

## ***Influence of Magnetic Saturation of Iron-Core on Performance of Thyristor Phase Control Circuit***

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### Synopsis

The influence of magnetic saturation of iron-core on the performance of thyristor phase control circuit with series *RLC* elements is described. The circuit is analyzed by applying an approximate model of three straight lines to the flux  $\Phi$  vs. current  $i$  curve of the iron-core reactor. And the influence on waveforms, r.m.s. values, power factor and response are discussed.

### 1. Introduction

The AC power control circuits of inverse parallel thyristor pair are widely available for the reasons of simplicity of circuit configuration and easy controllability, etc.<sup>1)2)</sup> In most case, the load has an iron-core reactor, which has non-linear characteristics such as hysteresis or magnetic saturation<sup>3)4)</sup>. So, the iron-core reactors are designed and/or used usually under the condition of no-influence by the non-linear characteristics at a given supply voltage. However, when the thyristor phase control circuit has series *RLC* elements, it may cause an abnormal phenomenon such as extraordinarily high voltage and heavy current<sup>5)</sup>. Furthermore, if there is an iron-core reactor in the above circuit and it's flux level comes up to saturation, the phenomenon is more complicatedly and inscrutable affected by the non-linear characteristics of an iron-core. Therefore, it is necessary to make clear this influences of non-linear characteristics, especially

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magnetic saturation, on the performance for the security of power system connected to the AC power control circuit and the selection of thyristor rate.

Thus, the authors analyze the circuit by applying an approximate model of three straight lines to the flux  $\Phi$  vs. current  $i$  curve of the iron-core reactor. And the influences on current and capacitor voltage waveforms, r.m.s. values of current and voltage, power factor and transient response are discussed in detail.

## 2. Analysis of Circuit Performance

### 2.1 Circuit and Assumption

The thyristor phase control circuit with an iron-core reactor which has a magnetic saturation is shown in Fig.1.

Now, we introduce the following assumptions into this analysis.

- (1) The thyristor is an ideal switching element and fired symmetrically in each half-cycle.
- (2) The source voltage waveform is sinusoidal, and its impedance is negligible.
- (3) The magnetization curve of reactor is approximated by the three straight lines as shown in Fig.2. In this figure,  $\phi_s$  is the flux when the reactance changes from  $L_1$  to  $L_2$ , and  $\phi_m$  is the maximum flux, in the circuit where the reactor of  $L(\phi)$  is replaced to a linear reactor with inductance  $L_1$  and the thyristors are shorted.

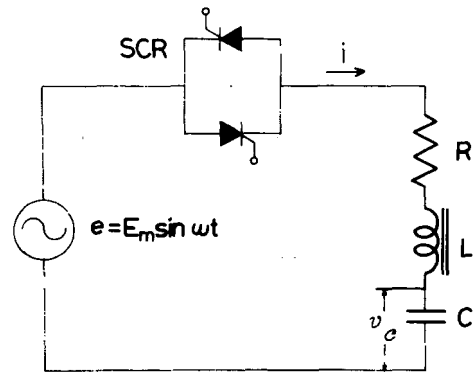


Fig.1. Phase control circuit with an iron-core reactor.

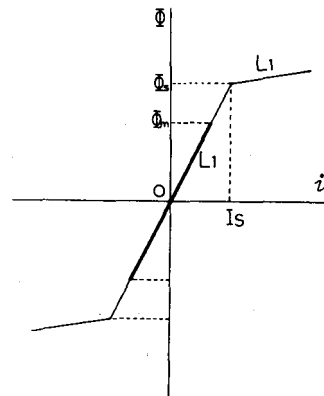


Fig.2. Approximate model of reactor magnetization.



e.g. waveforms, r.m.s. values and harmonics of current and voltage.

In the following analysis, both  $E$  and  $R$  are set to unity for normalization, and particularly the effects of parameters  $k$  and  $l$  on the circuit performance are discussed. Fig.3 shows the calculated waveforms.

### 3. Influences of Magnetic Saturation on Circuit Performance

#### 3.1 Influence on Current and voltage Waveforms

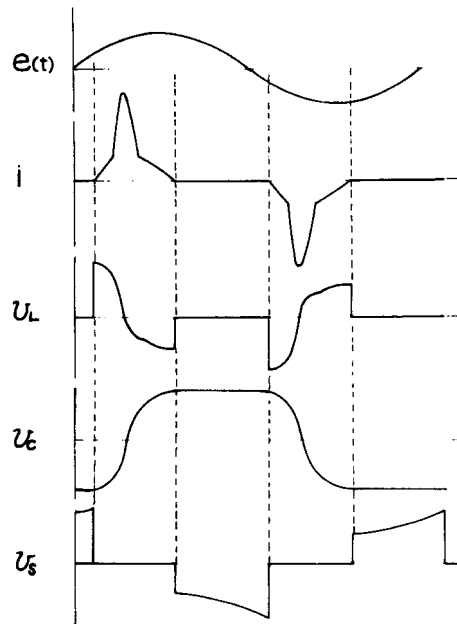
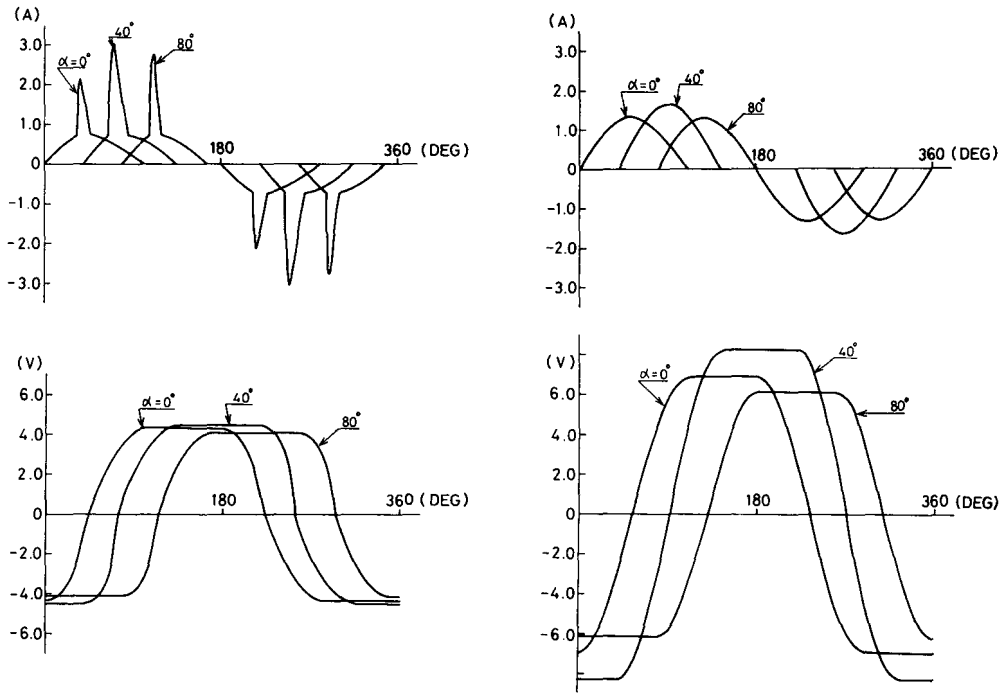


Fig.3. Waveforms.

The current and capacitor voltage waveforms in the thyristor phase control circuit shown in Fig.1 are illustrated in Fig.4(a). The waveforms with a load composed of linear elements are shown in Fig.4(b). Provided that the load has a saturable reactor, a cornu waveform of current flows. Namely, when the reactor operates in the saturation state, the current waveform becomes salient with a large peak, as shown in Fig.4(a). The waveform of capacitor voltage is also distorted more notably compared with that with a linear load.

Therefore, we clarify how the peak values of current and capacitor voltage are effected by the magnetic saturation. The variation of peak value of current is shown in Fig.5. As  $l$  is smaller, shown in this figure, the peak value of current becomes larger. For example, this value with  $l=0.01$  and  $\alpha=40^\circ$  is 12.7 times as large as one with thyristor shorted and about twice as large as one with a linear load. Namely, as  $k$  is larger, the period when the reactor operates in mode II becomes shorter, because the reactor can be regarded as a linear element and then a current waveform is not a salient one. On the other hand, as  $k$  is smaller, the period when operates in mode II becomes longer. Especially in case of  $k=0$ , the reactor can be regarded as a linear reactor of inductance  $L_2$ . Thus the peak value of current is dependent on the parameter  $l$ .

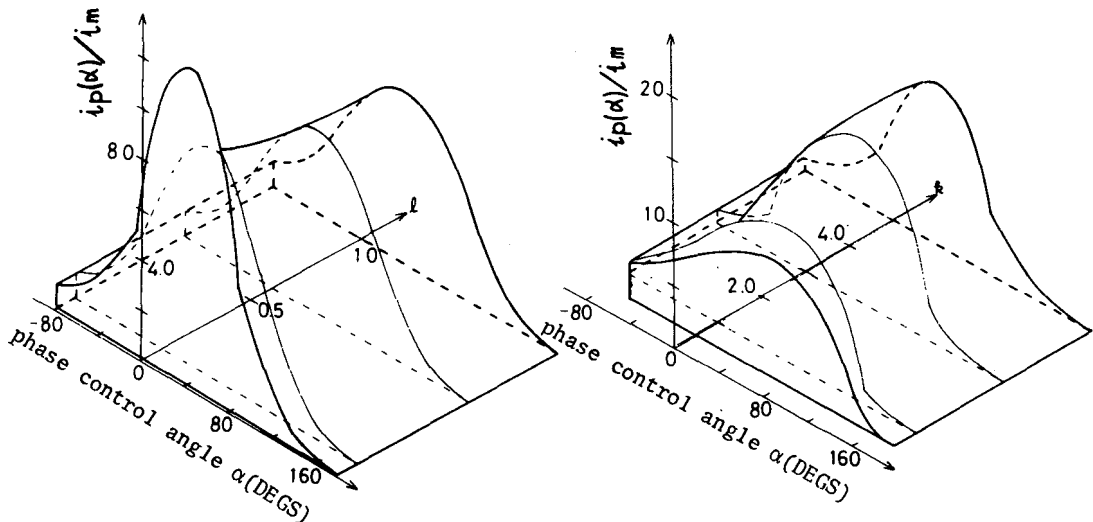
Next, the variation of peak value of capacitor voltage is shown in



(a) load with a saturable reactor  
 $(\phi_1 = -80^\circ, \delta_1 = 0.1, k = 5.0, l = 0.01)$ .

(b) linear load  
 $(\phi = -80^\circ, \delta = 0.1)$ .

Fig.4. Current and capacitor voltage waveforms.



(a)  $\phi_1 = -80^\circ, \delta_1 = 0.1, k = 5.0$ .

(b)  $\phi_1 = -80^\circ, \delta_1 = 0.1, l = 0.01$ .

Fig.5. Peak value of current.

Fig.6. As  $k$  and  $l$  are smaller, the ratio of the peak value of capacitor voltage with phase control to that with thyristor shorted becomes larger compared with that with a linear load. For example, the ratios are about 0.77 and 0.3 at  $k=5.0, l=0.01, \alpha=40^\circ$ , and  $k=1.0, l=0.01, \alpha=40^\circ$ , respectively.

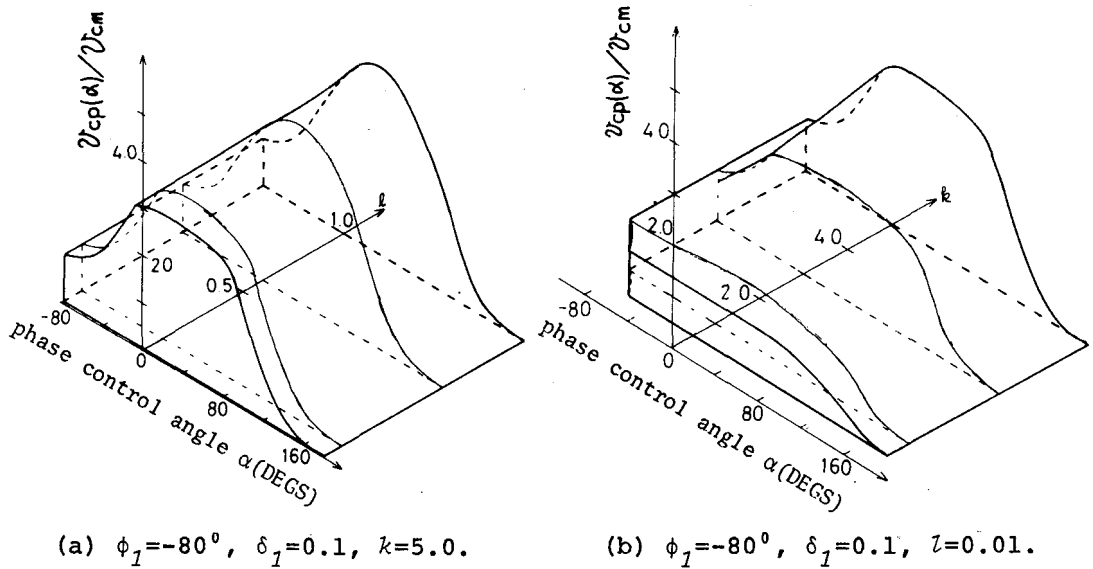


Fig.6. Peak value of capacitor voltage.

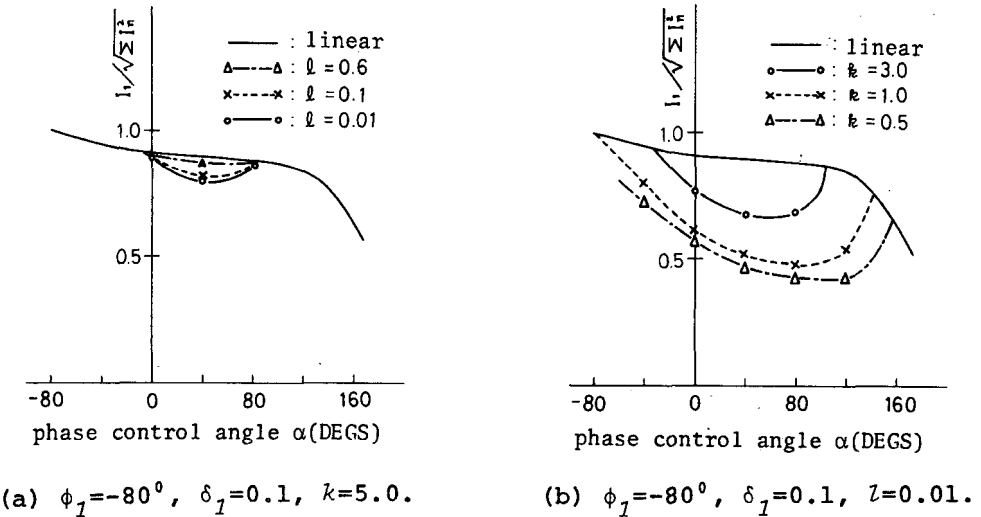


Fig.7.  $I_1 / \sqrt{LI_n^2}.$

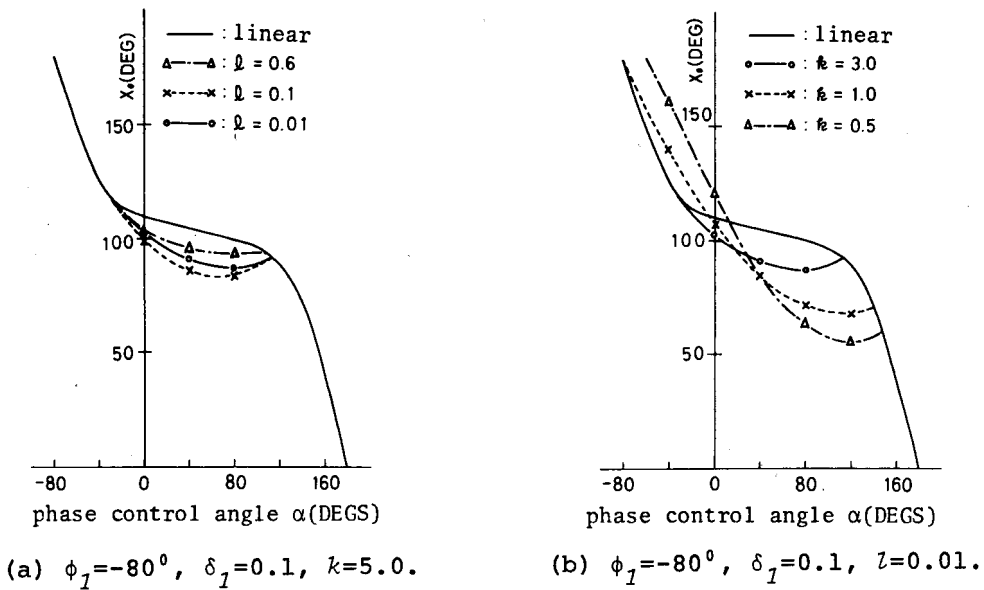


Fig.8. Conduction angle.

It is well known that the waveforms are distorted by a thyristor switching in thyristor phase control circuit. And also, as mentioned above, the current waveform is a more distorted and salient one with a non-linear load having a saturable reactor. Then, from the point aimed at clarifying these effects, the variation of  $I_1 / \sqrt{\sum I_n^2}$  ( $I_1$ : r.m.s. value of fundamental current,  $I_n$ : r.m.s. value of  $n$ th harmonic current) is shown in Fig.7. From this figure, the ratio of fundamental component to r.m.s. value of current with a linear load decreases as the phase control angle becomes lagger. But, provided that a load is composed of a saturable reactor, the ratio becomes very small as the reactor saturates. As  $k$  and  $l$  are smaller, the influence on them becomes remarkable. For example, the value of  $I_1 / \sqrt{\sum I_n^2}$  is 0.885 at  $\alpha = 40^\circ$  with a linear load, while it is 0.47 at  $k = 1.0$ ,  $l = 0.01$ , and  $\alpha = 40^\circ$  with a load composed of a saturable reactor.

Next, the variation of thyristor conduction angle vs. the phase control angle is shown in Fig.8. The conduction angle with a linear load decreases monotonously with an increase of phase control angle. On the other hand, it does not decrease monotonously with a non-linear load. In that case the conduction angle decreases till the phase control angle increases to a certain value and then increases till the phase control angle at which the curve agrees with that with a linear load.

### 3.2 Influence on Steady State Characteristics

The influence on r.m.s. values of current and capacitor voltage, fundamental power factor, and input power factor are investigated.

To begin with, the variation of r.m.s. value of current is shown in Fig.9. Further the variation of r.m.s. value of capacitor voltage is shown in Fig.10. Though the peak value of current becomes very

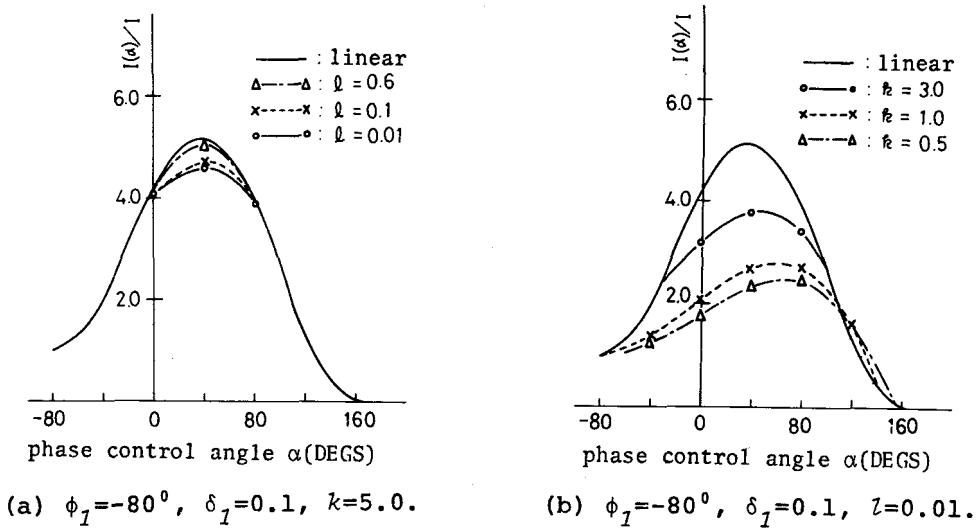


Fig.9. r.m.s. value of current.

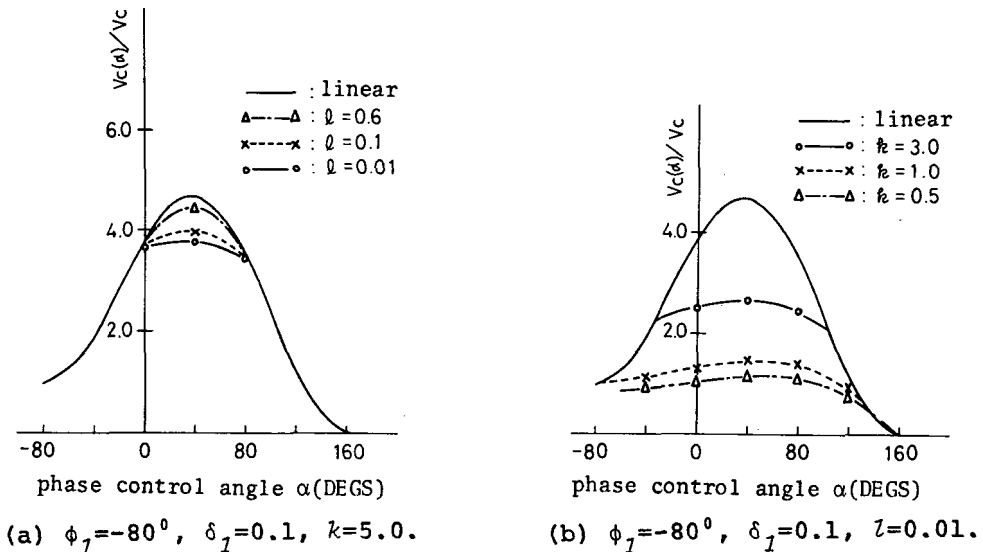


Fig.10. r.m.s. value of capacitor voltage.



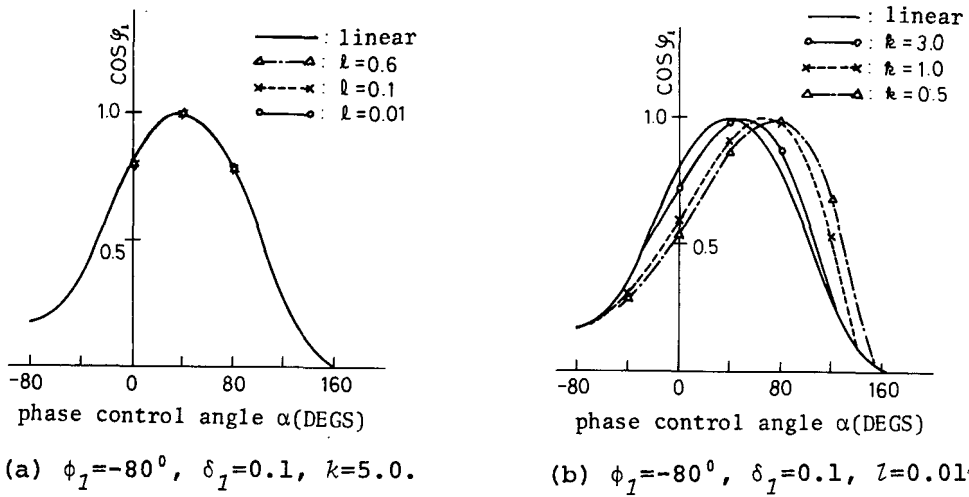


Fig.11. Fundamental power factor.

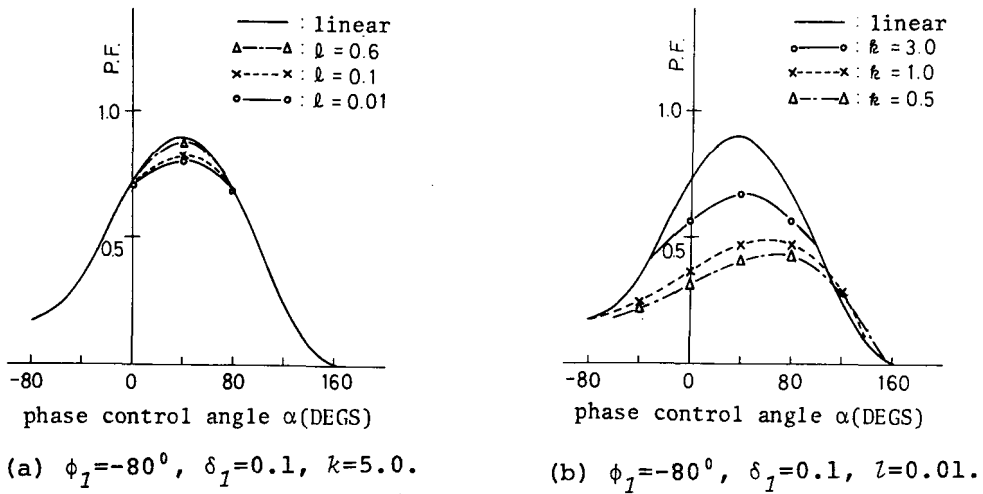


Fig.12. Input power factor.

large due to the magnetic saturation, the r.m.s. value decreases in opposition. Also the r.m.s. value of capacitor voltage decreases as well as its peak value. As  $k$  and  $l$  are smaller, the influence is more remarkable.

In the next, the variation of fundamental power factor is shown in Fig.11. The current waveform as mentioned in previous section is distorted to be salient by the magnetic saturation, so that the angle, at which the current waveform has a peak value, is shifted to leading

direction of conduction angle. For that reason, the phase control angle, at which the fundamental power factor equals to unity, becomes lag. Thus, the influence of magnetic saturation is more remarkable with smaller values of  $k$  and  $\lambda$ .

The variation of input power factor is shown in Fig.12. Where, the input power factor is expressed as follows:

$$P.F. = P/P_A = (I_1/\sqrt{\Sigma I_n^2}) \cos\phi_1, \quad (7)$$

$\cos\phi_1$ ; fundamental power factor.

That is, the input power factor can be expressed as the product of  $I_1/\sqrt{\Sigma I_n^2}$  in Fig.7 by the fundamental power factor in Fig.11. Then the input power factor is poor because of the distorted waveform of current compared with that with a linear load. For example, the power factor is 0.9 at  $\alpha=40^\circ$  with a linear load, but it is 0.47 at  $k=1.0$ ,  $\lambda=0.01$ , and  $\alpha=40^\circ$ . And also, the phase control angle, at which the fundamental power factor is equal to unity, is lagger. Therefore, the phase control angle, at which the input power factor is best, becomes lagger compared with that with a linear load.

### 3.3 Influence on Transient Characteristics

In case of thyristor phase control circuit with linear series  $RLC$  elements, the time delay appears owing to an electrostatic stored energy in capacitor which is a energy storage element. In this section, the influence of magnetic saturation on the time delay is discussed.

At first, the transient response waveform is shown in Fig.13. Now, we assume that the initial value of capacitor voltage is zero at the instance when the power source is switched on.

As soon as a power source is switched on and a thyristor is triggered, the thyristor burst into conduction and the current begins to flow. In the first few half-cycles, the circuit operation is similar to that with

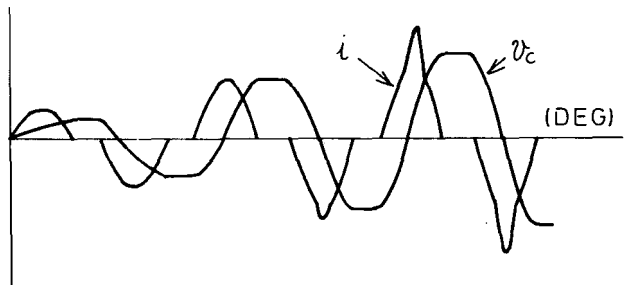
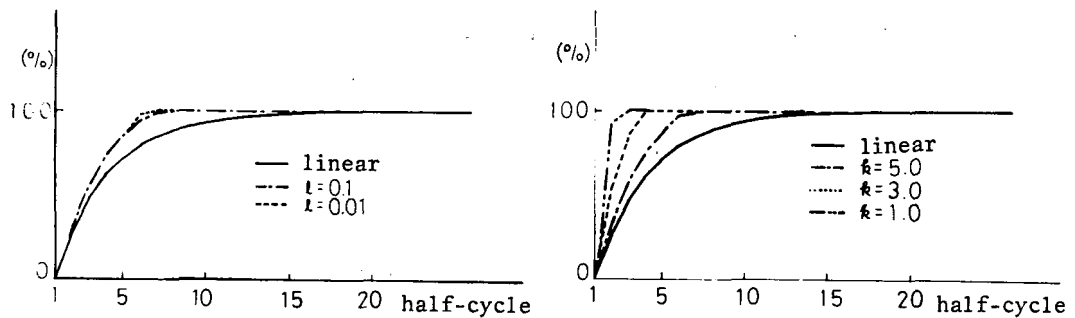


Fig.13. Transient waveforms.



(a)  $\phi_1 = -80^\circ$ ,  $\delta_1 = 0.1$ ,  $k = 5.0$ ,  $\alpha = 20^\circ$  (b)  $\phi_1 = -80^\circ$ ,  $\delta_1 = 0.1$ ,  $l = 0.01$ ,  $\alpha = 20^\circ$

Fig.14. Response time.

a linear load because the reactor is not saturated. After then, the reactor is saturated so that the current becomes a salient waveform and reaches a steady state.

In the next, the influence of magnetic saturation of the reactor on the transient response time, that is, the time delay is mentioned. The response time in half-cycle is shown in Fig.14. In consequence, as  $k$  and  $l$  are smaller, the transient response time becomes shorter. It is considered to be due to the cause that the electrostatic energy in capacitor is limited by the magnetic saturation and the damping factor of load is larger with the reactor saturation.

#### 4. Discussion

(1) The current waveform becomes a salient one due to the magnetic saturation, and the peak value of current with  $\phi_1 = -80^\circ$ ,  $\delta_1 = 0.1$ ,  $k = 5.0$ ,  $l = 0.01$ , and  $\alpha = 40^\circ$  is 12.6 times as large as that with thyristor shorted and twice as large as that with a linear load. On the other hand, the capacitor voltage waveform is distorted notably and its peak value is lower compared with a linear load. Then, the conduction angle decreases. The most noteworthy influence appears in the distortion and the peak value of current waveform. Therefore, it is necessary to consider them carefully on the selection of thyristor devices and the influence on a power source.

(2) The r.m.s. values of current and capacitor voltage are decreased due to the magnetic saturation of reactor. That is, the power into

a load decreases and the input power factor becomes poor. Because the angle, at which the current waveform has a peak value, is shifted to leading direction and the conduction angle decreases, the phase control angle, at which the fundamental power factor equals to unity, becomes lagger.

If active power, reactive power, harmonic power, and apparent power are represented as  $P$ ,  $P_R$ ,  $P_H$ , and  $P_A$  respectively,  $P/P_A$ ,  $P_R/P_A$ , and  $P_H/P_A$  with  $\phi=-80^\circ$ ,  $\delta=0.1$ , and  $\alpha=40^\circ$  are 0.9, 0.0, and 0.44 with a linear load respectively. While, in the case which a load has a saturable reactor and  $k=1.0$  and  $l=0.01$ ,  $P/P_A$ ,  $P_R/P_A$ , and  $P_H/P_A$  are 0.47, -0.21, and 0.86, respectively. The rate of harmonic power content becomes great and the reactive power is leading. It is considered that the decrease of input power factor is mainly due to the increase of harmonics.

(3) The transient response time on saturating of reactor decreases because the electrostatic energy is kept lower and the damping factor increases.

## 5. Conclusions

The influences of magnetic saturation of iron-core reactor on the performance of the thyristor phase control circuit with series *RLC* elements are analytically made clear by the numerical calculation using a simplified three straight lines approximate model. The results obtained are summarized as follows:

(1) The peak value of current waveform becomes larger. On the other hand, the peak value of capacitor voltage decreases. Furthermore, the conduction angle decreases.

(2) The r.m.s. values of current and capacitor voltage decrease.

(3) The phase control angle at which the fundamental power factor equals to unity becomes lag. The input power factor becomes lower and the phase control angle at the maximum input power factor becomes also lag.

(4) The transient response time becomes smaller.

References

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