

## *AC Chopper Circuit with Lagging Reactive Load*

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### Synopsis

An ac chopper circuit, which chops an ac voltage in a complete cycle for any lagging reactive load, is devised. The circuit is constructed of two ac-switches composed of power transistors and diodes. The load voltage is smoothly controlled by varying the time ratio of ac-switch. Transistors operate in a high-frequency chopping mode, thereby the ripples of the source current and the load current are easily filtered. Furthermore the input power factor of this model is better than that of the thyristor phase control circuit.

In this paper, the construction and the driving method of this model are described.

### 1. Introduction

The thyristor phase control circuit is widely used for light dimming, heater control and induction motor speed control. This circuit has the advantages of simple construction and capability of controlling large amounts of ac power for any load. On the other hand, this circuit has demerits as follows:

- 1) The input power factor becomes lower in proportion as the firing angle delays.
- 2) The lower components of higher harmonics, for the most part, appear, e.g. 3th and 5th.

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From such situations an ac chopper circuit using thyristors is proposed<sup>1)2)</sup>. For the reason of thyristor's switching time, however, the operating frequency isn't high and its commutation circuit is complicated. For these reasons an ac chopper circuit using power transistors is devised<sup>3)4)</sup>. In Literature<sup>4)</sup> a three-phase ac chopper circuit is constructed, and the operation of the circuit with resistive load and induction motor load is tested. This circuit, however, isn't capable of chopping an ac voltage in a part of cycle, with loads, at some lagging power factor angles, and then the load voltage and the load current waveforms are distorted.

Thus the authors devise the driving method of an ac chopper circuit using power transistors which chops an ac voltage in a complete cycle at any lagging power factor angle. The circuit is composed of two ac-switches with power transistors and diodes. The load voltage is smoothly controlled by varying the time ratio of ac-switch. Moreover the current ripples are easily filtered. This model has also ability to adjust the chopping frequency,  $f_c$ , as well as the time ratio,  $\tau$ .

In this paper, the construction and the driving method of an improved ac chopper circuit for a lagging reactive load are described.

## 2. AC Chopper Circuit with Reactive Load

### 2.1 Construction of Circuit and Driving Method

An ac chopper circuit, which chops an ac voltage in a complete cycle for any lagging reactive load, is shown in Fig.1. Because of transistor's unidirectional switching property, an ac-switch is composed of three power transistors and a diode bridge. Two ac-switches in series and in shunt chop an ac voltage in a high-frequency chopping mode.

Transistors,  $T_{r1}$  and  $T_{r2}$ , turn on and off in high frequency,  $f_c$ Hz. The diagram of driving circuit, which drives  $T_{r1}$  and  $T_{r2}$ , is shown in Fig.2(a).

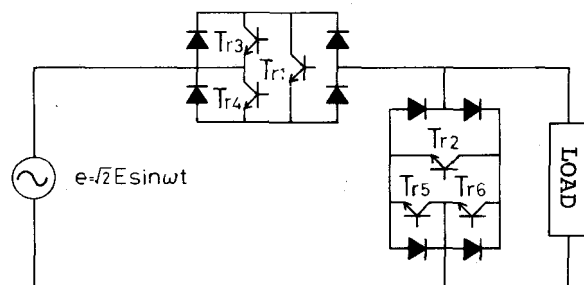


Fig.1. AC chopper circuit with lagging reactive load.

Transistors,  $T_{r3}$ ,  $T_{r4}$ ,  $T_{r5}$  and  $T_{r6}$ , turn on and off in frequency synchronized with the source. Then, transistors,  $T_{r3}$  and  $T_{r5}$ , are shut corresponding to the negative half cycle of source and transistors,  $T_{r4}$  and  $T_{r6}$ , are shut corresponding to the positive half cycle of source. The diagram of driving circuit, which drives transistors,  $T_{r3}$ ,  $T_{r4}$ ,  $T_{r5}$  and  $T_{r6}$ , is shown in Fig.2(b).

The ratings of a transistor and a diode used in this model are given in table 1 and 2, respectively.

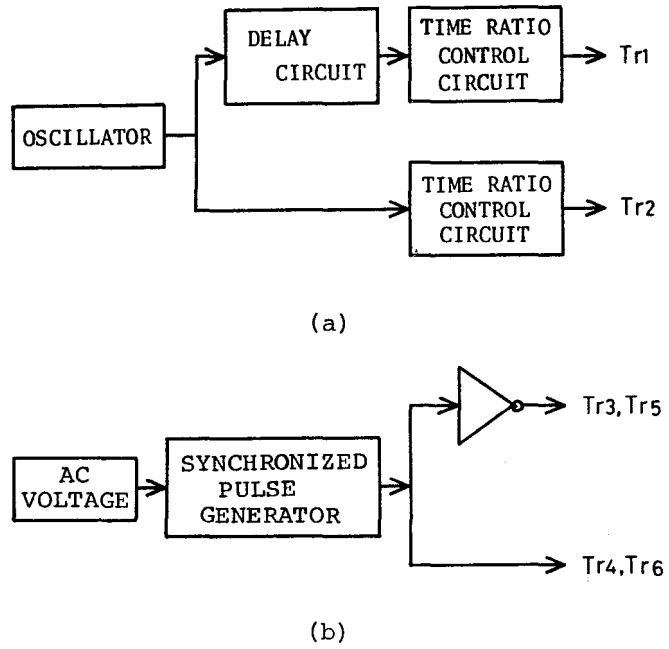


Fig.2. Diagrams of driving circuit.  
 (a) Driving circuit of  $T_{r1}$  and  $T_{r2}$ .  
 (b) Driving circuit of  $T_{r3}$ ,  $T_{r4}$ ,  $T_{r5}$  and  $T_{r6}$ .

Table.1. Rating of transistor (2SD641).

Term	Symbol	Rating	Unit
Collector to base voltage, dc, emitter open	V <sub>CB0</sub>	600	V
Collector to emitter voltage, dc, base open	V <sub>CE0</sub>	400	V
Emitter to base voltage, dc, collector open	V <sub>EB0</sub>	5	V
Collector current, dc	I <sub>C</sub>	15	A
Emitter current, dc	I <sub>E</sub>	-15	A
Base current, dc	I <sub>B</sub>	5	A
Collector power dissipation	P <sub>C</sub>	150	W
Junction temperature	T <sub>j</sub>	150	°C
Storage temperature	T <sub>stg</sub>	-65~150	°C

Table.2. Rating of diode (SR30C-10).

Term	Symbol	Rating	Unit
Repetitive peak reverse voltage	$V_{RRM}$	500	V
Non-repetitive peak reverse voltage	$V_{RSM}$	600	V
Reverse voltage, dc	$V_R(DC)$	400	V
RMS forward current	$I_F(RMS)$	47	A
Average forward current	$I_F(AV)$	30	A
Surge forward current	$I_{FSM}$	500	A
Junction temperature	$T_j$	-40~125	$^{\circ}C$
Storage temperature	$T_{stg}$	-40~150	$^{\circ}C$

## 2.2 Operation of Circuit

In order to state the operation of this model, as shown in Fig.3, a cycle of source is divided into two modes; mode I and mode II. Furthermore each mode is divided into submode I, in which the polarity of voltage and current is identical, and submode II, in which the polarity is opposite.

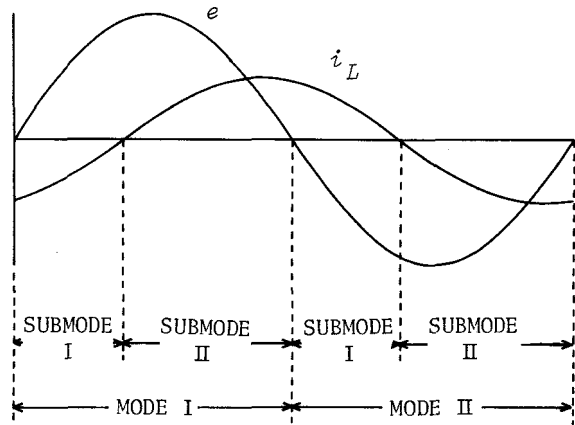


Fig.3. Operating modes.

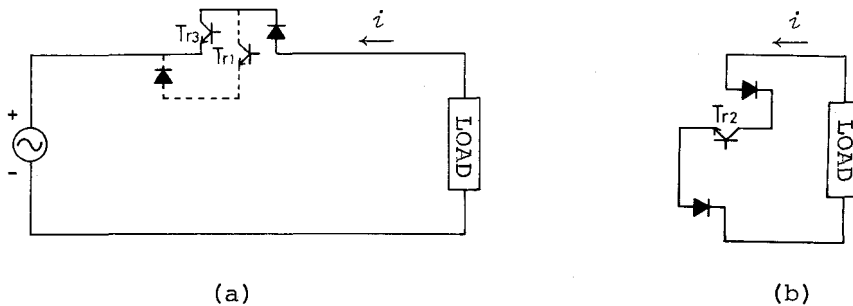


Fig.4. Operation in submode I (mode I).

(a)  $T_{r2}$ :open.(b)  $T_{r2}$ :closed.

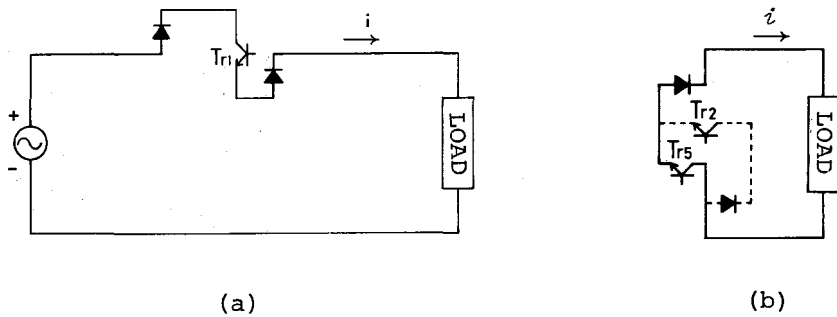


Fig.5. Operation in submode II (mode I).

- (a)  $T_{r1}$ :closed.
- (b)  $T_{r1}$ :open.

The operation of this model in submode I is shown in Fig.4. As shown in Fig.4, with  $T_{r2}$  open the current flows through  $T_{r3}$  or  $T_{r1}$ , and then the supply voltage is impressed across the load. With  $T_{r2}$  closed the current flows through  $T_{r2}$ , then the load voltage is zero. Similarly the operation of circuit in submode II is shown in Fig.5. With  $T_{r1}$  closed the current flows through  $T_{r2}$ , and then the supply voltage is impressed across the load. With  $T_{r1}$  open the current flows through  $T_{r5}$  and  $T_{r2}$ , then the load voltage is zero.

As mentioned above, the load voltage is smoothly controlled at even any lagging power factor angle by means of transistor

switching. Fig.6 shows the transistor base signals, the load voltage and the load current. Fig.7 shows the oscillograms of each waveform with a reactive load,  $R=40\Omega$  and  $L=293mH$ , where  $f_c=800Hz$ .

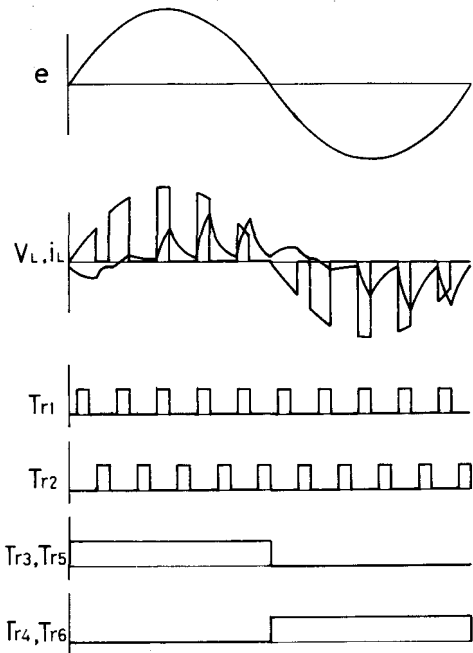


Fig.6. Driving circuit output waveforms.

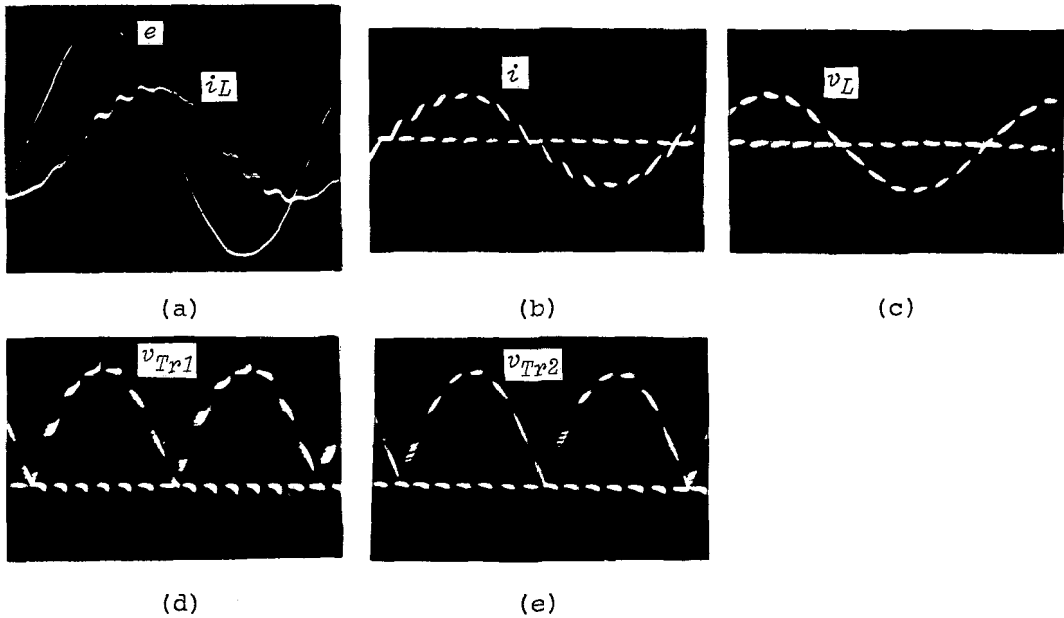


Fig.7. Oscillograms of waveform,  $E=50\text{V}$ ,  $f_c=800\text{Hz}$ ,  $R=40\Omega$ ,  $L=293\text{mH}$ , time base:  $2\text{ms/div}$ .

(a) Source voltage waveform,  $20\text{V/div}$ .

Load current waveform,  $20\text{V/div}$ .

(b) Source current waveform,  $500\text{mA/div}$ .

(c) Load voltage waveform,  $50\text{V/div}$ .

(d) Transistor,  $T_{r1}$ , voltage waveform,  $20\text{V/div}$ .

(e) Transistor,  $T_{r2}$ , voltage waveform,  $20\text{V/div}$ .

### 3. Characteristics of Circuit

#### 3.1 Calculation

In order to evaluate the characteristics of this ac chopper circuit the authors put into practice of its numerical calculation by computer. For the purpose of simplification, it is assumed that:

- (1) Transistors and diodes are idealized elements.
- (2) The source impedance is negligible.
- (3) The chopping frequency,  $f_c$ , is integer multiples of the source frequency.

Then, next differential equations in each submode are solved, and

the load voltage and the load current are evaluated.

1) Submode I

$$v_L = \begin{cases} E_m \sin x & (k\Delta x_T \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1} + \Delta x_{m2}) \\ 0 & (k\Delta x_T + \Delta x_1 + \Delta x_{m1} + \Delta x_{m2} \leq x \leq (k+1)\Delta x_T) \end{cases} \quad (1)$$

$$i_L = \begin{cases} \frac{E_m}{|Z|} \sin(x-\phi) + \{i_1(0) - \frac{E_m}{|Z|} \sin(k\Delta x_T - \phi)\} \cdot \epsilon^{-\frac{R}{L}(x-k\Delta x_T)/\omega} & (k\Delta x_T \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1} + \Delta x_{m2}) \\ i_2(0) \cdot \epsilon^{-\frac{R}{L}(x-k\Delta x_T - \Delta x_1 - \Delta x_{m1} - \Delta x_{m2})/\omega} & (k\Delta x_T + \Delta x_1 + \Delta x_{m1} + \Delta x_{m2} \leq x \leq (k+1)\Delta x_T) \end{cases} \quad (2)$$

$k=0, 1, 2, \dots$ , submode II.

2) Submode II

$$v_L = \begin{cases} E_m \sin x & (k\Delta x_T + \Delta x_{m1} \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1}) \\ 0 & (k\Delta x_T + \Delta x_1 + \Delta x_{m1} \leq x \leq (k+1)\Delta x_T + \Delta x_{m1}) \end{cases} \quad (3)$$

$$i_L = \begin{cases} \frac{E_m}{|Z|} \sin(x-\phi) + \{i_1(0) - \frac{E_m}{|Z|} \sin(k\Delta x_T - \phi)\} \cdot \epsilon^{-\frac{R}{L}(x-k\Delta x_T)/\omega} & (k\Delta x_T + \Delta x_{m1} \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1}) \\ i_2(0) \cdot \epsilon^{-\frac{R}{L}(x-k\Delta x_T - \Delta x_1 - \Delta x_{m1})/\omega} & (k\Delta x_T + \Delta x_{m1} \leq x \leq (k+1)\Delta x_T + \Delta x_{m1}) \end{cases} \quad (4)$$

$k=\text{submode II}, \dots, m-2$ .

$$v_L = \begin{cases} E_m \sin x & (k\Delta x_T + \Delta x_{m1} \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1}) \\ 0 & (k\Delta x_T + \Delta x_1 + \Delta x_{m1} \leq x \leq (k+1)\Delta x_T) \end{cases} \quad (5)$$

$$i_L = \begin{cases} \frac{E_m}{|Z|} \sin(x-\phi) + \{i_1(0) - \frac{E_m}{|Z|} \sin(k\Delta x_T - \phi)\} \cdot \varepsilon^{-\frac{R}{L}(x-k\Delta x_T)/\omega} & (k\Delta x_T + \Delta x_{m1} \leq x \leq k\Delta x_T + \Delta x_1 + \Delta x_{m1}) \\ i_2(0) \cdot \varepsilon^{-\frac{R}{L}(x-k\Delta x_T - \Delta x_1 - \Delta x_{m1})/\omega} & (k\Delta x_T + \Delta x_1 + \Delta x_{m1} \leq x \leq (k+1)\Delta x_T) \end{cases} \quad (6)$$

$$k=m-1$$

Where,  $E_m = \sqrt{2}E$ ,  $|Z| = \sqrt{R^2 + \omega^2 L^2}$ ,  $\phi = \tan^{-1} \frac{\omega L}{R}$ .

Fig.8 shows the waveforms of load current measured and calculated. The deviations of RMS load voltage between the calculated and the measured are about 3 per cent when  $f_c = 3\text{kHz}$  and about 10 per cent when  $f_c = 10\text{kHz}$ . These deviations are mainly due to the switching loss of transistors and diodes, so they will become larger in proportion as the chopping frequency is higher.

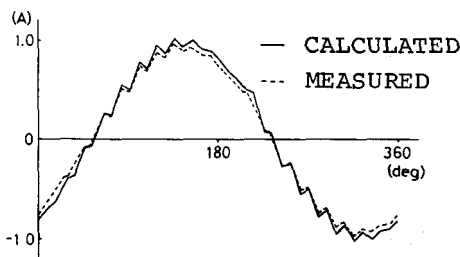


Fig.8. Load current waveforms measured and calculated,  
 $E=100\text{V}$ ,  $f_c=1200\text{Hz}$ ,  
 $R=44.3\Omega$ ,  $L=179\text{mH}$ .

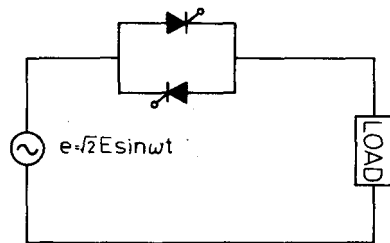


Fig.9. Thyristor phase control circuit.



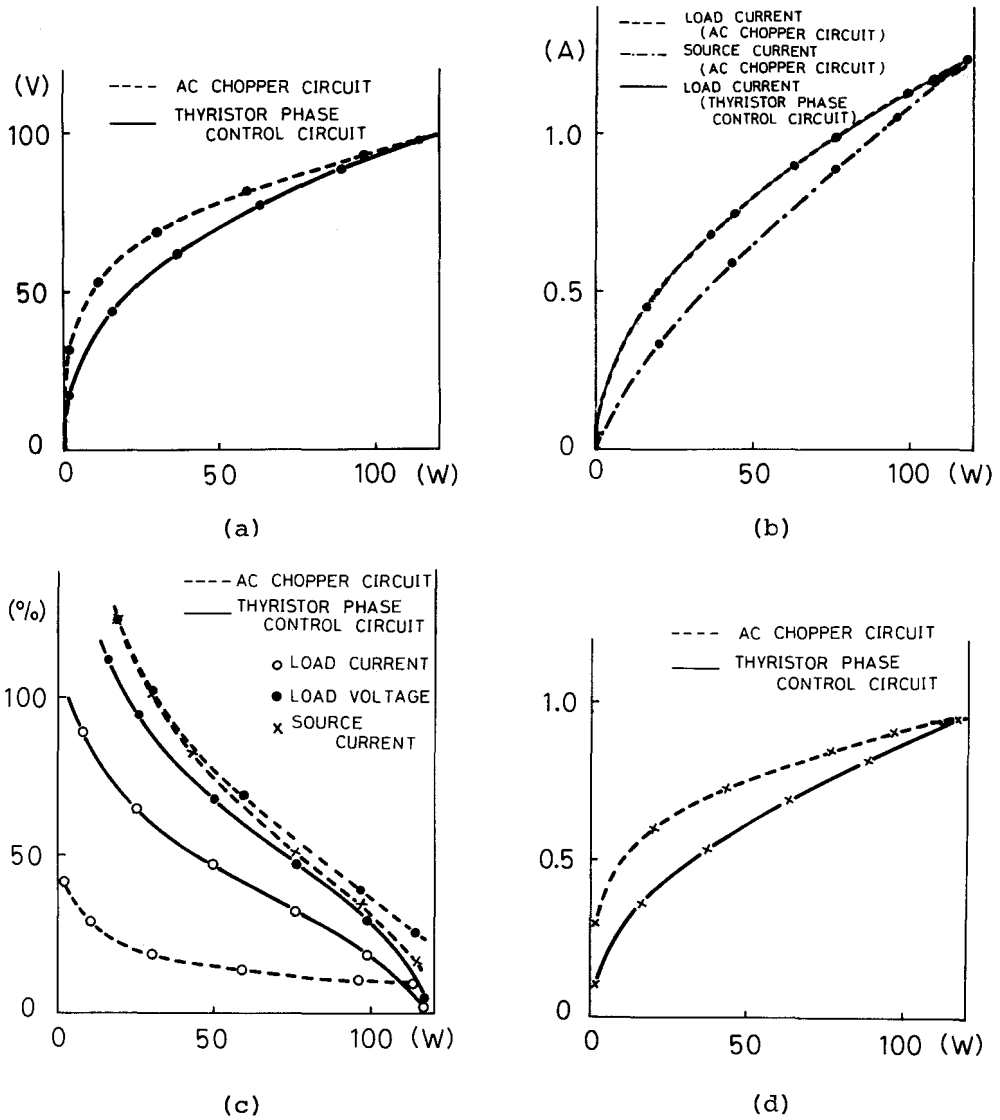


Fig.10. Characteristics of ac chopper circuit and thyristor phase control circuit.

- (a) RMS load voltage.
- (b) RMS load current.
- (c) Distortion factor.
- (d) Input power factor.

### 3.2 Characteristics of Circuit

From the results by the preceding calculation method, the characteristics of this ac chopper circuit are evaluated. Then the characteristics of this model are compared with those of the thyristor phase control circuit shown in Fig.9.

Fig.10 shows the comparisons of the characteristics between this ac chopper circuit and the thyristor phase control circuit. Where  $E=100V$ ,  $R=77\Omega$ ,  $L=63mH$  and  $f_c=1200Hz$ . Hence, it is found that:

- (1) The distortion factor of load current in this model is less than that in the thyristor phase control circuit. From the oscillogram in Fig.11 the distortion factor of load current in this model is very little in a high-frequency chopping mode.
- (2) The distortion factor of source current in this model is very large. However the lower components of high harmonics don't appear.

Then, the ripples of source current can be easily filtered. Fig.12 shows the oscillograms of source current

with and without the line filter.

- (3) As shown in Fig.10(b), RMS load current is larger than RMS source current in the ac chopper circuit. Hence the input power factor in this model is larger than that in the thyristor phase

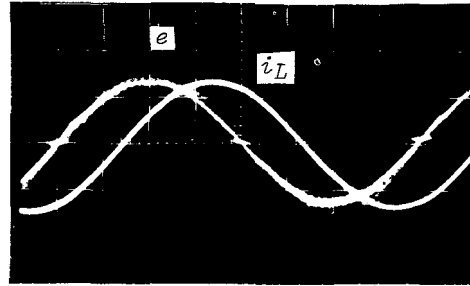
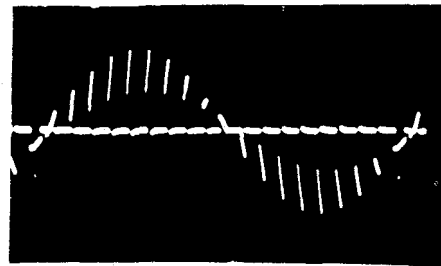
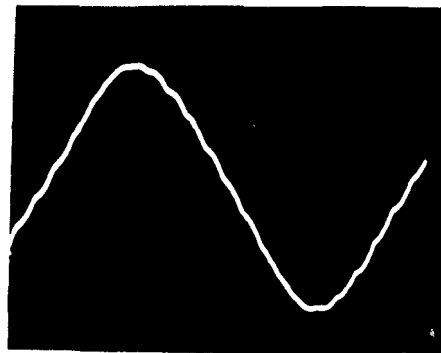


Fig.11. Load current waveform,  $f_c=10kHz$ .



(a)



(b)

Fig.12. Source current waveforms with and without filter,  $E=100V$ ,  $f_c=1000Hz$ ,  $R=49.3\Omega$ ,  $L=37mH$ , time base:2ms/div.

- (a) Source current waveforms without filter, 500mA/div.
- (b) Source current waveforms with filter, 100mA/div.

control circuit.

#### 4. Conclusion

The construction and the driving method of the ac chopper circuit using power transistors are described.

This circuit makes features of chopping an ac voltage in a complete cycle for any lagging reactive load. On the strength of transistor's operation in a high-frequency chopping mode the ripples of the load current is little, and also those of the source current can be easily filtered. Then, the characteristics of this circuit are compared with those of the thyristor phase control circuit. It is found that the distortion factor and the input power factor are improved.

#### Nomenclature

$E_m$	Peak amplitude of ac source voltage.
$\phi$	Angle of displacement between current and voltage.
$R$	Resistance.
$L$	Inductance.
$f_c$	Chopping frequency.
$\tau$	Time ratio.
$v_L$	Instantaneous value of load voltage.
$i_L$	Instantaneous value of load current.
$i_1(0), i_2(0)$	Initial value of load current.
$\Delta x_T$	Chopping period.
$\Delta x_1$	Period in which transistor $T_{r1}$ is closed.
$\Delta x_{m1}$	Period from the time transistor $T_{r2}$ turns off until the time transistor $T_{r1}$ turns on.
$\Delta x_{m2}$	Period from the time transistor $T_{r1}$ turns on until the time transistor $T_{r2}$ turns off.

#### References

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