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著者	石黒　章夫
journal or publication title	CONFERENCE RECORD OF THE 24th IEEE INDUSTRY APPLICATION SOCIETY ANNUAL MEETING, 1989
volume	24
number	1
page range	783-789
year	1989
URL	http://hdl.handle.net/10097/46383

doi: 10.1109/IAS.1989.96736

A NEW PWM CONTROL METHOD FOR AC TO DC CONVERTERS WITH HIGH-FREQUENCY TRANSFORMER ISOLATION

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ABSTRACT

This paper presents a novel PWM control method for switch mode rectifier (SMR) based on the idea of coordinate transformation. The proposed method realizes sinusoidal input current waveforms, controllable input displacement factor, and arbitrary output voltage waveform. This method is suitable for real time control.

Simulations and experiments are carried out to confirm feasibility of the proposed method.

INTRODUCTION

Transformer isolation is a usual practice for ohmic isolation between a source and a load. The transformer designed for commercial frequency makes the converter bulky and heavy. Therefore, high-frequency link converters have been studied minimize weight, size and cost of the converters by making the transformer smaller[1][2][3].

S.Manias and P.D.Ziogas proposed a novel switch-mode-rectifier(SMR) structure and showed a control method[4]. The structure having six force-commutated switches with bidirectional current flow is simpler than those of the conventional ac - dc - high freq. - dc type converters. The control method proposed in [4], which is a combination of the control method of PWM converters and that of PWM inverters, makes the input power factor controllable and reduces the harmonics in the input current. However, the method in [4] still generates lots of harmonics in the input current, and does not seem adequate for real time control of arbitrary output voltage waveforms.

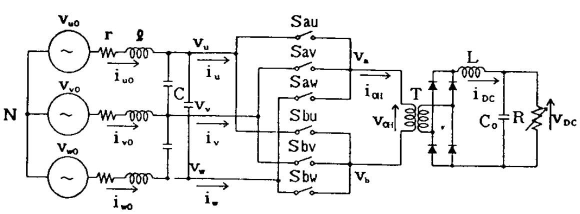
In this paper, a novel PWM control method for the SMR derived from the idea of coordinate transformation[5] is proposed. The proposed method realizes sinusoidal input current waveforms, controllable input displacement factor, and arbitrary output voltage waveforms. Moreover, this method is advantageous to reduce higher and fractional harmonic components of the input waveforms than the previous method, and is more suitable for real time control. Suppression of dc magnetization of the high-frequency transformer is easy to implement.

Simulations and experiments are carried out to confirm feasibility of the proposed method.

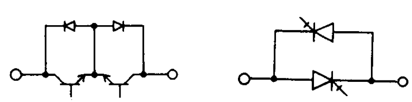
MAIN CIRCUIT

The main circuit of the SMR is shown in Fig.1(a), which consists of six self-turn-off bidirectional switches S_{au}-S_{bw}, input l-C-r filters, a high-frequency transformer T, a diode bridge and a L-C_o filter. The ohmic isolation between the source and the load is realized by the high-frequency transformer. Practical bidirectional switches for S_{au}-S_{bw} are shown in Fig.2(b). Each switch consists of two self-turn-off devices with reverse blocking capability. The efficiency of the SMR is to be improved by using GTO's. The GTO's reduce number of devices connected in series in the operation of the SMR. The input l-C-r filters are used to eliminate high frequency components in the input current of the SMR. The inductance of the source line is included in the filter reactor l and the resistor r is a sum of the resistor of the reactor and that of the source line. The filter L-C_o suppresses the high-frequency components of the output voltage of the SMR.

The source voltages v_{uo}, v_{vo}, v_{wo} and the voltages after the input l-C-r filters v_u, v_v, v_w are given as the following expressions:



(a) Main circuit



(b) Practical switching device

Fig. 1 Switch mode rectifier

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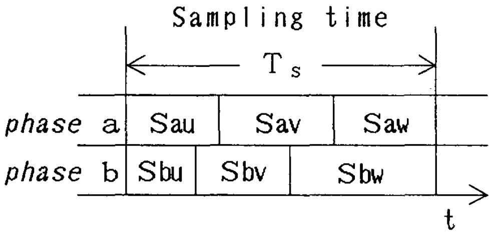

Fig. 2 Switching pattern

$$\begin{bmatrix} v_{uo} \\ v_{vo} \\ v_{wo} \end{bmatrix} = V_s \begin{bmatrix} \cos \omega t \\ \cos(\omega t - 2\pi/3) \\ \cos(\omega t + 2\pi/3) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = V \begin{bmatrix} \cos(\omega t - \delta) \\ \cos(\omega t - \delta - 2\pi/3) \\ \cos(\omega t - \delta + 2\pi/3) \end{bmatrix} \quad (2)$$

where ω is the angular frequency of the source, V_s is the amplitude of the source voltages, V is the amplitude of the voltages after the input l-C-r filters and δ is the phase lag caused by the input l-C-r filters.

CONTROL FUNCTIONS

Since the filter capacitor C's are connected on the source side of the bidirectional switches S_{au}-S_{bw}, short-circuit of the capacitors by the switches is not allowed. Since the high-frequency transformer with a leakage inductance is connected on the output side of the switches, open-circuit of the output terminals is not favorable. Therefore, the switches S_{au}-S_{bw} are controlled as shown in Fig.2. For real-time control, switching patterns are generated at every sampling period T_s. A control function for each switch is defined as a duty ratio within each T_s, and is denoted by a_u - b_w. For instance, a_u is defined as follows:

$$a_u = (\text{on-time of } S_{au} \text{ during } T_s)/T_s. \quad (3)$$

The following constraints are imposed on the control functions:

$$\begin{aligned} a_u + a_v + a_w &= 1 \\ b_u + b_v + b_w &= 1 \end{aligned} \quad (4)$$

where

$$0 \le a_q \le 1,\ 0 \le b_q \le 1 \quad (q = u, v, w).$$

The voltages on the primary side of the high-frequency transformer are denoted by v_a and v_b. These voltages are viewed from the neutral point N. The average values of the voltages v_a, v_b during the sampling period T_s are given as follows:

$$\begin{bmatrix} \bar{v}_a \\ \bar{v}_b \end{bmatrix} = \begin{bmatrix} a_u & a_v & a_w \\ b_u & b_v & b_w \end{bmatrix} \begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix}. \quad (5)$$

The input currents are denoted by i_u, i_v, i_w. The average values of the input currents during the sampling period $\bar{i}_u$, $\bar{i}_v$, $\bar{i}_w$ are given by using the current of the primary winding of the high-frequency transformer i_{OH} as:

$$\begin{bmatrix} \bar{i}_u \\ \bar{i}_v \\ \bar{i}_w \end{bmatrix} = \begin{bmatrix} a_u & b_u \\ a_v & b_v \\ a_w & b_w \end{bmatrix} \begin{bmatrix} i_{OH} \\ -i_{OH} \end{bmatrix}. \quad (6)$$

We propose the following control functions based on the idea of coordinate transformation [5]:

$$\begin{aligned} \begin{bmatrix} a_u \\ a_v \\ a_w \end{bmatrix} &= A_v \cdot Y_a \cdot \begin{bmatrix} X_u \\ X_v \\ X_w \end{bmatrix} + \begin{bmatrix} h_u \\ h_v \\ h_w \end{bmatrix} \\ \begin{bmatrix} b_u \\ b_v \\ b_w \end{bmatrix} &= A_v \cdot Y_b \cdot \begin{bmatrix} X_u \\ X_v \\ X_w \end{bmatrix} + \begin{bmatrix} h_u \\ h_v \\ h_w \end{bmatrix} \end{aligned} \quad (7)$$

where A_v determines the amplitude of the output voltage on the primary side of the high-frequency transformer. Functions h_u, h_v, h_w are introduced to satisfy the constraints in (4). X_u, X_v and X_w are given as follows:

$$\begin{bmatrix} X_u \\ X_v \\ X_w \end{bmatrix} = \begin{bmatrix} \cos(\omega t + \phi_s) \\ \cos(\omega t + \phi_s - 2\pi/3) \\ \cos(\omega t + \phi_s + 2\pi/3) \end{bmatrix} \quad (8)$$

where ϕ_s is the demand of the phase difference between the input voltages v_u, v_v, v_w and the input currents i_u, i_v, i_w. By substituting (2), (7) and (8) into (5), the average values of the voltages during the sampling period $\bar{v}_a$, $\bar{v}_b$ are obtained as follows:

$$\begin{bmatrix} \bar{v}_a \\ \bar{v}_b \end{bmatrix} = \frac{3}{2} \cdot A_v \cdot V \cdot \cos(\phi_s + \delta) \begin{bmatrix} Y_a \\ Y_b \end{bmatrix} + \begin{bmatrix} v_o \\ v_o \end{bmatrix} \quad (9)$$

where v_o is expressed as:

$$v_o = h_u v_u + h_v v_v + h_w v_w. \quad (10)$$

Then the average value of the voltage across the primary winding of the high frequency transformer during the sampling period $\bar{v}_{OH}$ is obtained as:

$$\begin{aligned} \bar{v}_{OH} &= \bar{v}_a - \bar{v}_b \\ &= \frac{3}{2} \cdot A_v \cdot V \cdot \cos(\phi_s + \delta)(Y_a - Y_b). \end{aligned} \quad (11)$$

Functions Y_a and Y_b in (7) and (11) appears across the primary winding of the high-frequency transformer. These functions determine the waveform of the voltage v_{OH}. The output dc voltage v_{DC} is obtained by rectifying and smoothing the voltage v_{OH}. Therfore the output dc voltage v_{DC} can be controlled by the value A_v. The output voltage generated by the functions h_u, h_v, h_w is a zero-phase component and does not appear across

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the primary winding of the high-frequency transformer.

The functions Y_a and Y_b can be any kind of waveforms. To realize the least switching frequency of the switches S_{au}-S_{bw} under the link frequency ω_o, the functions are chosen as:

$$\begin{bmatrix} Y_a \\ Y_b \end{bmatrix} = \begin{bmatrix} \mathrm{sgn}(\sin \omega_o t) \\ \mathrm{sgn}(-\sin \omega_o t) \end{bmatrix}. \qquad (12)$$

Assuming that the dc output current i_{DC} does not contain ripple component (i.e. i_{DC} = I(constant)), the primary current of the high-frequency transformer i_{OH} is expressed as:

$$i_{OH} = I \cdot (Y_a - Y_b)/2. \qquad (13)$$

The average value of the input currents during the sampling period $\bar{i}_u$, $\bar{i}_v$, $\bar{i}_w$ are obtained by substituting (7), (8), (12), (13) into (6).

$$\begin{bmatrix} \bar{i}_u \\ \bar{i}_v \\ \bar{i}_w \end{bmatrix} = A_v \cdot I \cdot \begin{bmatrix} X_u \\ X_v \\ X_w \end{bmatrix}$$

$$= A_v \cdot I \cdot \begin{bmatrix} \cos(\omega t + \phi_s) \\ \cos(\omega t + \phi_s - 2\pi/3) \\ \cos(\omega t + \phi_s + 2\pi/3) \end{bmatrix} \qquad (14)$$

The input currents are sinusoidal. ϕ_s is the value introduced in (8) and determines the displacement factor of the input current.

FUNCTIONS h_u, h_v, h_w AND THE MAXIMUM OUTPUT VOLTAGE

The functions h_u, h_v, h_w are derived from (4) and (7) as follows:

$$-A_v X_q \min Y_p \le h_q \le 1 - A_v X_q \max Y_p \qquad (X_q \ge 0)$$

$$-A_v X_q \max Y_p \le h_q \le 1 - A_v X_q \min Y_p \qquad (X_q < 0)$$

$$(q = u, v, w) \qquad (15)$$

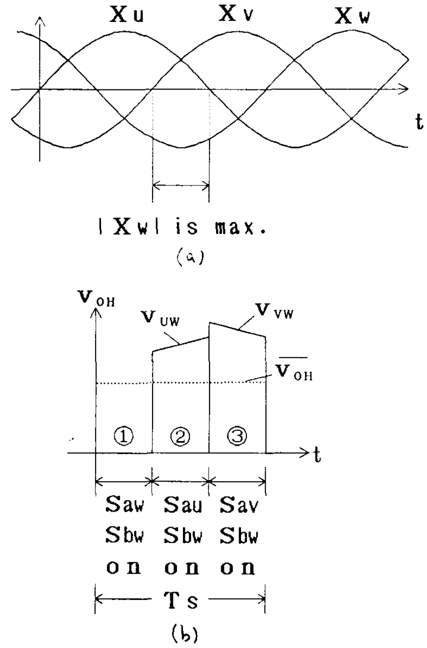

Fig. 3 Example of switching seqeunce with least switching frequency

where

$$\min Y_p = \min(Y_a, Y_b)$$

$$\max Y_p = \max(Y_a, Y_b).$$

Also from (4) and (7),

$$h_u + h_v + h_w = 0. \qquad (16)$$

Assumes that the absolute value of X_w is the largest among those of the functions X_u, X_v, X_w and X_w is negative in a sampling period, and Y_a = 1, Y_b = -1. Then the switching

Table.1 Example of h_u, h_v, h_w and switching sequence.

MODE	1	2	3	4	5	6
X_u	+	+	−	−	−	+
X_v	−	+	+	+	−	−
X_w	−	−	−	+	+	+
h_u	$1-A_U \cdot X_u \cdot \max Y_o$	$-A_U \cdot X_u \cdot \min Y_o$	$-A_U \cdot X_u \cdot \max Y_o$	$1-A_U \cdot X_u \cdot \min Y_o$	$-A_U \cdot X_u \cdot \max Y_o$	$-A_U \cdot X_u \cdot \min Y_o$
h_v	$-A_U \cdot X_v \cdot \max Y_o$	$-A_U \cdot X_v \cdot \min Y_o$	$-A_U \cdot X_v \cdot \max Y_o$	$-A_U \cdot X_v \cdot \min Y_o$	$-A_U \cdot X_v \cdot \max Y_o$	$1-A_U \cdot X_v \cdot \min Y_o$
h_w	$-A_U \cdot X_w \cdot \max Y_o$	$1-A_U \cdot X_w \cdot \min Y_o$	$1-A_U \cdot X_w \cdot \max Y_o$	$-A_U \cdot X_w \cdot \min Y_o$	$1-A_U \cdot X_w \cdot \max Y_o$	$-A_U \cdot X_w \cdot \min Y_o$
SWITCHING SEQUENCE	u→v→w	w→u→v	v→w→u	u→v→w	w→u→v	v→w→u

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frequency is reduced by keeping the switch S_{bw} on and the switches S_{bu}, S_{bv} off, and by controlling the output voltage with the switches S_{au}, S_{av}, S_{aw} as illustrated in Fig.3. A sampling period in which $|X_w|$ is maximum is expanded in Fig.3 (b). The voltage across the primary winding of the high frequency transformer v_{OH} consists of three waveforms in the sampling period. These waveforms are (a) zero-voltage short-circuited by the switches S_{aw} and S_{bw}, (b) line-to-line voltage v_{uw} (S_{au} and S_{bw} on), (c) line-to-line voltage v_{vw} (S_{av} and S_{bw} on). There is a freedom in the sequence of (a), (b), (c). An example of h_u, h_v, h_w and a switching sequence is listed on TABLE I. There are six modes depending on the maximum value of $|X_u|$, $|X_v|$, $|X_w|$. The switching sequence is denoted by the subscripts of the switches to be turned on/off in the mode. For example, Figure 3 is the case of mode 2. The switches S_{au}, S_{av} and S_{aw} are turned on/off in the case. Thus the switching sequence is $w \to u \to v$. The distortion of the input currents of the SMR is reduced by the sequence on TABLE I [5].

Using the functions Y_a and Y_b of (12), the control functions of the switches a_u - b_w are determined for each mode. For example, in mode 1,

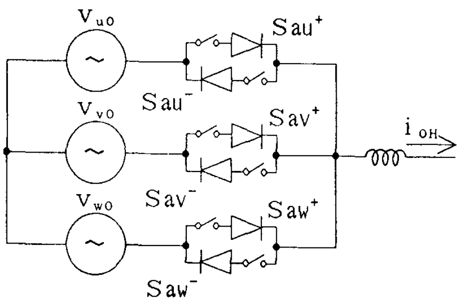

Fig. 4 Equivalent circuit of a-phase of SMR

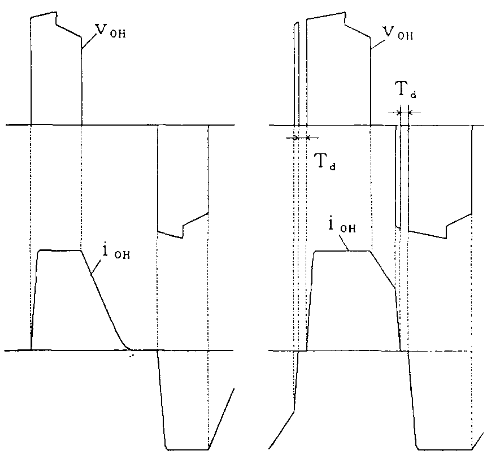

Fig. 5 Waveforms of valtages and currents of primary winding of high-freqency transformer

if $Y_a = 1$ and $Y_b = -1$

$$\begin{aligned} a_u &= 1 \\ a_v &= 0 \\ a_w &= 0 \\ b_u &= 1 - b_v - b_w \\ b_v &= -2 \cdot A_v \cdot X_v \\ b_w &= -2 \cdot A_v \cdot X_w, \end{aligned}$$

if $Y_a = -1$ and $Y_b = 1$

$$\begin{aligned} a_u &= 1 - a_v - a_w \\ a_v &= -2 \cdot A_v \cdot X_v \\ a_w &= -2 \cdot A_v \cdot X_w \\ b_u &= 1 \\ b_v &= 0 \\ b_w &= 0. \end{aligned} \tag{17}$$

The control functions obtained above are simple. In the case that $\phi_s = 0$, the functions X_u, X_v, X_w are in phase with the input voltage v_u, v_v, v_w. It is found that on-times of the switches S_{av}/S_{bv} and S_{aw}/S_{bw} are in proportion to the absolute value of the input line-to-neutral voltage v_v and v_w in mode 1, respectively. As for u-phase, the switches S_{au}/S_{bu} is kept on in mode 1. Since the output dc current i_{DC} is constant, the resulting input currents i_u, i_v, i_w are in phase with the input line-to-neutral voltages v_u, v_v, v_w, respectively.

The range of the function A_v in which the average value of the output voltage during the sampling period $\bar{v}_{OH}$ is kept constant in every sampling period is:

$$0 \le A_v \le 1/2. \tag{18}$$

The maximum value of the voltage $\bar{v}_{OH}$ is derived from (11) as $(3/2) \cdot V \cdot \cos(\phi_s + \delta)$. If $\phi_s = 0$ and $V\cos\delta = V_s$, then the output voltage $\bar{v}_{OH}$ is 1.5 times as much as the amplitude of the line-to-neutral voltage V.

SUPPRESSION OF DC MAGNETIZATION OF HIGH-FREQUENCY TRANSFORMER

A dead time T_d is introduced against the short-circuit of the input filter capacitor C. Figure 4 shows an equivalent circuit with two reverse blocking self-turn-off devices for each switch. Assuming that $v_{uo} > v_{vo}$ and $i_{OH} < 0$, i_{OH} goes to opposite sign at the time of commutation from s_{av}^- to s_{au}^-. If no dead time is set, s_{au}^+ is to be turned on while the switch s_{av}^- is still in on-state. A small dead time is effective against the short-circuit.

Figure 5 shows examples of the voltage across the primary winding of the high-frequency transformer v_{OH} and the current of the primary winding of the transformer i_{OH}. Figure 5 (a) shows the case that the demand of the output voltage is small. The current i_{OH} goes to zero in the period of zero-voltage output. In Fig.5 (b), the demand of the output voltage is large. The period of zero-voltage output is short and the current i_{OH} has a certain amount when the voltage of opposite

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sign is generated. Then the output voltage has a dip caused by the dead-time. If dc component is contained in the output current, the dip may appear in the output voltage of only one polarity. In this case, the voltage drop causes positive feedback and the dc componet is increased. Then the dc magnetization of the high frequency transformer is aggravated.

This dc magnetization can easily be suppressed by detecting the dc component of the output current and by modifying the functions Y_a and Y_b properly.

SIMULATIONS

Figure 6 shows a generating method of on-signal of the switches S_{au} - S_{bw}. The control functions a_u and $a_u + a_v$ are sampled and held during the sampling period T_s. These functions are compared with a sawtooth waveform synchronized with the sampling time and the on-signals of S_{au} - S_{aw} are generated. The on-signals of S_{bu} - S_{bw} are generated using the control functions b_u and $b_u + b_v$. The switching sequence is u → v → w in this case. The switching sequence can be changed by the control functions to be sampled and held. For example, the switching sequence is v → w → u with the control functions of a_v and $a_v + a_w$.

Figure 7 shows simulation results with (a) A_v = 1/4, (b) A_v = 3/8, (c) A_v = 1/2. The sampling period is set at one 64th of the period of the source voltage. Then the frequency of the high-frequncy link is 32 times as much as the source frequency (i.e. 60Hz*32 = 1.92 kHz). Simulation conditions are listed on TABLE II. The capacitor on the dc side C_o is large enough to absorb the switching ripple of the dc voltage. The switches are ideal and no dead time is set. The input currents i_{uo} in Fig.7 (a), (b), (c) are nearly sinusoidal. The phases of input currents i_{uo} lead to the source voltage v_{uo} due to the input filter capacitor C. The average value of the voltage across the primary winding of the high-frequency transformer is constant in every sampling period.

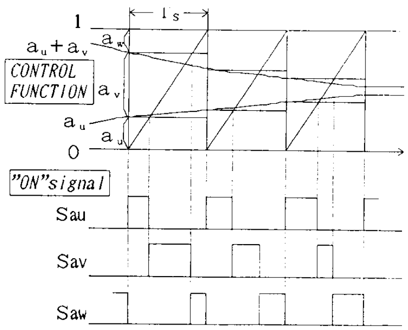

Fig. 6 Generation method of switching patterns

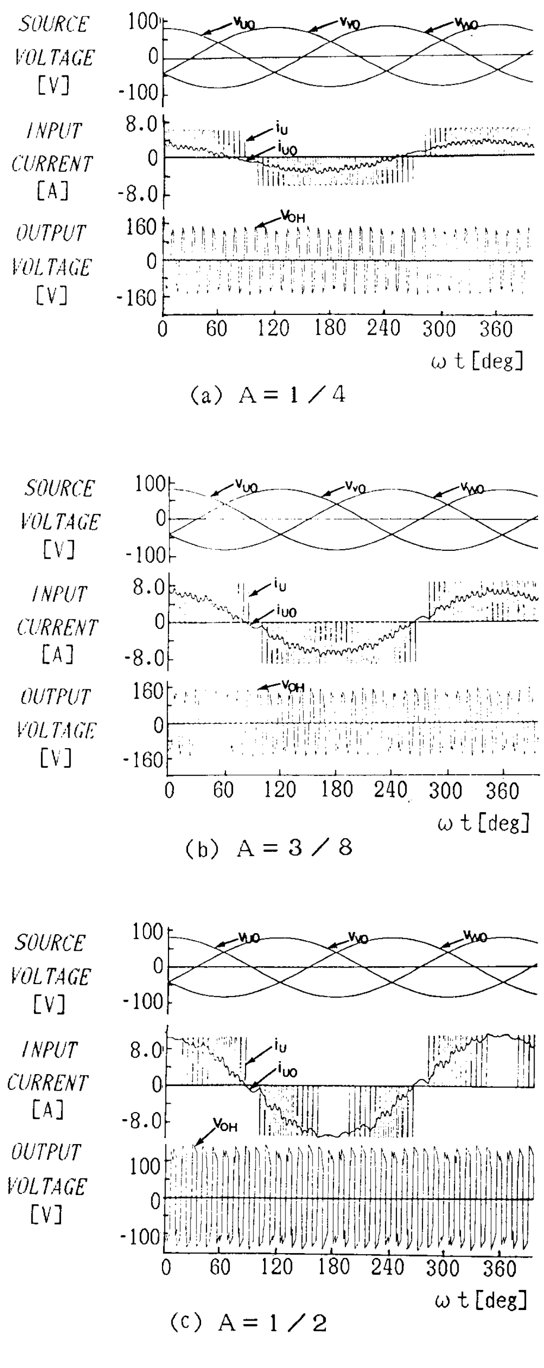

Fig. 7 Simulation results

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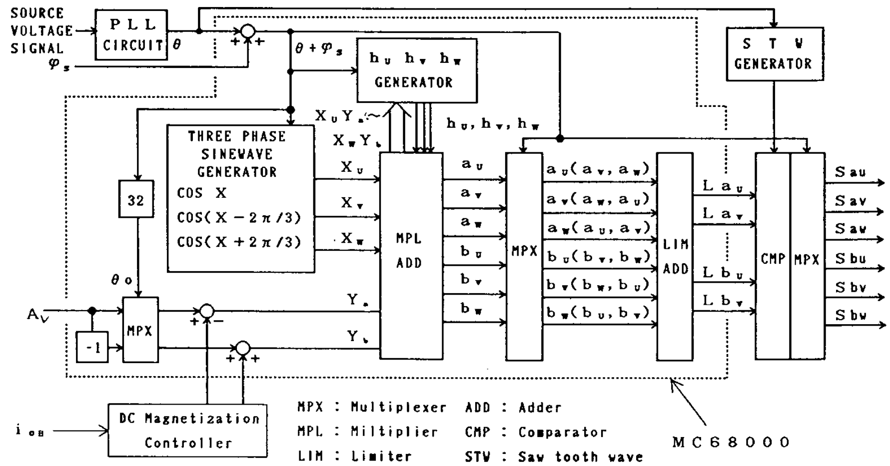

Fig. 8 Block diagram of control circuit

EXPERIMENTS

Figure 8 shows the block diagram of the controller. The electrical angle of the source voltage θ is obtained by the PLL circuit. Functions X_u, X_v, X_w are generated with θ and ϕ_s using a table. The electrical angle of the output voltage θ_o is obtained as $32 \cdot (\theta + \phi_s)$. Functions Y_a and Y_b are generated by using the demand of the output dc voltage A_v and the $_o$. Functions h_u, h_v, h_w are generated by using TABLE I. The limitter works in case that the control functions a_u - b_w do not satisfy the constraints in (4). The on-signals of S_{au} - S_{bw} are obtained by comparing L_{au} - L_{bv} with the sawtooth wave. The portion enclosed by the broken line is realized with a microprocessor MC68000.

Figure 9 shows the circuit for suppressing the dc magnetization of the high-frequency transformer. The dc component is detected by a Hall sensor and a low-pass filter and then the functions Y_a and Y_b are modified.

Experimental results are shown in Figure 10. Two bipolar transistors and two diodes are used as a bidirectional switch as shown in Fig.1 (b). The voltage demand A_v is 1/4 (Fig.10 (a)), 3/8 (Fig.10 (b)) and 1/2 (Fig.10 (c)). Other conditions are the same as those in the simulations. The dead time T_d for preventing the short-circuit of the input filter capacitor is set at 20 us. The ripples in the input current i_{uo} are larger than those in the simulations. The large ripples are caused by the dead time. The obtained dc output voltages are a little bit smaller than the demands. This difference is mainly due the dead time and the high-frequency transformer which is not suitable for high-freqeuncy use.

TABLE II PARAMETERS OF SIMULATIONS AND EXPERIMENTS

Source line-to -neutral voltage		100 V
Source frequency		60 Hz
Link frequency		1.92 kHz
Input displacement angle ϕ_s		0 deg
Input filter	r	0.5 ohm
	l	0.6 mH
	C	10 uF
Winding ratio of high-frequency transformer		1:1
Output filter	L	20 mH
	C_o	4400 uF
Load	R	20 ohm

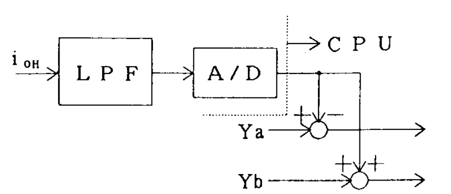

Fig. 9 Circuit for dc demagnetization

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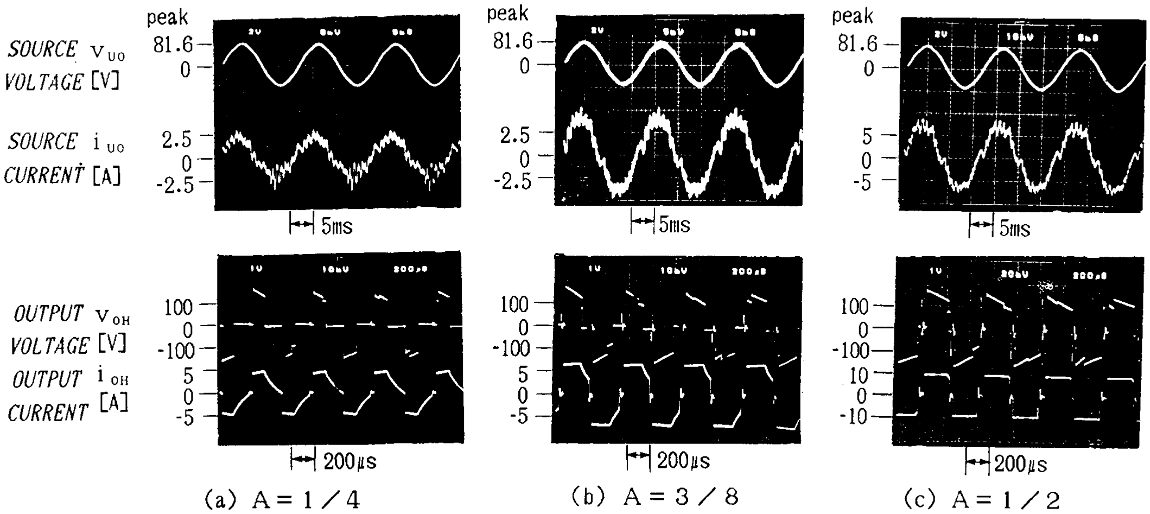

Fig. 10 Experimental results

CONCLUSIONS

This paper presented a new control method for the SMR. The new method is based on the idea of coordinate transformation. Results are the followings:

(1) The proposed method realized sinusoidal input current, arbitrary output voltage waveform and controllable input displacement factor. The maximum input-to-output vlotage ratio was 3/2.

(2) The proposed method was suitable for real-time control of the voltage on the primary side of the high-frequency transformer. Thus the suppression of the dc magnetization of the high-frequency transformer was easy to implement. Control of the output dc voltage was also easy.

(3) Feasibility of the proposed method was confirmed by simulations and experiments.

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