Auxiliary Supply-Assisted 12-Pulse Phase-Controlled Rectifiers With Reduced Input Current Harmonics

Shoji Fukuda, *Senior Member, IEEE*, and Issei Hiei

***Abstract*—Three-phase thyristor rectifiers have been used in industries for obtaining a variable dc voltage, but they have a problem of including large lower-order harmonics in the input currents. For high-power applications, a 12-pulse configuration is useful for reducing the harmonics, but it still includes the $(12m \pm 1)$th (m: integer) harmonics. In order to further reduce the harmonics, this paper proposes to insert an auxiliary supply producing a square wave voltage to the dc bus of a 12-pulse phase-controlled rectifier. Theoretical investigation to reduce harmonics is presented, and a strategy to control the auxiliary supply voltage based on pulse-width-modulation is proposed. Reduction in the current harmonics is verified by simulation and experimental results. The volt–ampere (VA) rating of the auxiliary supply is about 5% of the rectifier output.**

***Index Terms*—AC–DC power conversion, power conversion harmonics, power electronics, thyristor applications, thyristor converters.**

I. Introduction

DIODE rectifiers and phase-controlled thyristor rectifiers are very popular in several industrial applications: chemical processes, dc arc furnaces, HVdc transmission systems, adjustable speed ac drives, etc. [1]. However, such rectifiers include large lower-order harmonics in the input currents and do not meet harmonic current content restrictions, as imposed by several international standards such as IEC 61000 and IEEE 519 [2]–[4]. For high-power applications, installation of passive filters is mandatory [5] to reduce the current harmonics introduced by the rectifier to the power system, but they make the overall rectifier system bulky and expensive. Another solution for the harmonic reduction is the utilization of active power filters [6], [7], but it is a very expensive solution.

Diode rectifiers with special configurations using additional switching devices and/or passive components [8]–[12] were proposed to reduce harmonics, but they are too complicated to be employed in high-power applications. A 12-pulse configuration [1], [5], [13]–[15] consisting of two sets of six-pulse rectifiers is popular for high-power applications. This enables to offset the harmonic components such as the fifth and seventh produced by each of the two rectifiers, but the $(12m \pm 1)$th (m: integer) harmonics still remain in the resultant input currents. It is usual to use passive power filters tuned to harmonics 11 and 13, and an additional high-pass filter to eliminate the remaining harmonics.

Several strategies [16]–[22] were proposed for 12-pulse diode rectifiers to further reduce the $(12m \pm 1)$th harmonics. Miyairi *et al.* [16] proposed the use of an interphase reactor equipped with multiple switched taps. Choi *et al.* [17] proposed a parallel connected diode rectifier with an active interphase reactor. Masukawa and Iida [18] proposed to use an interphase reactor having secondary windings with an auxiliary circuit, and Nishida and Nakaoka [19] proposed series-connected double three-phase diode rectifiers with auxiliary circuits. A problem of them is that the operation of the auxiliary circuit is very complicated.

Fujita and Akagi [20] proposed to use a series active filter to a 12-pulse rectifier, and Cheng *et al.* [21] proposed to use a square-wave inverters-based dominant harmonic active filter. A problem of them is an expensive system because they employ an active power filter.

Okuyama [22] proposed to insert an auxiliary voltage supply (AVS) to the middle dc bus of a cascade-connected capacitor-input 12-pulse rectifier. Fukuda and Ohta proposed the control strategy [23] of an AVS for the same configuration in [22], and demonstrated the reduction in the 11th and 13th harmonics in the resultant input current. However, since these eight references treat 12-pulse diode rectifiers, a novel strategy is required for treating 12-pulse phase controlled rectifiers having a dc voltage control function.

Iwaji and Okuyama [24] proposed to expand the same idea in [22] to a cascade-connected capacitor-input 12-pulse thyristor rectifier, but the control method of an AVS was not established. Fukuda and Ohta tried to expand the application of the method in [23] to 12-pulse phase-controlled thyristor rectifiers to reduce the input current harmonics. There are several configurations of 12-pulse thyristor rectifiers, but the method is applicable to only two configurations illustrated in Fig. 1(a) and (b). Fig. 1(a) is a parallel-connected choke-input type and Fig. 1(b) is a cascade-connected capacitor-input type. Fukuda and Hiei applied the method to a cascade-connected 12-pulse thyristor rectifier [25] and revealed that the AVS was effective only in a narrow output voltage range. This is because the insertion of AVS to a 12-pulse rectifier is effective only if the dc current of the original six-pulse rectifier flows continuously. The dc current $i_{\mathrm{rec}1}$ or $i_{\mathrm{rec}2}$ in Fig. 1(b) with $V_i = 0$ flows continuously only in a very narrow firing angle range, say, $\alpha = 0$–$20°$ because the rectifier is of capacitor-input type. In contrast, the current $i_{\mathrm{rec}1}$ or $i_{\mathrm{rec}2}$ in Fig. 1(a) with $V_i = 0$ flows continuously in a wide firing angle range because the rectifier is of choke-input type.

This paper deals with a parallel-connected choke-input 12-pulse thyristor rectifier, and inserts an AVS to each of the dc

Paper IPCSD-07-049, presented at the 2005 Industry Applications Society Annual Meeting, Hong Kong, October 2–6, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Electrostatic Processes Committee of the IEEE Industry Applications Society. Manuscript submitted for review January 27, 2006 and released for publication July 16, 2007.

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Digital Object Identifier 10.1109/TIA.2007.912805

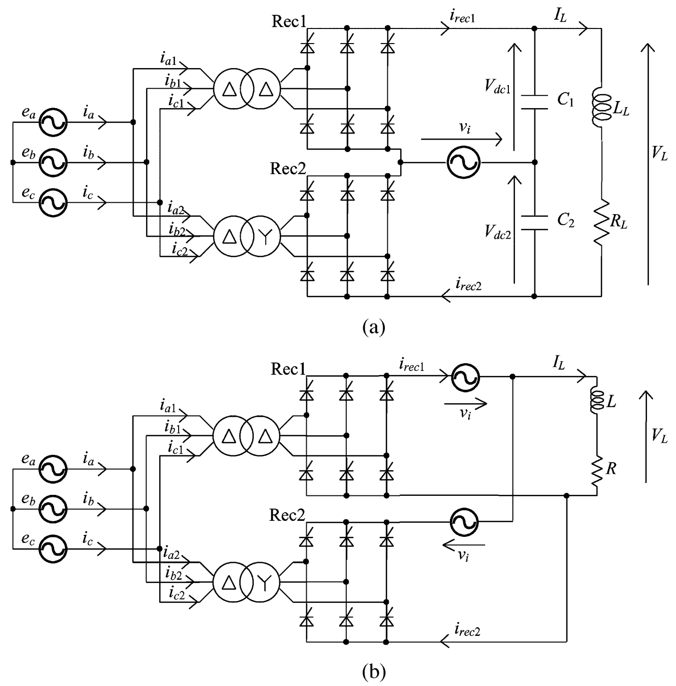

Fig. 1. Configurations of phase-controlled 12-pulse thyristor rectifier with AVS v_i. (a) Choke-input type. (b) Capacitor-input type.

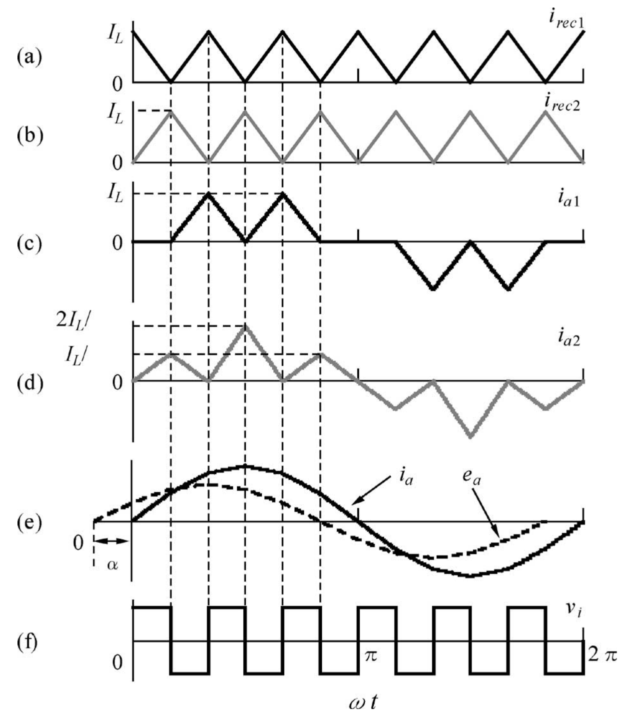

Fig. 2. Hypothetical 12-pulse rectifier current waveforms with AVS.

bus, as shown in Fig. 1(a) to reduce the harmonics, especially the 11th and 13th components. It presents theoretical investigations on the principle of reducing the harmonics. It also presents a method to control the AVS voltage in relation to the load current and firing angle of the thyristors. It is shown that AVS is effective almost over a whole output voltage range. Finally, the usefulness of the proposed configuration and control method is verified by simulation studies and experimental results.

In order to reduce input current harmonics, Tanaka *et al.* [26] proposed the insertion of an interphase reactor having an appropriate leakage inductance to the dc bus of a 12-pulse choke-input phase-controlled rectifier. It is shown that their idea is included in this paper as a special case.

II. Circuit Configuration and Operation

Fig. 1(a) shows the configuration of a phase-controlled 12-pulse thyristor rectifier with AVSs proposed in this paper. It consists of two three-phase thyristor rectifiers, Rec1 and Rec2, connected in parallel; and two AVSs having a voltage v_i. The Rec1 and Rec2 are supplied from identical two sets of three-phase voltage systems having a phase difference of 30° each other. A conventional 12-pulse configuration includes an interphase reactor in the dc circuit to equally share the dc currents I_L in Rec1 and Rec2, but it is not necessary with the proposed configuration because i_{rec1} and i_{rec2} flow alternately.

Assume that the dc output currents i_{rec1} and i_{rec2} were triangular with a frequency six times that of the utility having a dc component $I_L/2$, as shown in Fig. 2(a) and (b). Then, the input currents of the each rectifier, i_{a1} and i_{a2}, and the resultant input current $i_a (= i_{a1} + i_{a2})$ would be as shown in Fig. 2(c)–(e), respectively. From the figure, one can observe that the harmonics almost disappear in i_a. Total harmonic distortion (THD) of i_a is as low as 1.06%.

In order to shape i_{rec1} and i_{rec2} as indicated in Fig. 2(a)–(b), two AVSs, having an identical voltage v_i, are introduced. They are inserted in each dc bus of Rec1 and Rec2, as shown in Fig. 1(a) and generate a square-wave voltage with adjustable amplitude V_i. The AVS is synchronized with the triggering signals of the thyristors, and has a frequency six times that of the mains voltage, as shown in Fig. 2(f). In the figure, α denotes the firing angle of the thyristors and v_i changes its polarity synchronized with each commutation instant of the thyristors.

III. Analysis of Operation

Defining the following two sets of three-phase mains voltage systems, e_1 and e_2, for Rec1 and Rec2, respectively. They are illustrated in Fig. 3.

$$e_{a1} = E\,\sin\left(\omega t + \frac{2\pi}{3}\right) \qquad e_{a2} = E\,\sin\left(\omega t + \frac{5\pi}{6}\right)$$
$$e_{b1} = E\,\sin\,\omega t \qquad e_{b2} = E\,\sin\left(\omega t + \frac{\pi}{6}\right)$$
$$e_{c1} = E\,\sin\left(\omega t - \frac{2\pi}{3}\right) \qquad e_{c2} = E\,\sin\left(\omega t - \frac{\pi}{2}\right).$$

Consider a time period, $\theta = \alpha$ to $\theta = \alpha + \pi/6$ with $\theta = \omega t$. The commutation in Rec2 starts at $\theta = \alpha$ from phase-*a*2 to phase-*b*2, and it finishes instantaneously as explained later. Fig. 4 gives the equivalent dc circuit, and the following equation holds.

$$2x\frac{d(i_{\mathrm{rec1}} - i_{\mathrm{rec2}})}{d\theta} = 2v_i - e_{11} + e_{22}$$

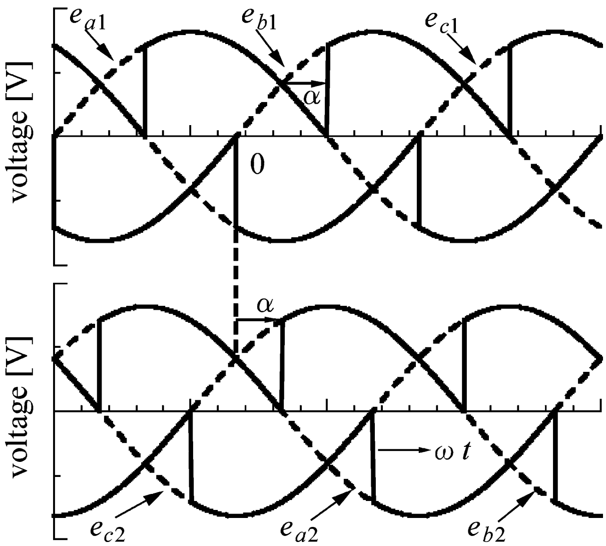

Fig. 3. Two sets of three-phase mains voltages, $e_{a1} - e_{c1}$ for Rec1 and $e_{a2} - e_{c2}$ for Rec2.

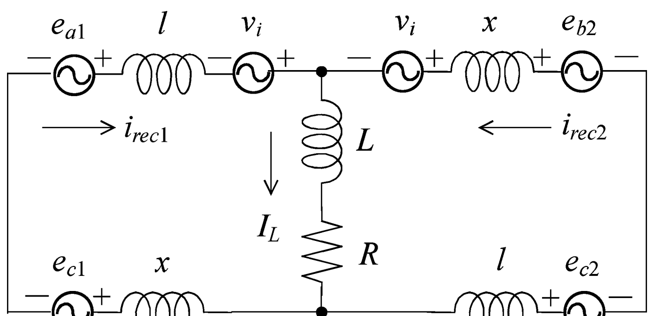

Fig. 4. Equivalent dc circuit during $\theta = \alpha$ to $\alpha + \pi/6$.

$$e_{11} \equiv (e_{a1} - e_{c1}),\ e_{22} \equiv (e_{b2} - e_{c2}) \tag{1}$$

where $x = \omega l$ denotes the leakage reactance of the transformer per phase, and e_{11} and e_{22} represent the instantaneous dc voltages of Rec1 and Rec2, respectively. Since the dc load current $I_L (= i_{\rm rec1} + i_{\rm rec2})$ is constant, the following equations hold.

$$4x\frac{di_{\rm rec2}}{d\theta} = V_S \tag{2}$$

$$V_S \equiv 2v_i + 2\sqrt{3}E\,\sin\left(\frac{\pi}{12}\right)\sin\left(\omega t - \frac{\pi}{12}\right). \tag{3}$$

If the voltage V_S is constant, (2) indicates that $i_{\rm rec2}$ increases linearly with time. Assume that the variations in $i_{\rm rec2}$ were as shown in Fig. 5, as indicated in Fig. 2(b). The initial condition would be $i_{\rm rec2} = 0$ at $\theta = \alpha$, and the final condition would be $i_{\rm rec2} = I_L$ at $\theta = \alpha + \pi/6$. Hence, the following relation is obtained.

$$V_S = \left(\frac{24}{\pi}\right)xI_L. \tag{4}$$

In the same manner, one can understand that $i_{\rm rec1}$ decreases linearly with time in the same period, as shown in Fig. 5. Thus, the voltage V_S forces $i_{\rm rec1}$ and $i_{\rm rec2}$ to vary in a triangular shape indicated in Fig. 2(a) and (b), respectively.

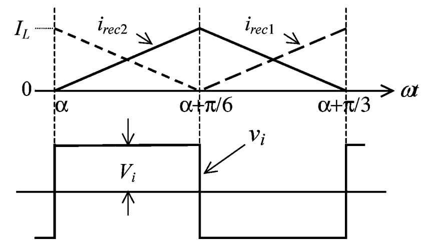

Fig. 5. Waveforms of dc output currents with AVS voltage v_i.

For simplicity, assume that the second terms of V_S in (3) is constant, averaging it over the period $\theta = \alpha$ to $\alpha + \pi/6$. Then, the amplitude of v_i will be given by

$$\begin{aligned} V_i &= \left(\frac{12}{\pi}\right)xI_L - \left(\frac{6\sqrt{3}}{\pi}\right)\left(1 - \frac{\sqrt{3}}{2}\right)E\,\sin\,\alpha \\ &= \left(\frac{12}{\pi}\right)xI_L - 0.443E\,\sin\,\alpha. \end{aligned} \tag{5}$$

In the following period, since $i_{\rm rec2}$ is forced to decrease from I_L to $0, \theta = \alpha + \pi/6$ to $\alpha + \pi/3$, the right-hand side of (2) must be negative, $-V_S$. The average value of the second term of V_S in (3) is the same as that in the previous period but takes a negative sign. Hence, v_i should be a square wave with an amplitude V_i, and changes its polarity at every commutation instant of the thyristors. The commutation takes place at every 60° in Rec1 and Rec2 alternately. Thus, the frequency of v_i must be six times that of the mains frequency. Equation (5) is very important, and it requires that the amplitude V_i should be controlled in relation to the load current I_L and the firing angle α, in order to get the best results in terms of harmonic distortion.[1] It is interesting that there is a special combination between I_L and α, which makes $V_i = 0$ or minimizes THD without AVS. This coincides with the conclusion in [26]. The following commutation starts at $\theta = \alpha + \pi/6$ in Rec1. It finishes immediately because $i_{\rm rec1}$ is already reduced to zero at that instant as Fig. 5 indicates. The thyristors commutate instantaneously.

The authors confirmed that the proposed harmonic reduction method is also effective to an inverter mode of operation. However, practical applications of 12-pulse choke-input type rectifiers [1], [5] do not require an inverter mode of operation.

[1]In order for AVS to maintain an optimal voltage at any load conditions, feed-forward control of V_i is required with the detection of the load current I_L. The voltage V_i is adjusted according to (5) as a function of α and I_L. It is easy because a linear relation holds between V_i and I_L.

IV. Characteristics of Proposed Rectifier

A. DC Output Voltage and Output Power

The average dc output voltage V_{L0} and output power $P_{\rm out}$ of the rectifier will be

$$V_{L0} = \left(\frac{3\sqrt{3}}{\pi}\right) E \cos\alpha \qquad P_{\rm out} = \left(\frac{3\sqrt{3}}{\pi}\right) E I_L \cos\alpha.$$

If AVS is not used, at light load, either Rec1 or Rec2 having a higher instantaneous dc voltage provides the dc current to the load for a 30°-period and the rest stops conducting the dc current, but at heavy load, both Rec1 and Rec2 provide the dc current simultaneously. If AVS is used, Rec1 and Rec2 provide the dc current simultaneously, but the current of extinguishing thyristor is reduced to zero at every commutation instant. The average dc voltage V_{L0} is exactly proportional to cos α because no current overlap occurs at thyristor commutation. Accordingly, the proposed rectifier provides a slightly lower dc average voltage than a conventional 12-pulse rectifier.

B. Volt–Ampere Rating of AVS

From (5), the amplitude of AVS V_i depends on α and I_L. It is obvious that the maximum volt–ampere (VA) will occur at $\alpha = 0$, because it provides the highest dc voltage and current. Thus, one has

$$V_i = \left(\frac{12}{\pi}\right) x I_L.$$

Since rms values of the rectifier resultant input current I and the current flowing through AVS I_i are

$$I = \left(\sqrt{\frac{2}{3}}\right) I_L = 0.816 I_L \qquad I_i = \frac{I_L}{\sqrt{3}} = 0.577 I_L$$

the VA rating of AVS will be given by

$$\mathrm{VA}_i = \left(\frac{12}{\pi}\right) x I_L I_i = \left(\frac{12}{\pi}\right) x_{\rm pu} E \frac{I_L}{\sqrt{2}} = 3.82 x_{\rm pu} E I_L$$

where $x_{\rm pu}$ denotes the per-unit based leakage reactance of the transformer per phase. The ratio of the AVS rating to the rectifier output power will be

$$\frac{\mathrm{VA}_i}{P_{\rm out}(\alpha = 0)} = \left(\frac{4}{\sqrt{3}}\right) x_{\rm pu} = 2.31 x_{\rm pu}.$$

If $x_{\rm pu} = 2\%$, the VA rating of AVS would be less than 5% of the 12-pulse rectifier output.

It is noted that an interphase reactor is unnecessary with the proposed rectifier. It results in increasing the VA rating of AVS, because the inductance of an interphase reactor increases the reactance x in (1).

C. Auxiliary Voltage Supply

The author used a single-phase pulse width modulation (PWM) inverter illustrated in Fig. 6 for AVS with an adjustable output voltage. The AVS feeds voltage v_i to Rec1 and Rec2 through a transformer having two identical secondary windings. The amplitude V_i is adjusted according to (5) depending on the load current I_L and the firing angle α. The output power of AVS is calculated as

$$P_{i\rm out} = \left(\frac{6}{\pi}\right) \int_{\alpha}^{\alpha+\pi/6} V_i (i_{\rm rec2} - i_{\rm rec1}) d\theta = 0.$$

There is no net power flow between the rectifier and AVS. The diode rectifier charges the dc capacitor C_i just at starting. Therefore, the input current of the diode rectifier at steady state would be zero if the capacitor C_i is large enough. Thus, it would not distort the mains currents. But, in practice, as some resistance components exist in the transformer windings, there is a slight power flow between the rectifier and AVS.

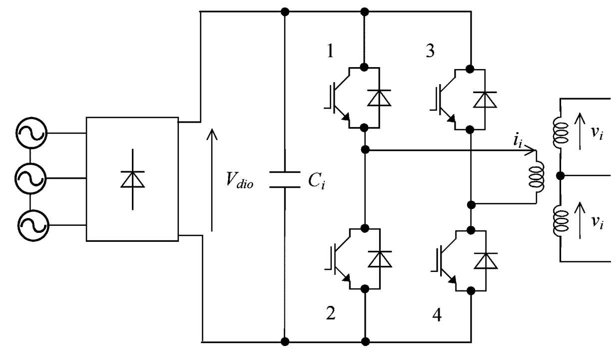

Fig. 6. Configuration of AVS.

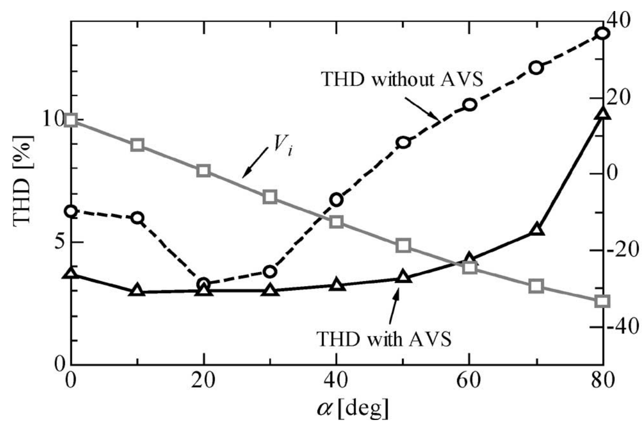

Fig. 7. Improvement in input current THD by inserting AVS with optimal amplitude.

V. Simulation Results

Simulation studies are carried out with the parameters listed in Table I. It is noted that the DC load resistance *R* is kept constant with this simulation.

The relation between optimal V_i that minimizes THD of the resultant input current and α is illustrated in Fig. 7. Also, the comparison of THD with and without AVS is presented in Fig. 7. If V_i is controlled with α, as indicated in the figure, THD is less than 5% over a wide adjustable output voltage range, $\alpha = 0$–$60°$. It is obvious that AVS is effective on reducing harmonic distortion of the rectifier input currents. It is interesting that if $\alpha = 20°$, THD is minimized without AVS. This is because with

TABLE I
PARAMETERS USED FOR SIMULATION

Rectifier output		2.5kW
Line-to-line voltage in RMS		100V
Frequency	f	50Hz
Leakage inductance of Tr.	l	0.638mH
	x	2.5%
Resistance of Tr.		0.883Ω
DC load inductance	L	50 [mH]
DC load resistance	R	6.5 [Ω]

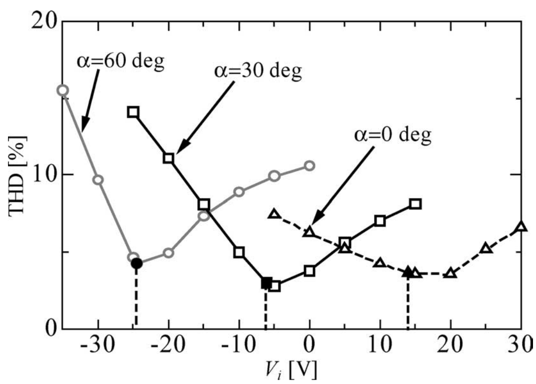

Fig. 8. Dependency of current THD on amplitude of AVS. (a) Without AVS. (b) With AVS.

the parameters given in Table I, it happened that V_S satisfied (4) without AVS (or with $V_i = 0$) at $\alpha = 20°$.

Fig. 8 demonstrates how V_i affects on THD of the input current. The V_i values given by (5) are represented with dotted lines. One can see that (5) gives almost the exact V_i values that minimize current THD. Optimal V_i strongly depends on the firing angle α and the load current I_L. It will be positive as well as negative.

Fig. 9(a) and (b) show the comparison of current waveforms with and without AVS under $\alpha = 60°$. If AVS is not used, the dc output currents $i_{\rm rec1}$ and $i_{\rm rec2}$ flow alternately, because either Rec1 or Rec2 having a higher instantaneous dc output voltage conducts the dc current to the load for a 30°-period and the rest stop conducting current. Hence, i_{a1} and i_{a2} also flow alternately.[2] Current THD is 10.6%. If AVS with optimal $V_i = -24.8$V is inserted, however, the dc output currents flow simultaneously. Current THD is improved to 4.64%.

Frequency spectra of i_a with and without AVS are compared in Fig. 10. One can observe that the 11th and 13th harmonics are drastically reduced if AVS is used.

Fig. 11 illustrates voltage and current waveforms at various locations under $\alpha = 30°$ when an optimal AVS voltage v_i, shown

[2]If the load is heavier, $i_{\rm rec1}$ and $i_{\rm rec2}$ flow simultaneously and continuously. Then, i_{a1} and i_{a2} flow simultaneously as well. The AVS is also effective in this case.

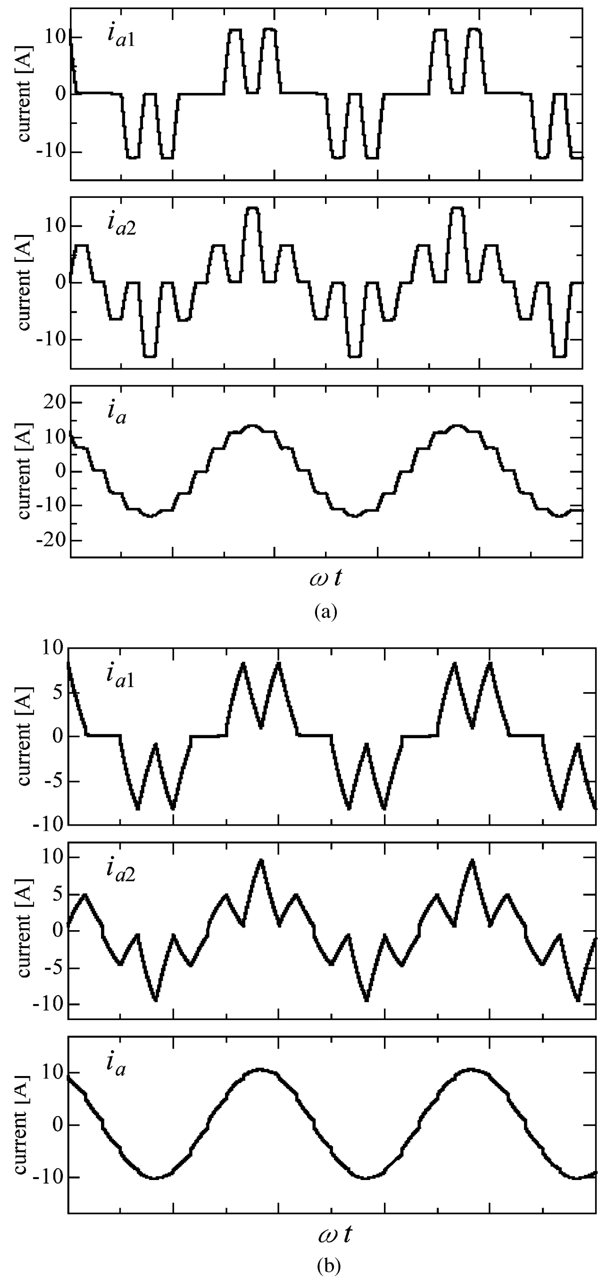

Fig. 9. Input current waveforms at $\alpha = \pi/3$.

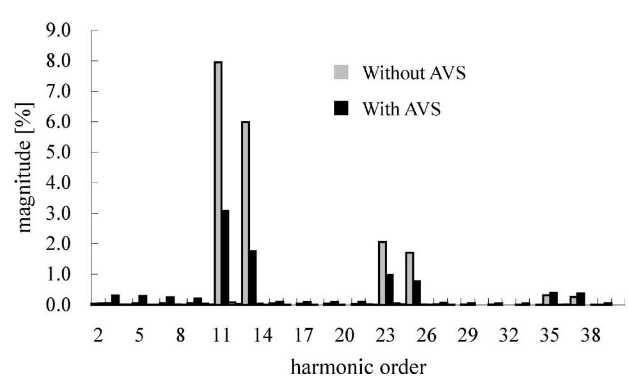

Fig. 10. Comparison of input current frequency spectra with and without AVS.

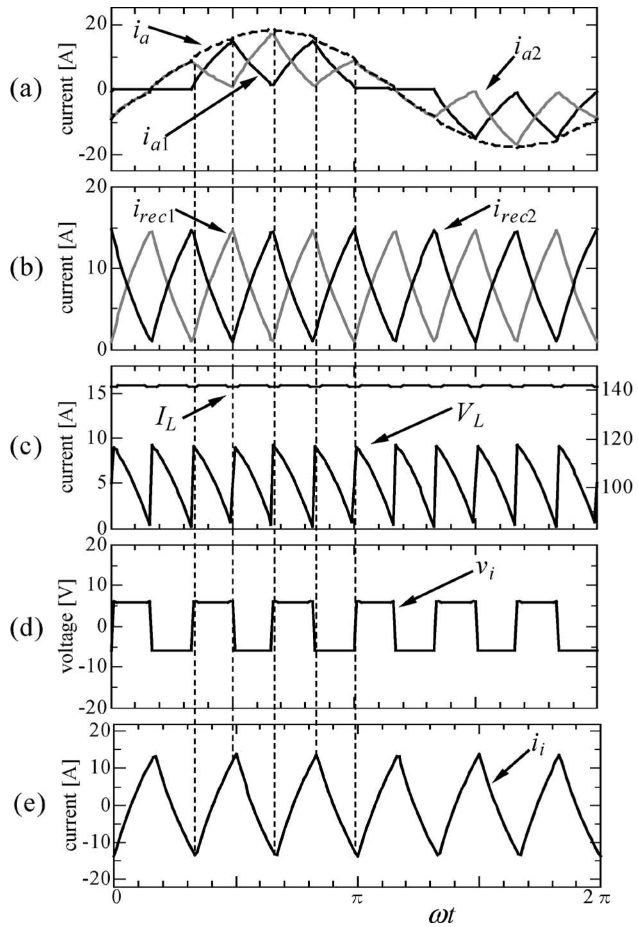

Fig. 11. Voltage and current waveforms at $\alpha = \pi/6$.

in Fig. 11(d), is inserted. The current i_{a1}, i_{a2}, and i_a are shown in Fig. 11(a). THD of i_a is reduced to 2.8%. The load current I_L and instantaneous dc voltage V_L are also shown in Fig. 11(c). One can confirm that I_L is ripple-free, and the current overlap between two phases, which occurs at every commutation of thyristors with conventional 12-pulse rectifiers, is not observed in the V_L waveform. The AVS current, $i_i = i_{\mathrm{rec1}} - i_{\mathrm{rec2}}$, is also shown in Fig. 11(e).

Twelve-pulse choke-input thyristor rectifiers have been used for large current applications such as dc arc furnaces and copper refining industries [1], [5]. If insulated-gate bipolar transistor (IGBT) modules of $V_{\mathrm{CE}} = 1700$ V and $I_C = 2400$ A [27] were used, a 1-MVA AVS could be built. Then, it could be employed for, e.g., a copper refining system of 20-MVA.

VI. Experimental Results

Experiment was carried out under the parameters listed in Table II. Two three-phase transformers having a turns-ratio 2:1 and 2:1/$\sqrt{3}$ were used for the 12-pulse phase-controlled rectifier. Measured current waveforms at various locations without and with AVS are compared under $\alpha = 60^\circ$ in Figs. 12 and 13, respectively .

Fig. 12(a) shows that if AVS is not used, Rec1 and Rec2 conduct currents i_{rec1} and i_{rec2} alternately, but Fig. 13(a) shows that

TABLE II
Parameters of Experimental Setup

Rectifier output		2.5kW
Line-to-line utility voltage in RMS	$\sqrt{3}\,E$	200V
Frequency	f	50Hz
Leakage inductance of Tr. referred to secondary	l x	0.425mH 1.82%
Resistance of Tr. referred to secondary	r	0.221Ω
DC load inductance	L	50mH
DC load resistance	R	8.0Ω
DC input voltage of AVS	V_{dio}	80V

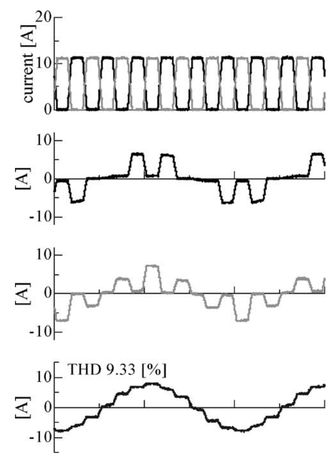

Fig. 12. Current waveforms without AVS at $\alpha = \pi/3$.

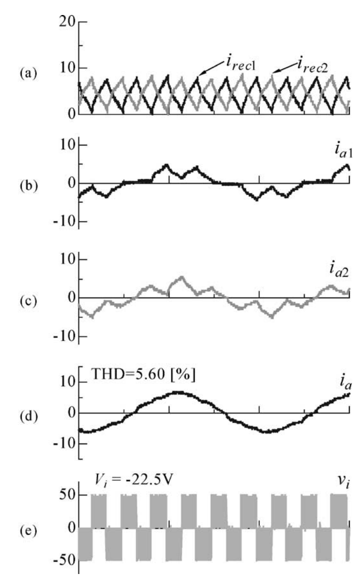

Fig. 13. Current and voltage waveforms with AVS at $\alpha = \pi/3$.

they conduct current simultaneously if AVS is used. Fig. 13(b) and (c) show currents i_{a1} and i_{a2}, respectively, when AVS was used. Both currents are similar to the simulation results given in Fig. 2(c) and (d), respectively.

Figs. 12(d) and 13(d) show the resultant input current i_a. Since the dc output voltage decreases if AVS is used, i_a with

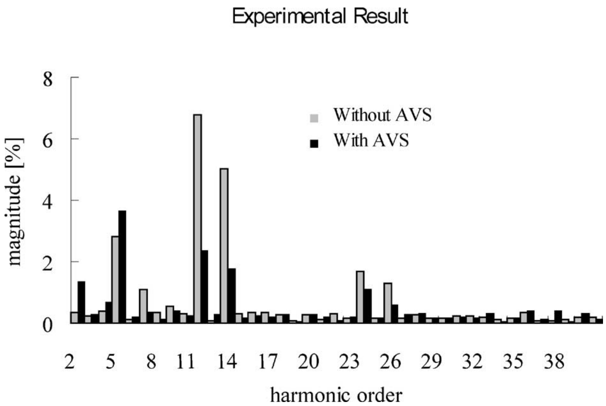

Fig. 14. Comparison of measured input current frequency spectra with and without AVS at $\alpha = \pi/3$.

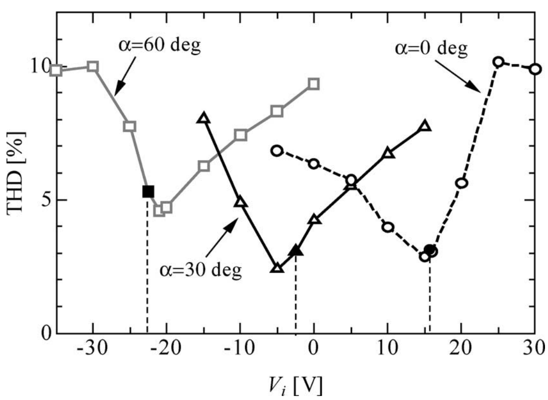

Fig. 15. Dependency of measured current THD on amplitude of AVS.

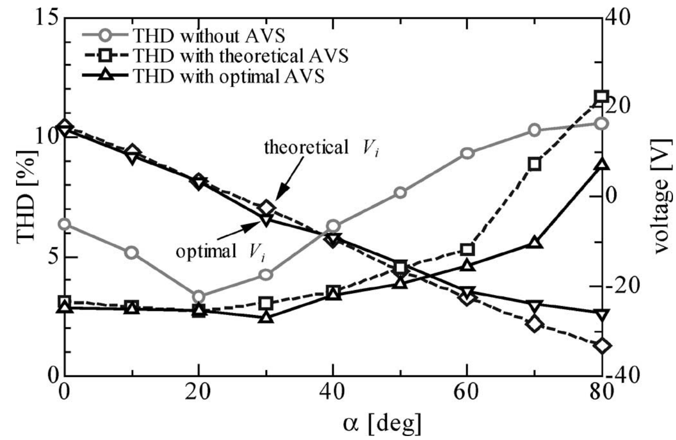

Fig. 16. Comparison of theoretical and measured characteristics, with optimal V_i and current THD vs. α.

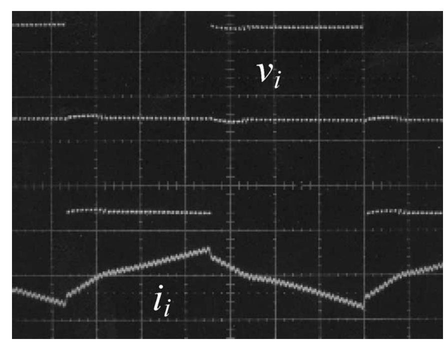

Fig. 17. Voltage and current waveforms of AVS at $\alpha = \pi/3$; upper: $2v_i$, 50 V/div; lower: i_i, 5 A/div, 0.5 ms/div.

AVS was smaller than that without AVS. If AVS was not used, THD of i_a was 9.33%, but it was improved to 5.30% if AVS was used.

Fig. 13(e) shows the AVS voltage. It seems a square wave with the amplitude 50 V, but, actually, it is a PWM shape and is equivalent to a square wave with the amplitude $V_i = -22.5$ V.

Fig. 14 shows frequency spectra of i_a. One can observe that AVS remarkably reduced the 11th and 13th harmonics. The fifth and seventh harmonics, which theoretically do not exist, were observed. Imbalance of the transformer leakage inductances would be one reason.

Fig. 15 shows the measured V_i vs. THD characteristics. THD strongly depends on V_i and α. The solid lines indicate theoretical V_i values given by (5). They almost coincide with the measured optimal V_i that minimizes current THD.

Fig. 16 compares the theoretical and measured optimal V_i as a function of α. Close agreement between them was observed. It is noted that THD took a minimum value at $\alpha = 20°$ without AVS and was close to the minimized value with AVS. This coincides with the simulation result in Fig. 7.

Fig. 17 shows the voltage and current waveforms of AVS at $\alpha = 60°$. The configuration of employed AVS was shown in Fig. 6, and the transformer having a turns-ratio of 2:1 was used. The upper trace shows the output voltage of the inverter $2v_i$. It is pulse-width modulated with a carrier frequency of 10 kHz and dc input voltage of $V_{\mathrm{di0}} = 100$ V. The lower trace shows the inverter output current i_i. One can see that the measured i_i is different from a pure triangular shape. This is because the approximation of the voltage $e_{22} - e_{11}$ in the dc equivalent circuit in Fig. 4 to a constant value is not exact if α is large. The approximation is done in the second term on the right-hand side of (3) when calculating (5).

VII. Conclusion

This paper proposed a current harmonic distortion reduction method for parallel-connected 12-pulse choke-input phase-controlled thyristor rectifiers. The method employs a single-phase square wave AVS and inserts it into the dc bus of the rectifier. If the AVS is appropriately controlled, this configuration enables one to reduce the harmonic distortion of the rectifier resultant input currents almost equivalent to that of a phase-controlled 24-pulse rectifier.

This paper theoretically investigates the principle of harmonic reduction especially in the 11th and 13th harmonics in the input currents, and presents how the AVS should be adjusted in relation to the load current and firing angle to get the best results in terms of harmonic reduction. The usefulness of the proposed configuration and control strategy of the auxiliary supply is verified by simulation and experimental results. The VA rating of the auxiliary supply is around 5% of that of the 12-pulse thyristor rectifier.

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