New magnetic frequency tripler with delta connection suited for high power unit

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NEW MAGNETIC FREQUENCY TRIPLER WITH DELTA CONNECTION SUITED FOR HIGH POWER UNIT

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ABSTRACT

A magnetic frequency tripler having a new configuration is proposed. The tripler is composed of three series-connected reactor circuits connected in delta. Because a triple frequency current circulates in delta-connection and does not flow into the input line, the input current has very little distortion. Therefore, the tripler is very suited for a high power unit.

This paper presents the analyses of the delta circuit as a basic circuit to clarify the characteristics of the tripler. Moreover, the relations between characteristics and circuit constants were examined. The results may be used as a basis for design.

INTRODUCTION

Magnetic frequency tripler using saturable reactors has practical application as a static triple frequency source. The characteristics and analyses have been reported often.[1~3]

The new frequency tripler proposed by the authors is composed of three series-connected reactor circuits.[2,3] The primary windings are connected in delta and the secondary in open-delta. Therefore, compared to a conventional tripler, the new tripler has a different configuration. The delta connection prevents the third harmonic from flowing into a three-phase source both on no load and on load. Moreover, in order to obtain a constant output voltage. a parallel ferro-resonance circuit is connected with the secondary windings of the delta connection.

The paper presents elementary analyses of the new tripler with a new configuration and other unique features.

NEW MAGNETIC FREQUENCY TRIPLER

The new magnetic frequency tripler is shown in Fig.1. The main circuit of the tripler is composed of three series-connected reactor circuits which consist of saturable and linear reactors. The detailed connection is shown in Fig.1.

A parallel ferro-resonance circuit is connected with terminals of the open-delta circuit to obtain a constant triple frequency voltage. In practice, the fundamental frequency voltage is induced across terminals of the open-delta circuit because of the unbalanced reactors in each phase. In order to filter the fundamental frequency component, the saturable reactor L_0 has an air-gaped core. Therefore, the circuit operates as a resonance circuit for triple frequency voltage.

The circuit (C_{in}, L_{in}) is connected on the input side of the delta circuit to improve the power factor of the input current and not to filter harmonic current from the input line.

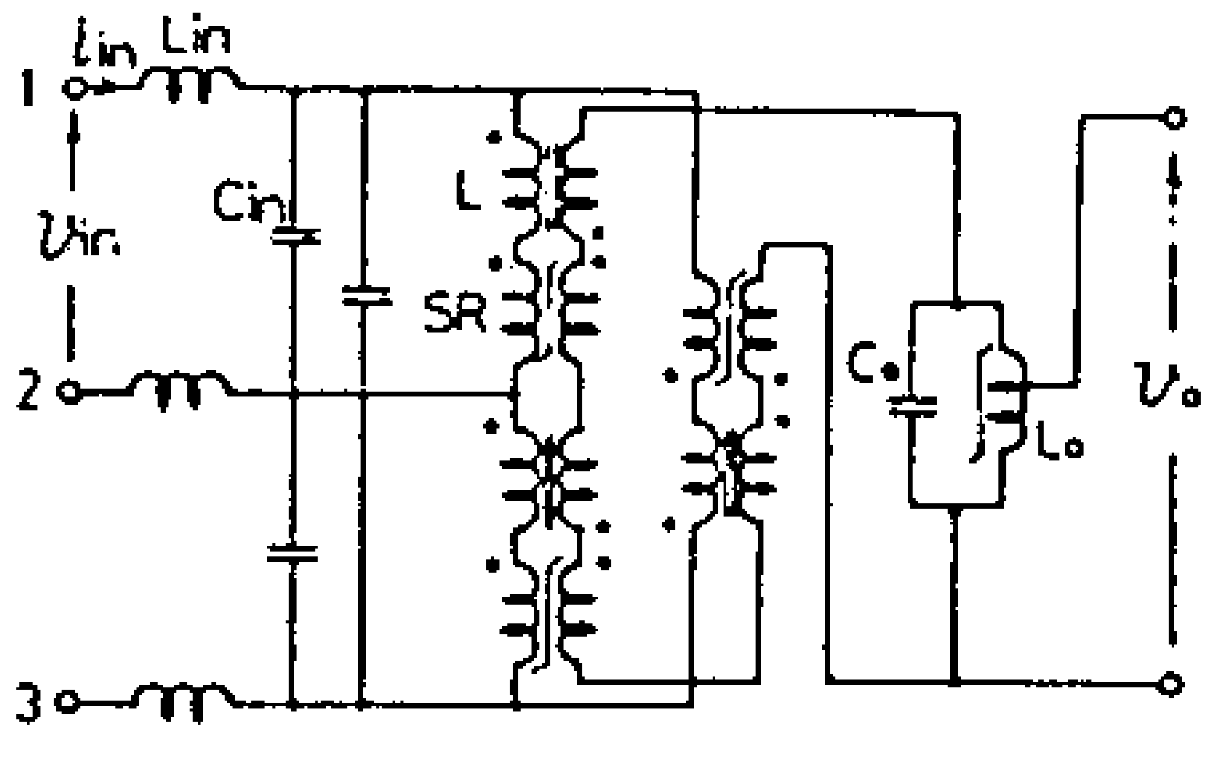

Fig.1 The new magnetic frequency tripler

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The tripler operates with low input current distortion. Moreover, linear and saturable reactors are connected in series in each phase. As the saturable reactor saturates completely, an input current increases proportionally to the impedance of linear reactor and does not abruptly vary with fluctuations of the input voltage. Therefore, it is easy to improve the power factor.

ANALYSES OF BASIC CIRCUIT

The basic circuit of the tripler is the delta circuit shown in Fig.2. In order to analyze the operation of the basic circuit, various characteristics on open-circuit and short-circuit conditions (a-b terminals) are examined.

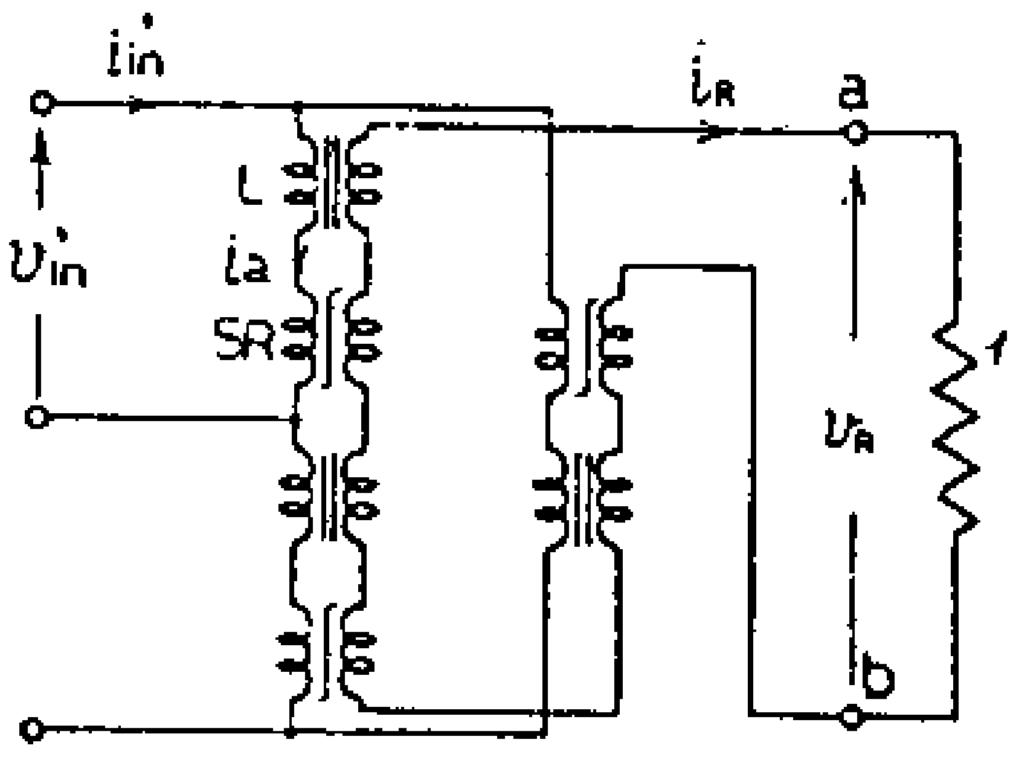


Fig.2 The basic circuit of the tripler

(a) Characteristics on open-circuit condition

The output voltage E_0 of the basic circuit on open-circuit condition is considered to be the sum of output voltages on the three series circuits. The linear reactor L and the saturable reactor SR in each phase have the idealized magnetization curve as shown in Fig.3. The output voltage at the secondary windings of the series circuit is shown in Fig.4. The saturable reactor enters saturation two times per cycle. The phase angle θ_s is given by the expression,

$$\theta_s = \cos^{-1}(\omega \lambda_k / V) \,, \qquad \ldots.(1)$$

where λ_k is saturation flux linkage.

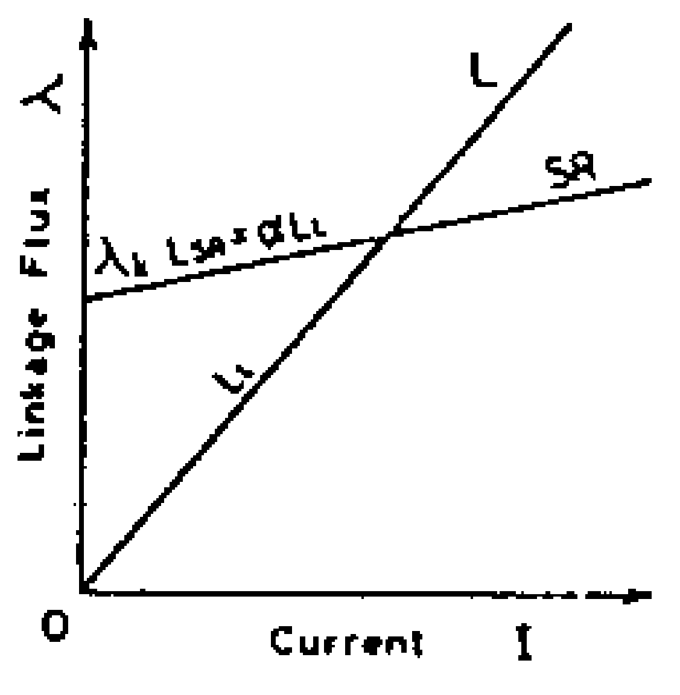


Fig.3 Magnetization curve

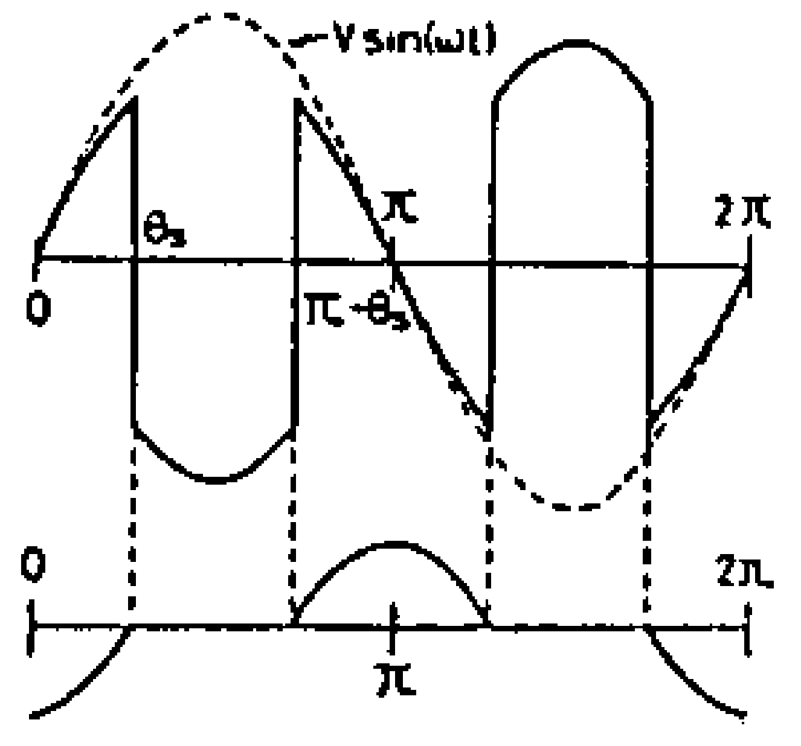


Fig.4 Waveforms on series-connected reactor circuit

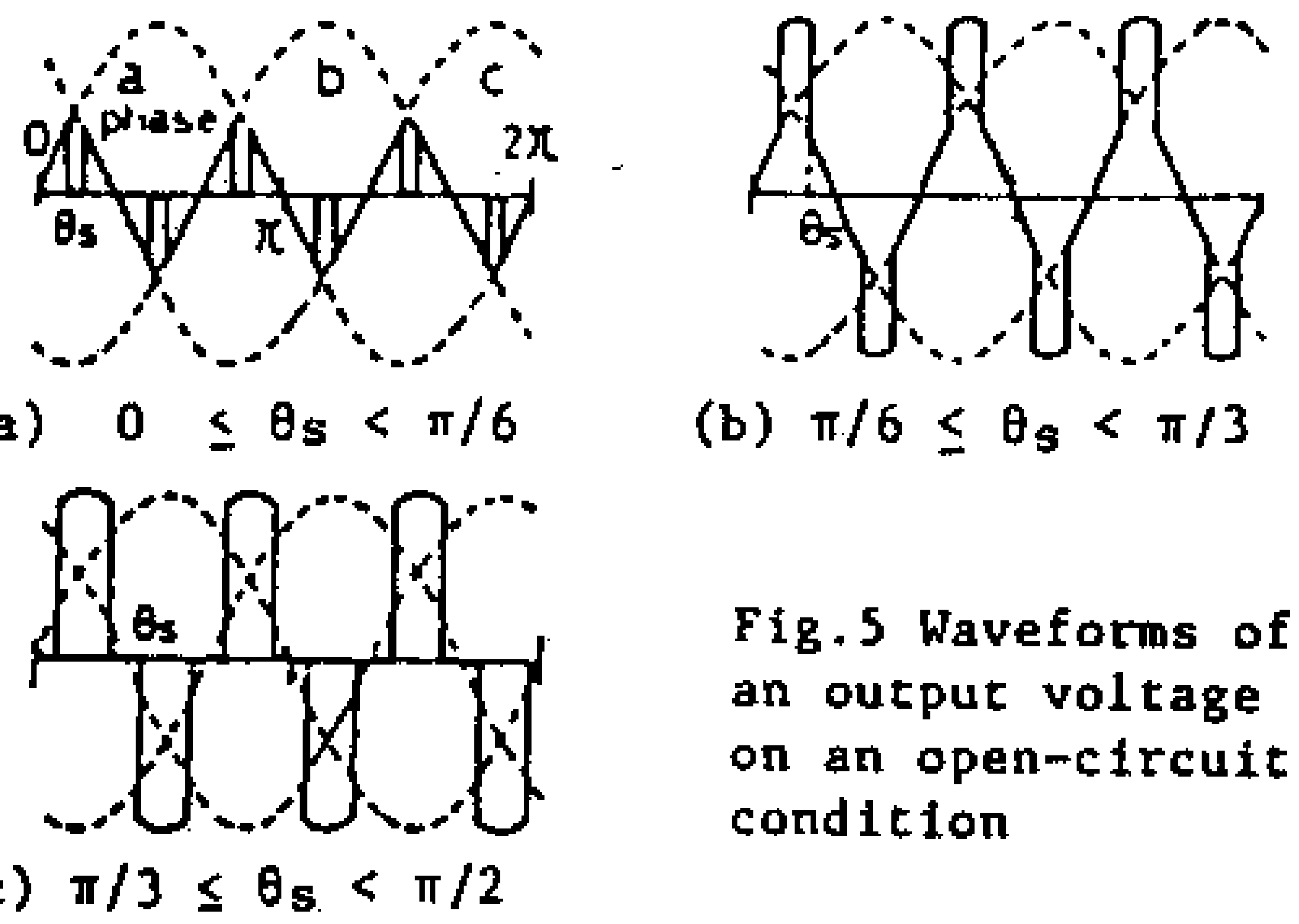
The waveform at the terminal of the open-delta circuit is the sum of the waveforms shown in Fig.4. As the supplied voltage increases, the waveform of the output voltage changes as shown in Fig.5. Figures 6(a) and (b) show the analyses of the waveform of a function of the ratio α, where

$$\alpha = \frac{\text{saturated inductance of SR}}{\text{inductance of linear reactor L}} = \frac{L_{sr}}{L_L} \,. \qquad \ldots..(2)$$

Expressed as a Fourier series, an output voltage mostly consists of the triple frequency component.

(b) Characteristics on a short-circuit condition

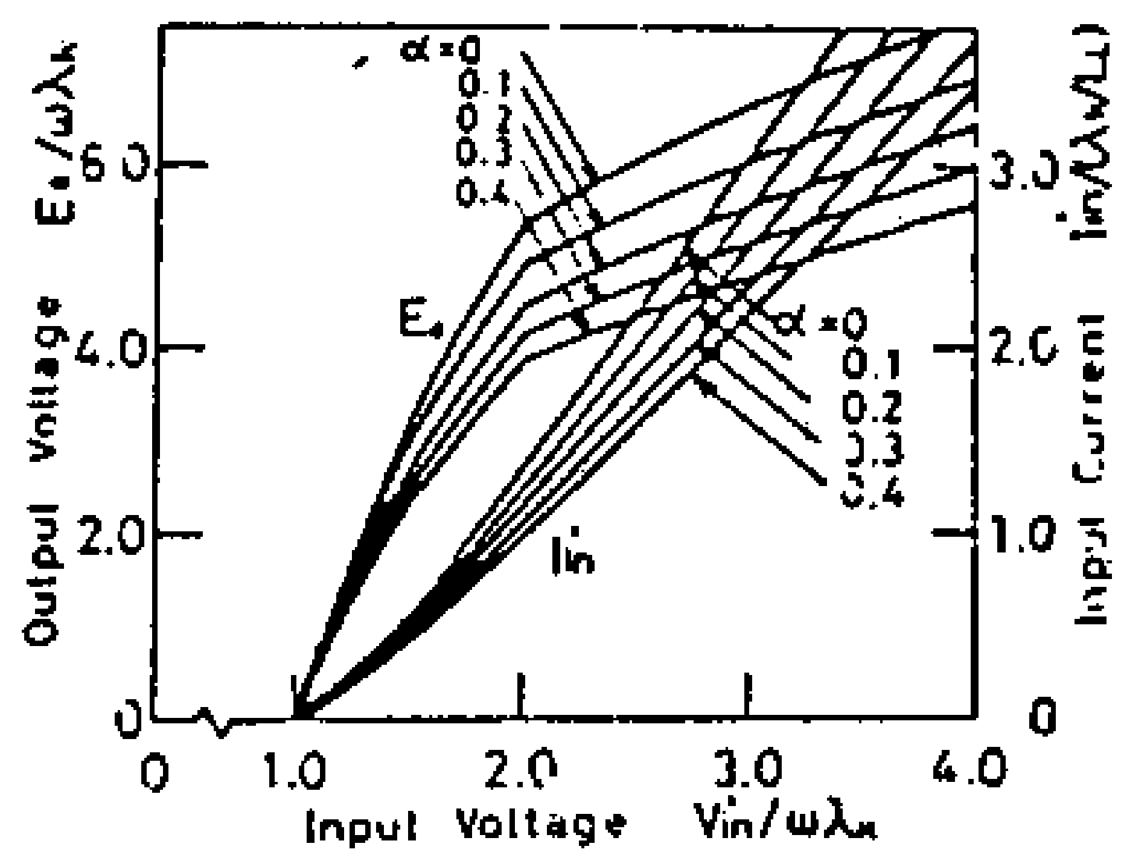
As the terminals a-b are shorted, the expression of



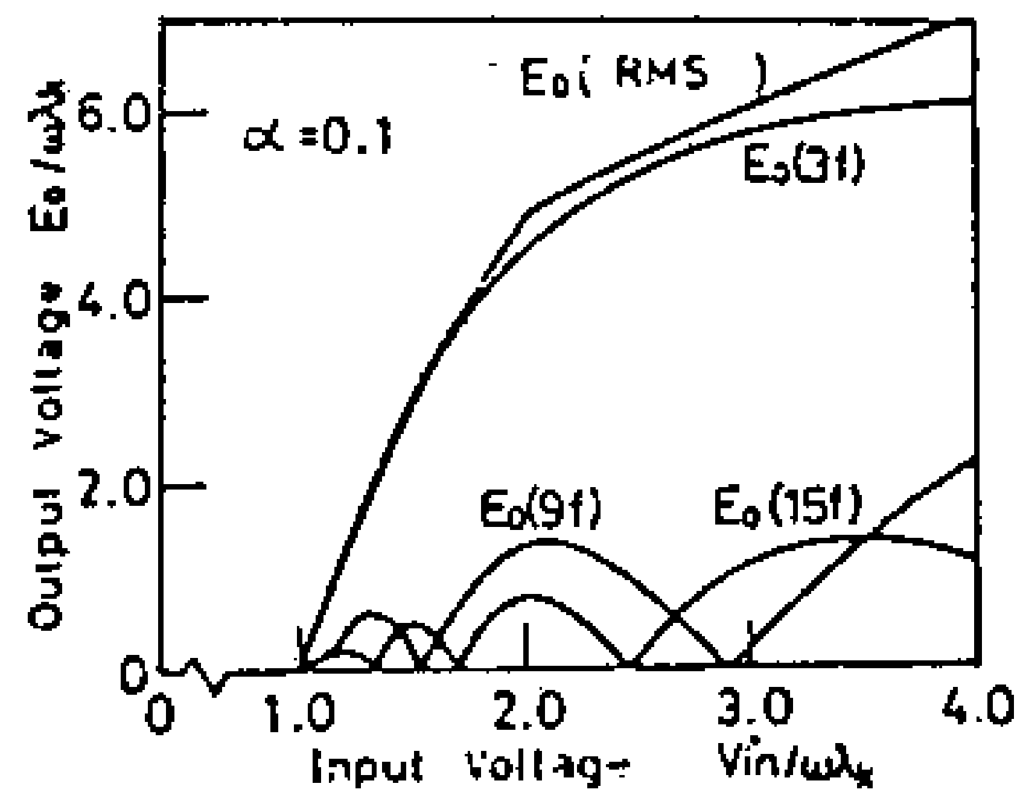
(a) $0 \le \theta_s < \pi/6$ (b) $\pi/6 \le \theta_s < \pi/3$

(c) $\pi/3 \le \theta_s < \pi/2$

Fig.5 Waveforms of an output voltage on an open-circuit condition



(a) Characteistics (rms)



(b) Components of E_0 for each frequency

Fig.6 Characteristics on an open-circuit condition

a short-circuit current is divided into two equations according to the interval of saturation of each saturable reactor. When a saturable reactor in only one phase, for example a-phase, is saturated, the phase currents and the short current i_s are given by the expressions,

$$i_s = -i_b = -i_c = i_a / 5 \quad \cdots\cdots(3)$$

$$\frac{d\,i_a}{d\,t} = \frac{5\,v_a}{4\,(1 + 3/2\,\alpha)L_L} \quad \cdots\cdots(4)$$

As the supplied voltage increases, saturable reactors in two phases are saturated simultaneously. Phase currents are given by the expressions,

$$i_s = -i_b \quad \cdots\cdots(5)$$

$$i_a + i_b + i_c = 3 i_s \quad \cdots\cdots(6)$$

$$\frac{d\,i_b}{d\,t} = \frac{v_b}{2(1+3\alpha)L_L} \quad \cdots\cdots(7)$$

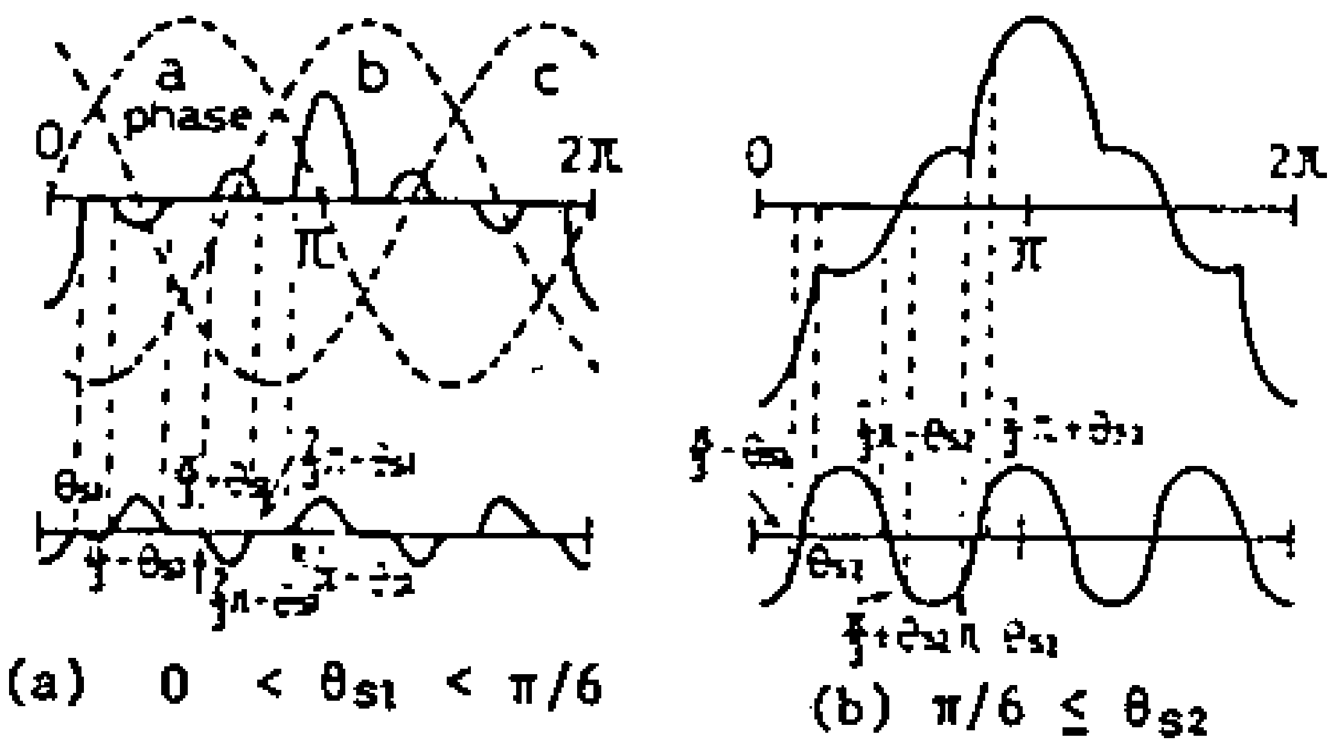
$$\frac{d\,i_a}{d\,t} = \frac{v_a}{(1+\alpha)L_L} + \frac{(\alpha - 1)v_b}{2(1+\alpha)(1+3\alpha)L_L} \quad \cdots\cdots(8)$$

when saturable reactors in a- and b-phase becomes saturated. The waveforms of a short-circuit current are shown in Fig.7. Phase angles θ_{s1} and θ_{s2} shown in Fig.7 are given by the expressions,

$$\theta_{s1} = \cos^{-1}(\omega\lambda_k / V) \quad \cdots\cdots(9)$$

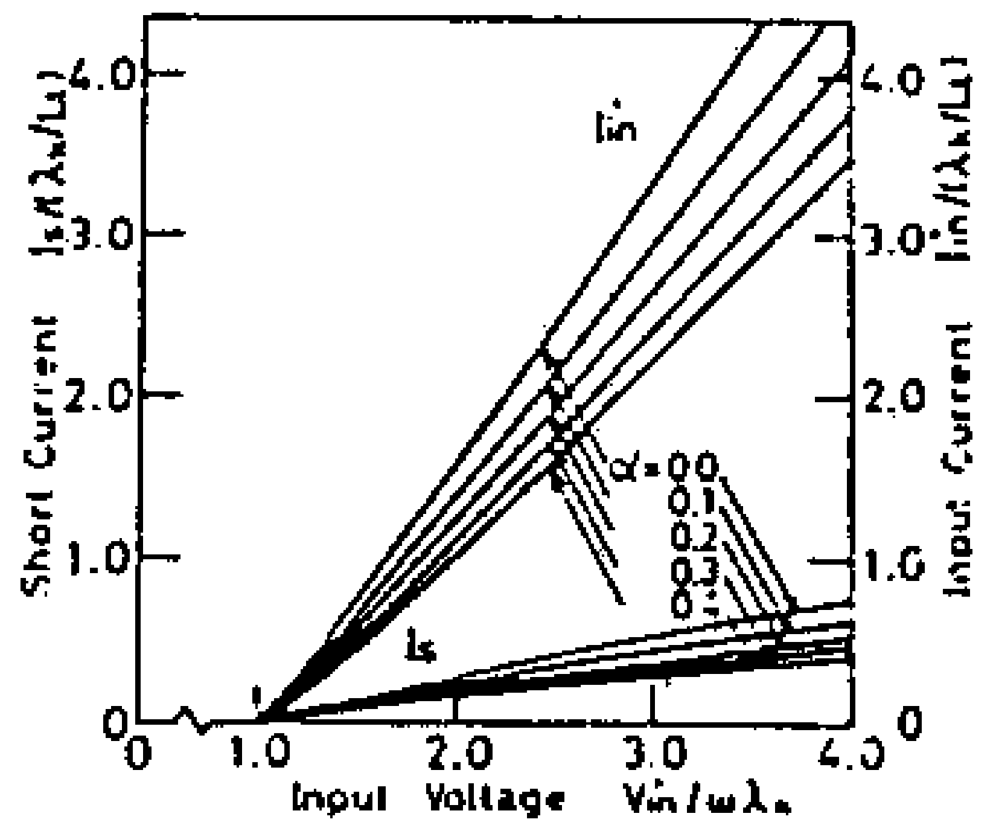
$$\frac{\omega\lambda k}{V} = -\sqrt{3}\,\sin(\theta_{s2}-\pi/3) - \frac{3\alpha}{1+3\alpha}\cos(\theta_{s2}+\pi/3) \cdots\cdots(10)$$

Figure 8 shows the calculated values of an input current and a short current. The compnents of a short current are plotted in Fig.8(b). The short current mostly consists of the third harmonic component.

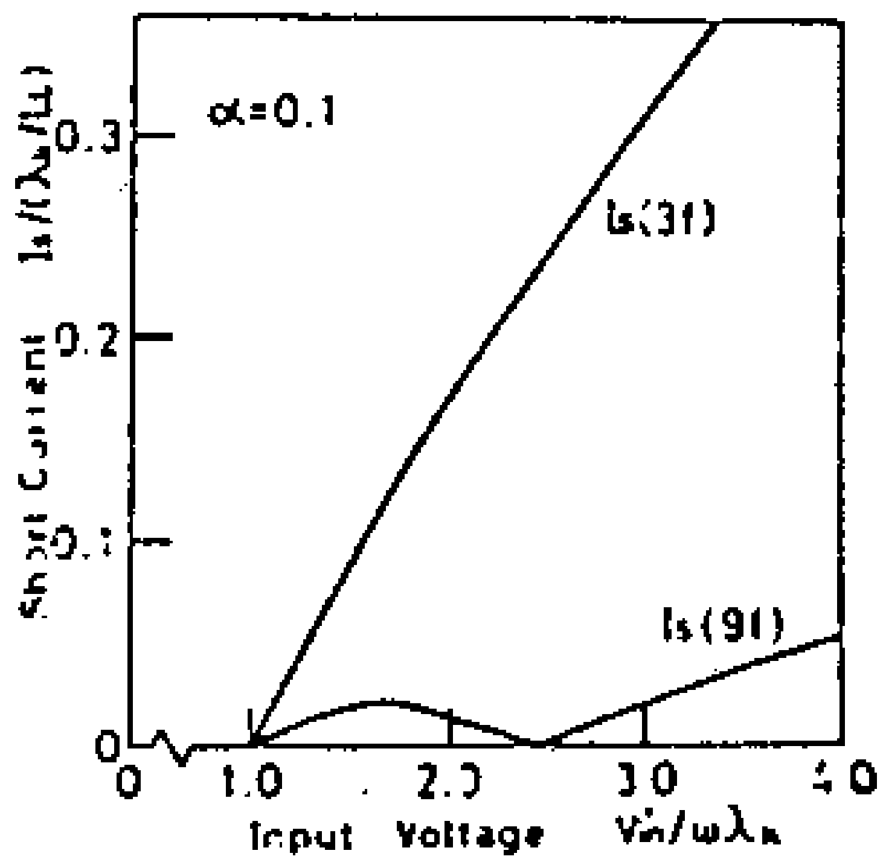


(a) $0 < \theta_{s1} < \pi/6$ (b) $\pi/6 \le \theta_{s2}$

Fig.7 Waveforms of currents on a short-circuit condition (upper : a-phase current i_a , lower : i_s)



(a) Characteristics (rms)



(b) Components of I_s for each frequency

Fig.8 Characteristics on a short-circuit condition

(c) The equivalent circuit

The equivalent circuit is useful for examining the operation of the tripler. The equivalent circuit shown in Fig.9 is similar to that in reference [1]. The value of the equivalent reactance X_{3f} is taken as the value E_0/I_s. The results are plotted in Fig.10. It is noted

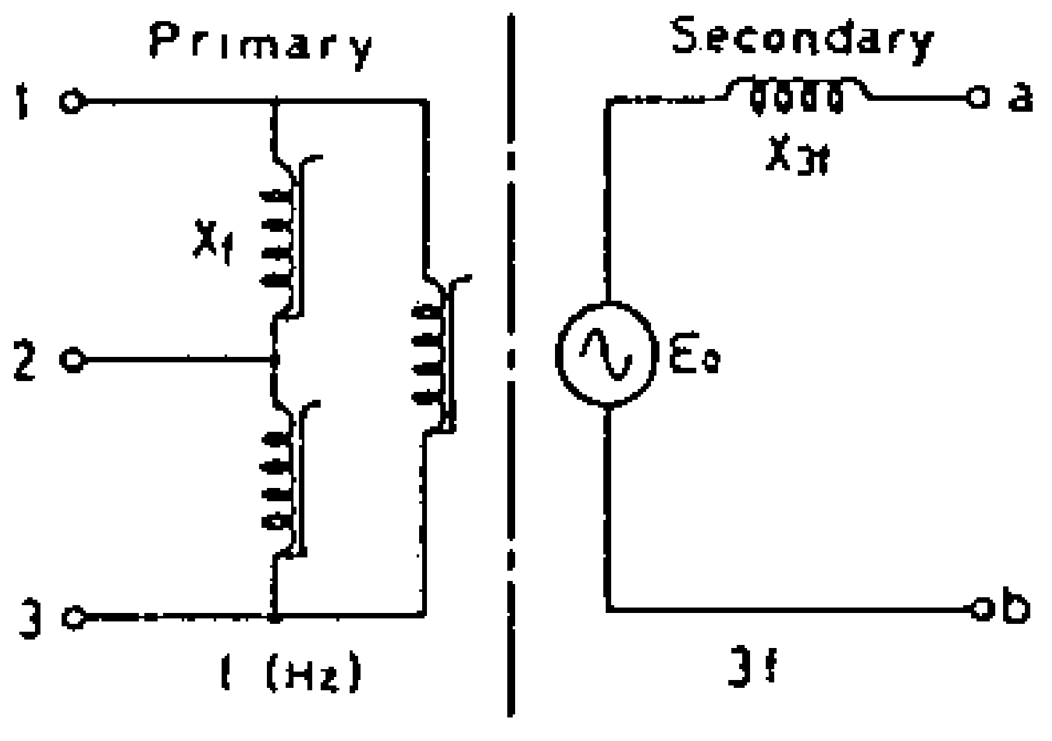


Fig.9 The equivalent circuit

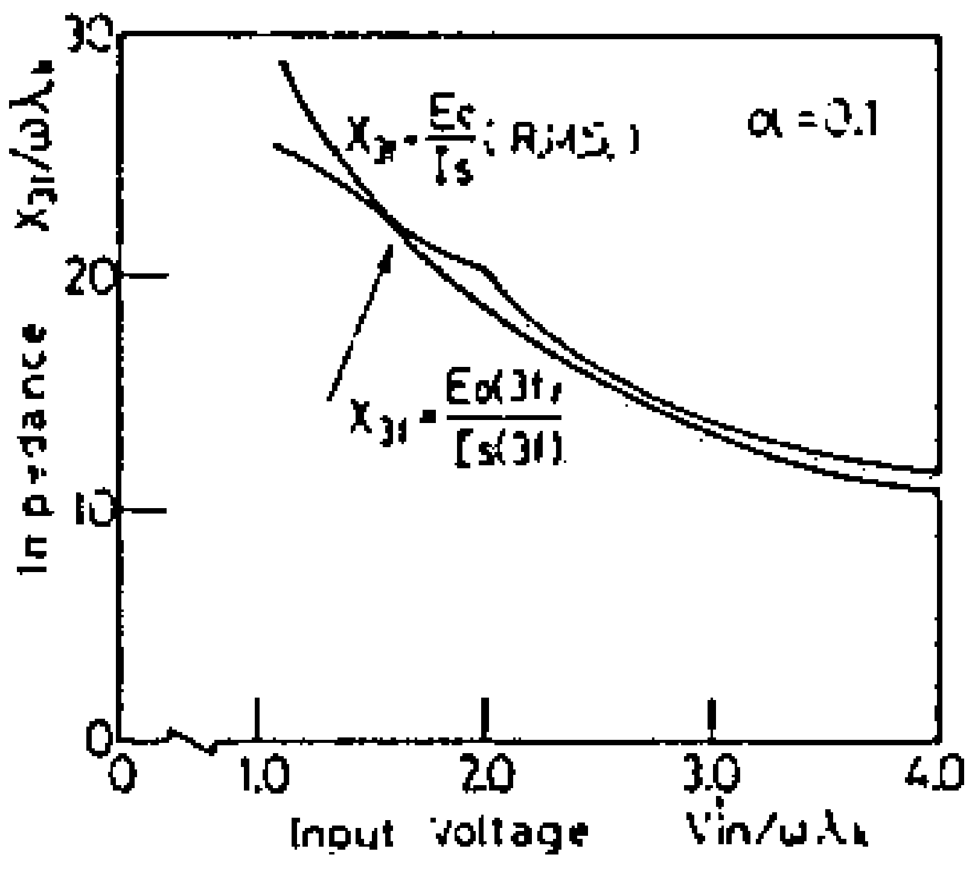


Fig.10 Equivalent reactance X_{3f}

that the value X3f obtained from the third harmonic components is approximately the same as obtained from the rms values.

EXAMINATION OF OPERATION ON THE TRIPLER

(a) The ferro-resonance circuit

The tripler has the ferro-resonance circuit on an output side. The relation between the resonance voltage and the output voltage E_o on an open-circuit condition is important to obtain the maximum output power. Figure 11 shows the experimental load characteristics for various resonance voltage values. The broken line in the figure indicates the value of the power which in the product of E_o and I_s. When the resonance voltage is low, a load current indicates the drooping characteristics near the value of a short-circuit current. As the resonance voltage is high, the constant voltage characteristics can not be obtained. It is desirable to choose the output voltage E_o on open-circuit condition as a resonance voltage. Therefore, the maximum output power is the product of E_o and I_s.

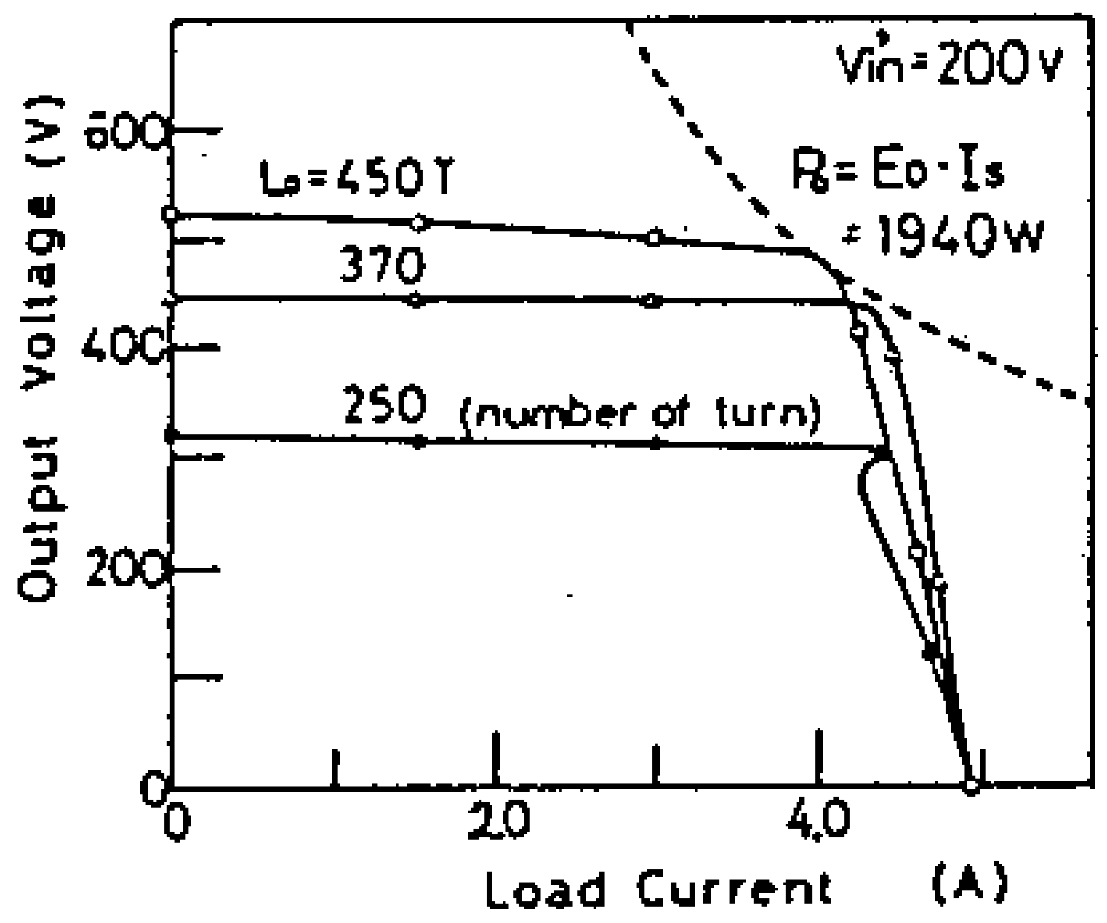


Fig.11 Load characteristics for various resonance voltage, which is proportional to the number of turns on the ferro-resonant reactor Lo

(b) Relation between the input voltage and the saturation voltage of SR

Both the open-circuit voltage E_o and the short-circuit current I_s vary directly with the input voltage. But the input power $V_{in}' \cdot I_{in}'$(VA) also increases. As the total rated capacity of SR and L is proportional to input power, it is desirable that the ratio of the maximum output power to an input power reaches the maximum value. The ratio k is given by the expression,

$$k = \frac{Po\ (W)}{Pin'(VA)} = \frac{Eo \cdot Is}{\sqrt{3}\ Vin' \cdot Iin'}$$

$$= \frac{(Eo/\omega\lambda_k) \cdot \{Is/(\lambda_k/L_L)\}}{\sqrt{3}(Vin'/\omega\lambda_k)\{Iin'/(\lambda_k/L_L)\}} \quad \cdots\cdots(11)$$

where P_o is the maximum output active power and P_{in}' the input power(VA).

The substitution of values from Figs.6 and 8 into (11) results in Fig.12. For example, the maximum ratio is about 24 percent when α is 0.1. It is at $V_{in}'/\omega\lambda_k = 2.0$ that the ratio indicates the maximum value. As a result, it is desired that the knee point flux λ_k is determined to be $\omega\lambda_k = V_{in}'/2$.

CHARACTERISTICS ON THE FREQUENCY TRIPLER

The authors have designed and tested a tripler having 24 KW active output power on a basis of the elementary analyses. The experimental results are shown in Fig.13. The circuit constants on the device are below,

$\omega L_L = 0.56\ \Omega$, $\omega\lambda_k = 106$ V, $\alpha = 0.08$,
resonance voltage = 560 V.

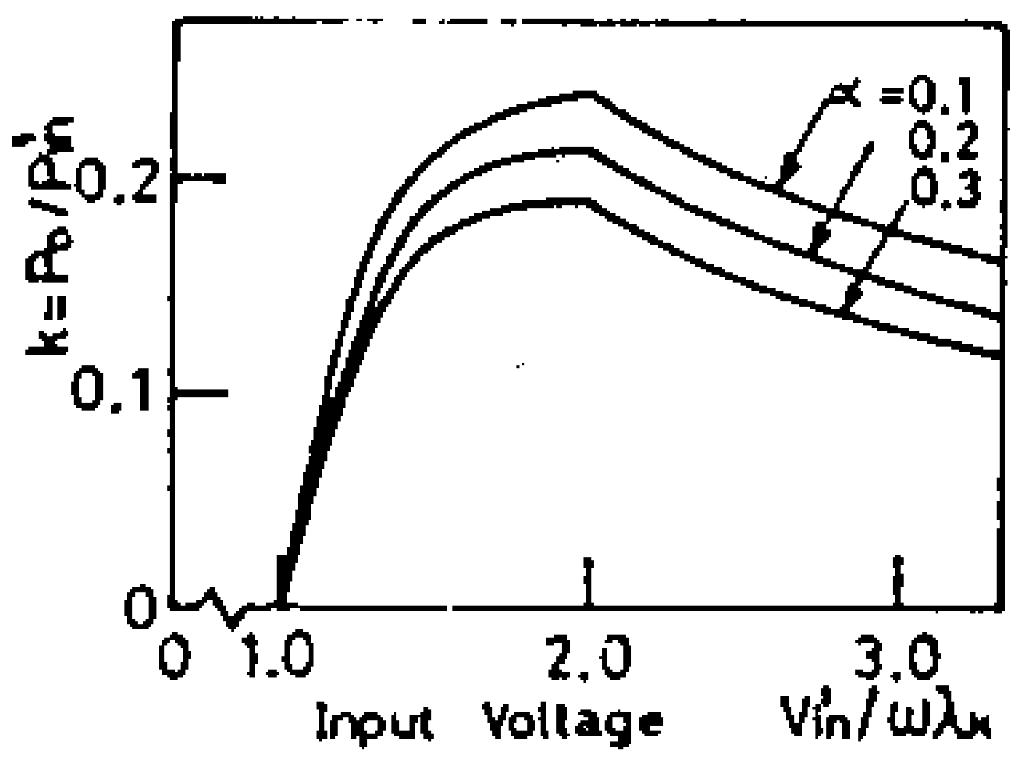
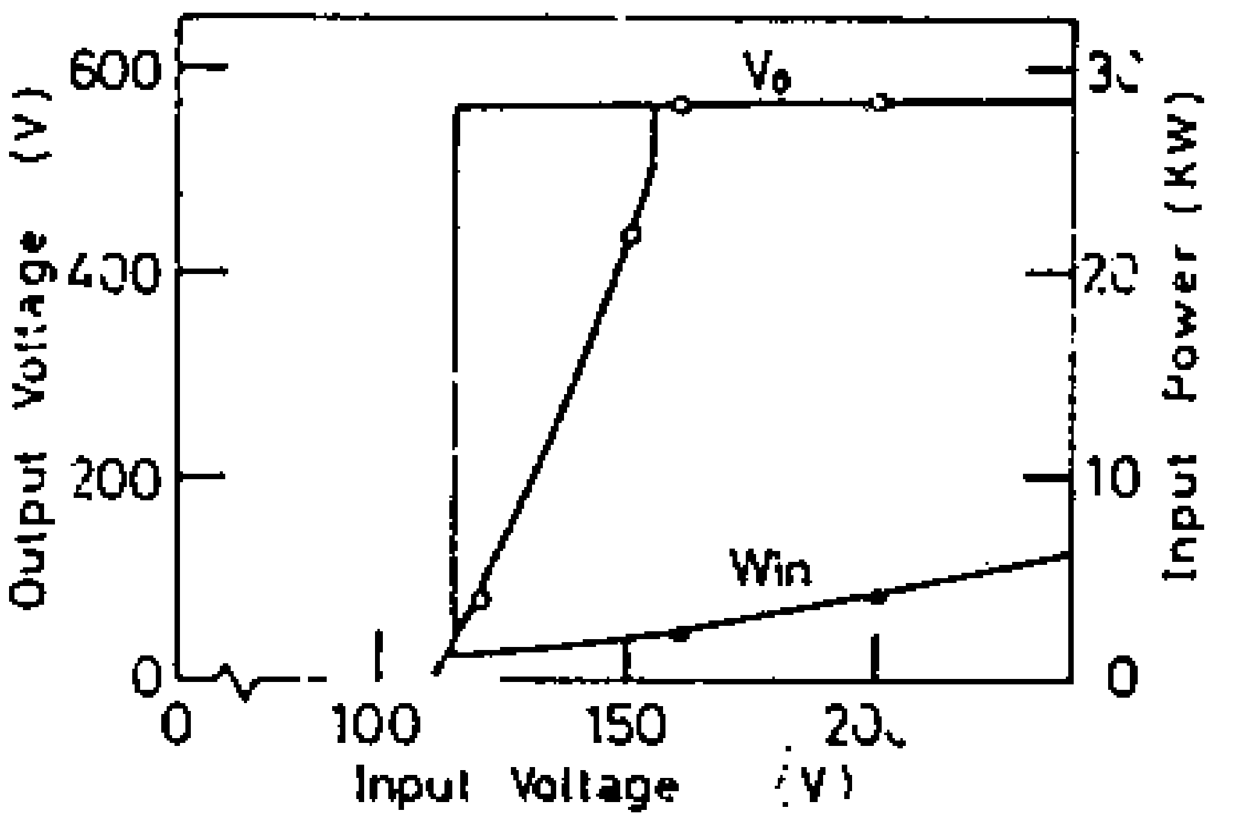
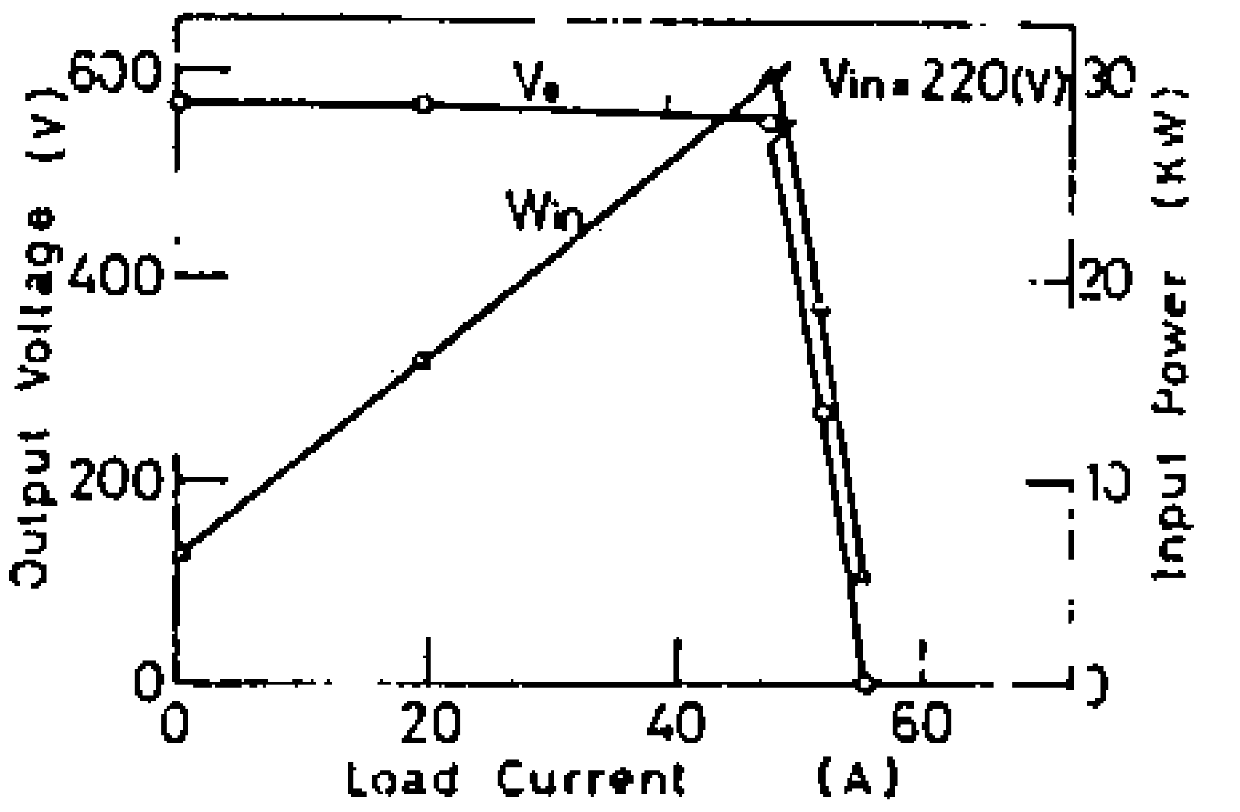


Fig.12 Ratio of maximum output power to input power



(a) Voltage characteristics



(b) Load characteristics

Fig.13 Characteristics of the new frequency tripler

The results show that regulating and drooping characteristics are obtained. In the experiment the maximum efficiency was 78 percent. The operation of the tripler was very stable both on no load and heavy load.

CONCLUSION

In this paper, a new frequency tripler with delta connection is proposed and detailed characteristics are clarified. The magnetic frequency tripler has wide application becauce it is simple in structure and reliable in operation. Moreover, in this tripler an input current does not have third harmonic distortion. Therefore, the device is suitable for a high power unit. We hope that the new tripler will be useful for the development of the magnetic frequency tripler.

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