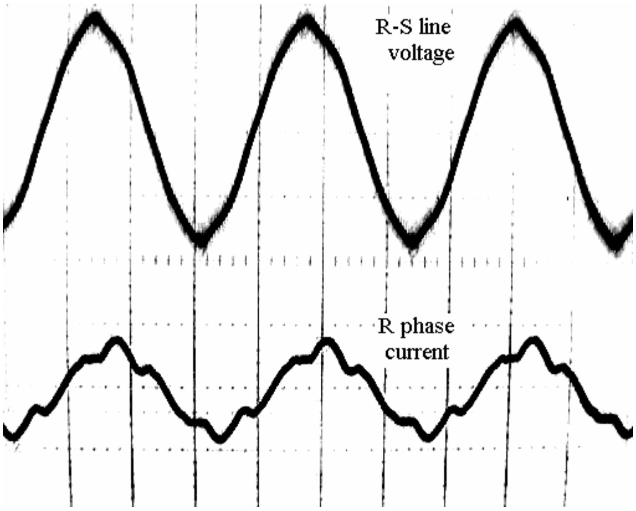

Fig. 7 Input voltage and current waveforms of conventional two-switch type boost converter (50V/div. 5.0A/div. 5.0mS/div.)

4.3 Circuit Evaluations

The two-transistor type three-phase PFC converter can perform low THD in AC reactor current and provide an improvement of power factor under a condition which is operating near to its maximum output. Figure 6 depicts the frequency spectrum of the input AC reactor current of two-transistor type three-phase PFC converter operated in 46% duty ratio for three-phase cases. However, when this PFC converter operates in a low power output state, it demonstrates poor characteristics. Figure 7 shows the experimental results of the R-S line to line voltage and the

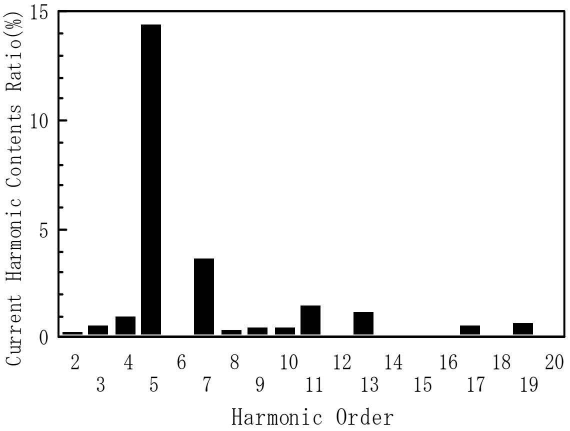

Fig. 8 Spectrum analysis of input current two-switch boost type three phase active PFC converter in case of 30% dutyfactor

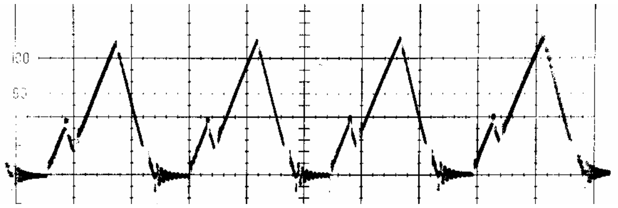

Fig. 9 Experimental result of an AC reactor current waveform at two-transistors type PFC converter.
(2A/div. 20 μ sec/div.)

R phase AC current waveforms of two-transistor boost converter type three-phase active PFC converter circuits shown in Figure 4, which can operate in 30% duty ratio. Although R phase voltage and R phase AC current are in phase, the AC current waveform is heavily distorted in practice.

Figure 8 shows the analytical frequency spectrum results of the input phase current waveform illustrated in Figure 7. This figure shows that the fifth harmonic current contains 14.4%, and the THD index has a large value of 15.0%.

The Figure 9 illustrates an AC reactor current waveform which is given on the basis of simulation of two-transistor boost converter type active three-phase PFC converter shown in Figure 4. The AC reactor current waveform includes large distortion both falling edge in Mode 3 and rising edge at Mode 8. Usually, an AC/DC converter has to provide constant output DC voltage in spite of load conditions.

Moreover, the output voltage has stabilized with the duty ratio control strategy in general.

It indicates that the three-phase PFC applications circuit configurations shown in Figure 1 and Figure 4 are not practically suited for three-phase PFC AC/DC power converters.

5. IMPROVED THREE-PHASE PFC CONVERTER WITH FOUR SWITCH BOOST CHOPPER

5.1 Circuit Description

The three-phase PFC power converter circuit topology demonstrated in Figure 4 generates a large fifth harmonic current spectrum in the input utility AC power source and engine generator AC power source side. This causes an increase in the THD index of the AC reactor current. The main cause of this, depending on the voltages applied to nine operating modes of the two switch boost converter circuit depicted in Figure 4, can be classified into two operating categories as has been mentioned: (i) The operating modes in which either phase voltage or the voltage difference between the phase voltage and the DC output voltage is applied to the three phase AC reactors, or (ii) The operating modes in which two AC reactors are connected in series, and the voltage difference between the line voltage and DC output voltage is applied to the series connected AC reactors. Figure 9 is indicating that both switching mode 3 and switching mode 8 in which categorized (ii) generates distortion of AC reactor current waveforms. Therefore, the existence of switching as operation categorized (ii) causes the large fifth harmonic current.

For that reason, a novel prototype version of three-phase active PFC power converter circuit displayed in Figure 10 is capable of removing the operating mode in category (ii). This makes all the operating modes the same as those of category (i).

Auxiliary active power switches S3 and S4, which are not included in the circuit depicted in Figure 4 are added. From the instant when S2 turns off until S1 turns on, S3 is off. During other periods, it remains on.

During these periods, the time duration when S1 turns off until S2 turns on, S4 is off. During other times, it is still on.

5.2 Steady-State Circuit Operation

An improved active three-phase PFC power converter circuit which is composed of AC filter reactor three phase diode rectifier and four switch boost converter has nine operating modes in accordance with the conduction stage of the switching power semiconductor devices as shown in Figure 11.

The steady-state circuit operation in each mode is described below. Note that the R phase voltage is positive, while S and T phase voltages are negative.

The experimental result in Figure 12 is represented, and the distortion of the AC reactor current waveform is less than the two-transistor boost converter type three-phase

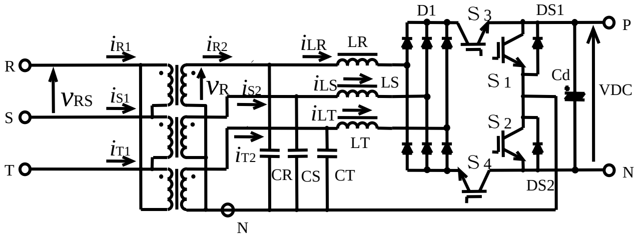

Fig. 10 Proposed circuit of boost type active AC/DC PFC converter

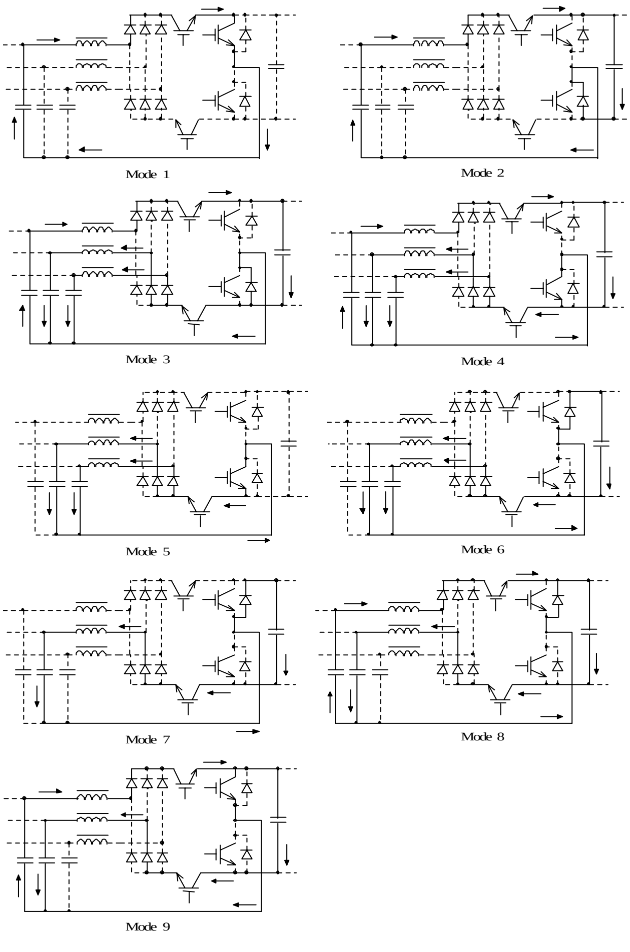
Mode 1
Mode 2
Mode 3
Mode 4
Mode 5
Mode 6
Mode 7
Mode 8
Mode 9

Fig. 11 Operation mode of improved three phase active PFC converter

PFC converter (see Figure 9).

Mode 1 When S_1 is switched on; the voltage across phase R is applied for L_R; the capacitor current i_{LR} increases.

Mode 2 When S1 is turned off, the current of LR flows through S2; its power is delivered to the voltage smoothing capacitor Cd. The voltage difference between the DC output voltage VDC and the voltage of phase R is applied to the reverse direction on LR, and i_{LR} decreases.

Mode 3 When S4 is turned on, the current also begins flowing through LS and LT.

Mode 4 i_{LR} decreases and is equal to the sum of i_{LS} and i_{LT}. D_{S2} turns off; The current begins flowing through S_2.

Mode 5 i_{LR} ceases flowing; i_{LS} and i_{LT} continue to increase in a negative direction.

Mode 6 S_2 turns off; the currents through L_S and L_T flow through S_1; its power is delivered to the capacitor Cd. The voltage difference between the DC output voltage V_{DC} and the voltages of all the phases is applied for the reverse direction of L_S and L_T, while i_{LS} and i_{LT} decrease.

Mode 7 The current through phase T ceases flowing.

Mode 8 S_4 turns on, and the current also begins flowing through L_R.

Mode 9 The S phase current decreases and becomes equal to the current through phase R. DS1 turns off. Its current begins flowing through S1.

Figure 13 illustrates the experimental results for the R-S line to line voltage and R phase input current waveforms of the improved four switch boost converter type three-phase active PFC power circuit depicted in Figure 10. This R phase current leads by 30 degrees for R-S line to line voltage. Thus, the steady-state line voltage and phase current are in phase.

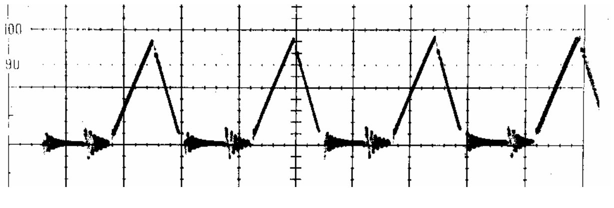

Fig. 12 Experimental result of AC reactor current waveform at improved three phase PFC converter(2A/div. 20 μ sec/div.)

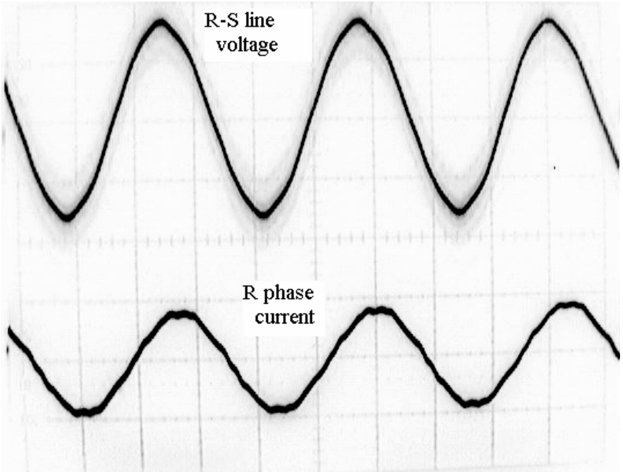

Fig. 13 Input voltage and current waveforms of improved type three-phase PFC active converter.
(50V/div. 2.5A/div. 5.0mS/div.)

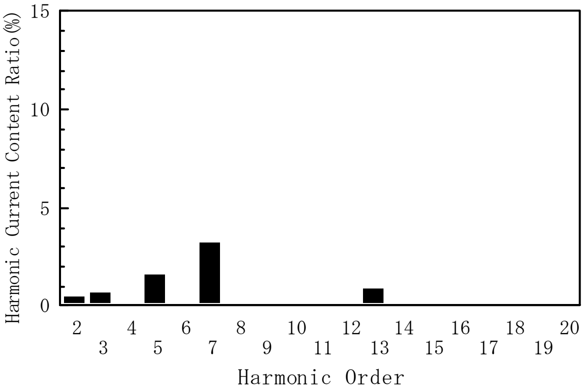

Fig. 14 Spectrum analysis of input current of improved active PFC converter in case of 30% dutyfactor

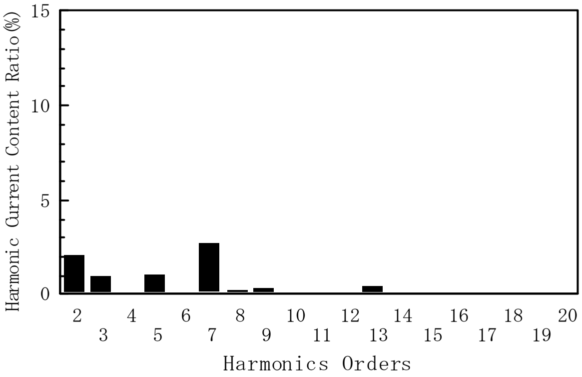

Fig. 15 Spectrum analysis of input current of improved active PFC converter in case of 46% dutyfactor

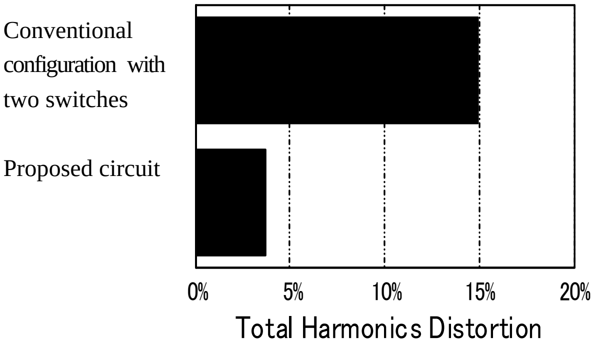

Fig. 16 Comparisons between THD of PFC converters in case of 30% dutyfactor

Figure 14 depicts the frequency spectrum results for the experimental input current waveforms shown in Figure 13. According to the operating circuit modes described above, the phase voltage or the voltage difference between the phase voltage and the DC output voltage is at all times applied to the AC reactors. Figure 15 displays the spectrum analysis of input current of the improved three-phase active PFC converter operated in the case of 46% duty ratio. This means the proposed three-phase active PFC power converter is able to perform to low phase current THD quality in any range of operating duty ratio.

When the auxiliary active power switches S3 and S4 turn on and off, their currents are always zero. This means that these active power switches have no switching power loss characteristics.

In addition, the maximum voltages experienced on the auxiliary switches are the peak values of the phase voltage. As a result, these maximum voltages do not require the particular high-voltage power semiconductor switching devices.

The total power factor of the improved three-phase PFC converter is unity. The fifth harmonic current component is held down to 1.6%. In addition to these, the THD of phase current is 3.8%. Each current THD of the three circuit topology types of the three-phase PFC power converter is compared in Figure 16. It is clear that the newly proposed three-phase PFC power converter circuit makes it possible to minimize the THD index of the line current.

6. CONCLUSIONS

In this paper, the novel prototype circuit topology of an active three-phase PFC power converter using a three-phase diode rectifier and four IGBTs boost converter, its control scheme for utility connected three-phase AC mains and an engine coupled AC power source have been presented. One switch boost converter type and two switch boost converter type represent conventional methods. The advanced three-phase PFC converter circuit topology employs a four switch boost converter type circuit configuration operating under a comparatively small specification to the AC reactors and switching power devices; IGBTs and the three-phase active PFC converter with a small line current THD to a certain level may be neglected.

A novel prototype topology of a four switch boost converter type three-phase PFC active converter has been built and tested which is composed of only two auxiliary active power switches added to the previously-proposed two transistor boost converter type three-phase active PFC converter circuit topology. It was proved that auxiliary active power switches always could perform under a condition of zero current switching, and the voltages across auxiliary active switches are relatively small. Thus, the significant influences on a power conversion efficiency and system cost were effectively minimized.

In the future, this advanced PFC circuit configuration of complete soft-switched mode four switch boost converter type three-phase active PFC converter should be investigated from a practical point of view.

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