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COMPOUND-TYPE THYRISTOR EXCITATION SYSTEM FOR LARGE CAPACITY GENERATOR

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I. INTRODUCTION

Compound-type static excitation systems with silicon rectifiers are now widely used in ac synchronous generators. Besides the fact that they do not require commutator maintenance and inspection needed in dc exciters, they also have excellent characteristics such as a highly increased excitation response.

In the last few years, the above-mentioned compound type static excitation systems with silicon rectifiers have been replaced by a new type excitation system containing thyristors. The new system is much more compact than the former type.

The thyristor type static excitation system as shown in *Fig. 1* is the most widely used. This system possesses a excellent response for such a disturbance as load or voltage changes during normal operation, which is not inferior, if not superior to that in the former system. However, there are difficulties in maintaining the field current during 3-phase short-circuits in the main bus lines etc. and it is impossible to the reestablish generator voltage if the faulty disconnection continues for a long time since the field current is reduced by the transient time constanty T_d'. This is a major drawback in large capacity generators which must contribute to transient stability.

In order to compensate for this fault, the secondary voltage rating of the excitation transformer can be increased by considering system bus line residual voltage during a short-circuit fault. The residual voltage during short-circuit faults has been reported as generally around 50%, but it is impossible for this idea to maintain sufficient field current for every system and operation time of protection relay. Further, since the excitation transformer secondary voltage is raised, the rated capacity increases. In addition the thyristor rated input voltage is also increased or else the use of two thyristors connected in series is required.

Another way to compensate for the above fault is to combine the thyristors and the ac exciter, but this plan is rather expensive.

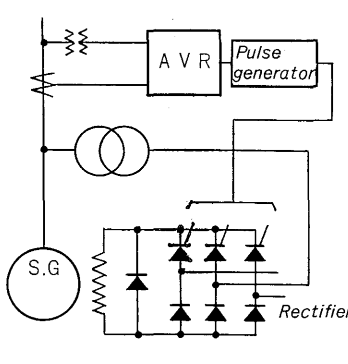


Fig. 1 Thyristor type static excitation system

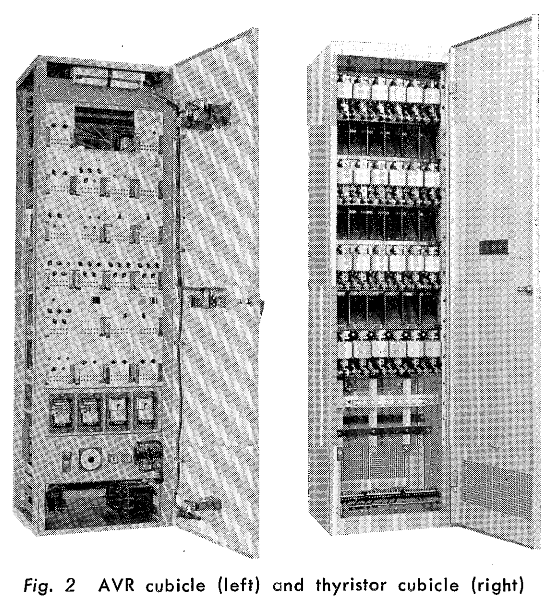


Fig. 2 AVR cubicle (left) and thyristor cubicle (right)

This paper will describe the compound type thyristor excitation system which has been developed to incorporate the features of high response, economy and ease of maintenance. In this system the compound characteristics are such that the thyristor input is the vector sum of the voltage related to generator terminal voltage obtained via an excitation transformer and the voltage related to generator output current obtained via a current/voltage converter. Since wave form of this input source voltage is extremely dis-

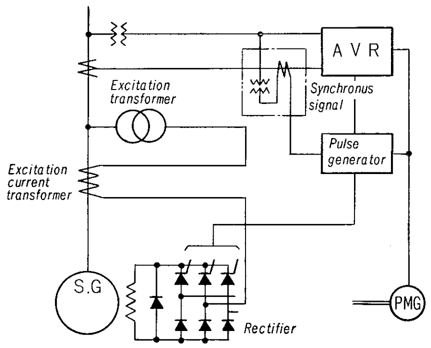


Fig. 3 Compound type thyristor excitation system

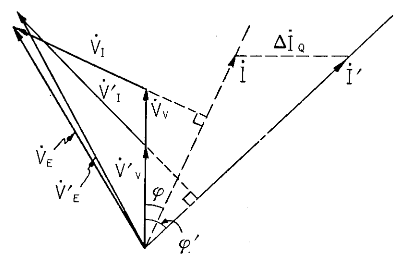


Fig. 4 Vector relation for input voltage

torted, thyristor firing angle control is impossible; Therefore, a small miniature source circuit especially for detection of a synchronous signal has been incorporated (Refer to *Fig. 3*) so that firing angle control is possible no matter what the disturbance in the system.

This system underwent various tests using a model generator and satisfactory results were obtained in each case. The system was incorporated for the first time in a water turbine generator for the Takayama Power Station of the Kansai Electric Power Co., of Japan which went into commercial operation at the end of last year.

The specifications of this generator are as follows;
Rated output: 6500 kva
Rated voltage: 6.6 kv
Frequency: 60 Hz
Rated power factor: 0.9
Speed: 450 rpm

II. OUTLINE OF COMPOUND TYPE THYRISTOR EXCITATION SYSTEM

In order to obtain compound characteristics in the thyristor excitation system of synchronous machines, the vector sum of the voltage component related to the generator terminal voltage ($\dot{V}_V$) and the voltage component related to the generator current ($\dot{V}_I$) is used for the thyristor input voltage. The latter voltage is extracted via a current/voltage converter (hereafter referred to as an excitation current transformer), for example a gap *CT* or "*CT*+*L*."

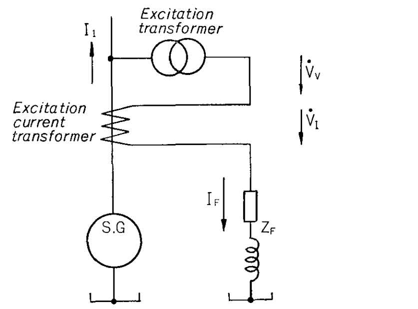
Referring to *Fig. 3*, the relationship between the voltage component $\dot{V}_V$ and the current component $\dot{V}_I$ is shown in *Fig. 4*. The vector sum of $\dot{V}_V$ (phase voltage) and $\dot{V}_I$ (phase voltage) becomes the thyristor input voltage. $\dot{V}_I$ is advanced in phase by 90° in respect to the generator current vector. With this vector relation, the thyristor input voltage can always be maintained at the required value even if there are drops in the generator terminal voltage during generator overloading or bus line short-circuits. When the generator terminal voltage $\dot{V}_V$ drops to $\dot{V}_V'$ as shown in *Fig. 4*, the generator current increases by ΔI_Q, the excitation transformer secondary output voltages changes from $\dot{V}_I$ to $\dot{V}_I'$, and $\dot{V}_E$ becomes $\dot{V}_E'$.

Even if the main bus line voltage becomes zero, the vector sum of $\dot{V}_I'$ due to the generator current and residual voltage $\dot{V}_V'$ due to the drop in generator-transformer impedance becomes $\dot{V}'_E$ (in this case, the directions of vectors $\dot{V}_I'$ and $\dot{V}_V'$ are almost in the same phase). $\dot{V}_V'$ changes in accordance with the generator impedances X_d'', X_d', X_d and the generator-transformer impedances, and $\dot{V}_I'$ becomes a value corresponding to the short-circuit transient current and the permanent short-circuit current.

The compound characteristics in respect to the thyristor input voltage can be obtained by using the above mentioned configuration. The synchronous signal for thyristor firing angle control must naturally be based on $\dot{V}_E$ to obtain the compound characteristics. However, since there is waveform distortion in the thyristor input voltage because of commutation phenomena in the rectifier and the impedance of the excitation transformer and current transformer, it is usually impossible to use this directly, as synchronous signal voltage for thyristor firing angle control. Therefore, the compound type thyristor excitation system could not be made practical previously.

In this system, however, firing angle control has been made possible in the following manner. Small miniature potential and current transformers with saturation characteristics and conversion ratios corresponding to the excitation voltage and current transformers of the thyristor input source are connected to a metering *PT* and *CT* respectively. The vector sum of their secondary output voltages becomes the synchronous signal. (Refer to *Fig. 3*).

With this method, the miniature circuits contain no rectifiers so that waveform distortion will never occur. The fundamental wave vector phase of the $\dot{V}_F$ of the main excitation circuit and the voltage vector phase for the synchronous signal in the miniature circuit are always the same even at the transient conditions in case of faults etc. and naturally during variations of the reactive power of the generator. Therefore, firing errors never occur.



$\dot{V}_V$: Secondary phase voltage of excitation transformer
$\dot{V}_I$: Secondary phase voltage of excitation transformer
$\dot{I}_I$: Generator output phase current
$\dot{I}_F$: Field ac side phase current
$\dot{Z}_F$: Ac side field impedance per phase (function of α)

Fig. 5 Equivalent circuit for excitation system

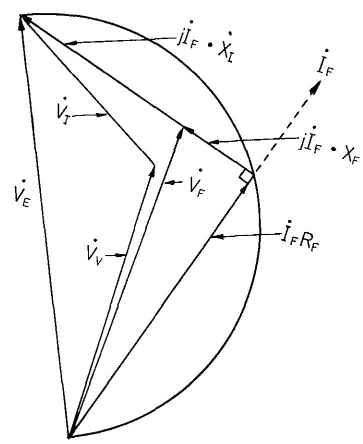


Fig. 6 Vector diagram

III. BASIC THEORY

Fig. 5 is an equivalent circuit for the excitation system circuit shown in *Fig. 3*. All vectors are as follows. The generator field resistance is converted on the ac side with the parameter of the thyristor firing angle α.

From *Fig. 5*, the following relation can be obtained

$$\dot{V}_V+\dot{V}_I=\dot{I}_F Z_F+j\dot{I}_F(X_V+X_I)$$
$$\fallingdotseq \dot{V}_F+j\dot{I}_F\cdot X_I \quad \cdots\cdots (1)$$
$$(\because\ V_F=\dot{I}_F Z_F,\ X_I \gg X_V)$$

where $\dot{V}_F$: The phase voltage of the field voltage converted to ac side or the thyristor input voltage

X_V: Converted secondary reactance of the excitation transformer

X_I: Converted secondary reactance of the excitation current transformer

The voltage/current conversion formula for the excitation current transformer is as follows:

$$\dot{V}_I=jX_I\cdot\frac{\dot{I}_1}{b} \quad \cdots\cdots (2)$$

where b: Turn ratio of the excitation current transformer

When $\dot{Z}_F$ is divided into a resistance component R_F and a reactive component X_F, equation (3) results R_F and X_F are both function of the thyristor firing angle α.

$$\dot{V}_F=\dot{I}_F\dot{Z}_F$$
$$=\dot{I}_F(R_F+jX_F) \quad \cdots\cdots (3)$$

The vector relationship of equations (1), (2) and (3) are shown in *Fig. 6*.

1. Field Resistance and Equivalent Ac Conversion Values

The relation between the dc output voltage and the ac input voltage, and the firing phase of the 3-phase thyristor-diode bridge is as shown in equation (4) when the rectifier load is inductive.

$$V_f=0.675\cdot\sqrt{3}\cdot V_F\cdot(1+\cos\alpha) \quad \cdots\cdots (4)$$

where V_f: mean value of the field voltage

$\sqrt{3}V_F$: effective value of ac input line voltage

The dc output current can be shown as in equation (5).

$$I_f=\frac{V_f}{R_f} \quad \cdots\cdots (5)$$

where R_f: Dc field resistance

I_f: Dc field current

The approximate relation between the ac input current and the dc output current of the 3-phase thyristor-diode bridge is shown in equation (6) and (7) in terms of α.

$$I_F=\sqrt{\frac{2}{3}}\cdot I_f \qquad 0\leqq\alpha\leqq\frac{\pi}{3} \quad \cdots\cdots (6)$$

$$I_F=\sqrt{\frac{\pi-\alpha}{\pi}}\cdot I_f \qquad \frac{\pi}{3}\leqq\alpha\leqq\pi \quad \cdots\cdots (7)$$

From equations (4), (5) (6) and (7), the conversion of the equivalent resistance of R_f for each phase on the ac side is shown in equations (8) and (9).

$$\left.\begin{aligned} &0\leqq\alpha\leqq\frac{\pi}{3}\\ &R_F=\frac{V_F}{I_F}\cos\theta\\ &=\frac{V_f}{0.675\cdot\sqrt{3}\cdot(1+\cos\alpha)}\cdot\frac{1}{0.82\cdot I_f}\cos\theta\\ &=K_1\cdot R_f\\ &K_1=\frac{\cos\theta}{0.954(1+\cos\alpha)} \end{aligned}\right\} \quad (8)$$

where $\cos\theta$ is hereafter referred to as a function of the firing angle α.

$$\left.\begin{array}{l} \dfrac{\pi}{3} \leqq \alpha \leqq \pi \\ R_F = K_2 \cdot R_f \\ K_2 = \dfrac{1}{1.17\,(1+\cos\alpha)} \times \sqrt{\dfrac{\pi}{\pi-\alpha}} \times \cos\theta \end{array}\right\} \cdots\cdots (9)$$

$\cos\theta$ in respect to the firing control angle α, i.e. the relation between R_F and X_F, can be obtained from the following equations.

$$\left.\begin{array}{l} 0 < \alpha < \dfrac{\pi}{3} \\ \cos\theta = \dfrac{V_f \cdot I_f}{\sqrt{3} \cdot V_F \cdot I_F} \\ \quad = 0.477\,(1+\cos\alpha) \end{array}\right\} \cdots (10)$$

$$\left.\begin{array}{l} \dfrac{\pi}{3} \leqq \alpha \leqq \pi \\ \cos\theta = \dfrac{V_f \cdot I_f}{\sqrt{3}\, V_F \cdot I_F} \\ \quad = 0.39\,(1+\cos\alpha) \times \sqrt{\dfrac{\pi}{\pi-\alpha}} \end{array}\right\} \cdots (11)$$

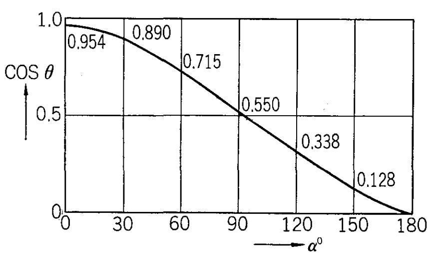


Fig. 7 Relation of cos θ and α

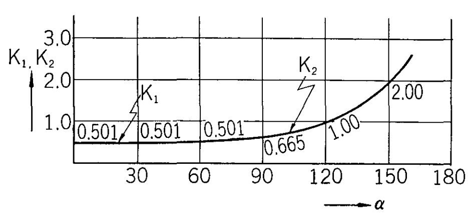
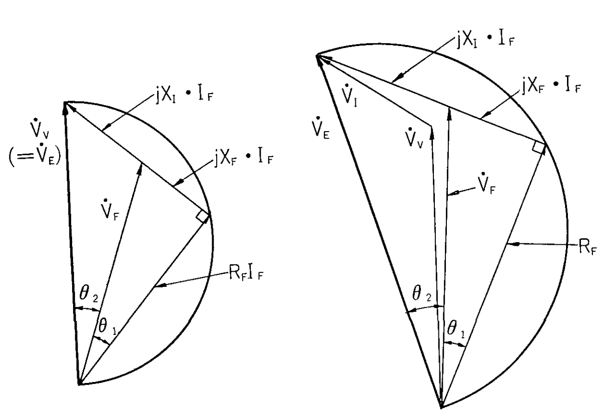


Fig. 8 Relation of K_1, K_2 and α



(a) On no-loading (b) On loading

Fig. 9 Vector diagram

When equations (10) and (11) are expressed in relation to α, a graph as shown in *Fig. 7* is obtained.

From *Fig. 7*, the effective resistance value R_F of the ac conversion of the field resistance R_f can be obtained in respect to the firing angle α. From equation (12), X_F can be obtained.

$$X_F = \frac{\sqrt{1-\cos^2\theta}}{\cos\theta} \times R_F \quad \cdots\cdots (12)$$

K_1 and K_2 in equation (8) and (9), can be expressed from *Fig. 7* as shown in *Fig. 8*.

The basic relation of the field voltage and current vectors for the load and no-load conditions of the main generator are shown in *Fig. 9*. The vector phase relation in *Fig. 9* (a) is shown by equation (13). This is the basic equation for selecting the secondary voltage of the excitation transformer from the amount of forced excitation during no-load operation of the generator.

$$\left.\begin{array}{l} \dfrac{|\dot{V}_F|}{|\dot{V}_V|} = \dfrac{\cos(\theta_1+\theta_2)}{\cos\theta_1} \\ \tan\theta_1 = \dfrac{X_F}{R_F} \\ \tan(\theta_1+\theta_2) = \dfrac{X_F+X_I+X_V}{R_F} = \dfrac{X_F+X_I}{R_F} \end{array}\right\} \cdots (13)$$

The vector phase relationship from *Fig. 9* (b) is shown by equation (14).

$$\left.\begin{array}{l} \dfrac{|\dot{V}_F|}{|\dot{V}_V+\dot{V}_I|} = \dfrac{\cos(\theta_1+\theta_2)}{\cos\theta_1} \\ \tan\theta_1 = \dfrac{X_F}{R_F} \\ \tan(\theta_1+\theta_2) = \dfrac{X_I+X_T+X_F}{R_F} \fallingdotseq \dfrac{X_I+X_F}{R_F} \end{array}\right\} \cdots (14)$$

The results of the above calculations are approximate values based on the following assumptions.

1) The square wave current of the ac side of the thyristors is determined by the calculation of the effective value.

2) There will be no overlapping angle during commutation.

In actual practice, the synchronous signal must be in phase with $\dot{V}_F$. However the the size of θ_2 which shifts according to α is determined by the size of X_I, but calculations as well as actual measurements have confirmed that in practice it is determined by the miniature vector of $\dot{V}_E$ which is not as large as X_I.

IV. DETERMINATION OF THE EXCITATION TRANSFORMER AND EXCITATION CURRENT TRANSFORMERS

From the basic theoretical formulae presented in section III as well as from the amount of forced excitation and the compound characteristics, the specifications of the excitation transformer and current transformers can be determined as follows.

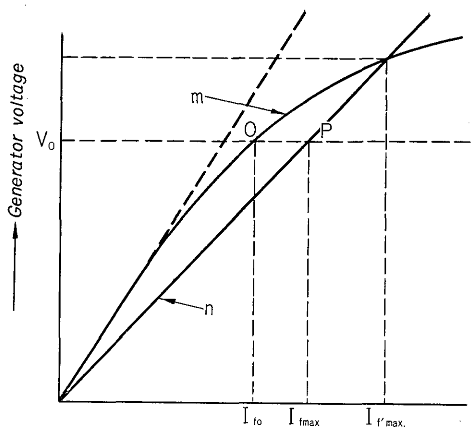


Fig. 10 No-load saturation curve and thyristor output

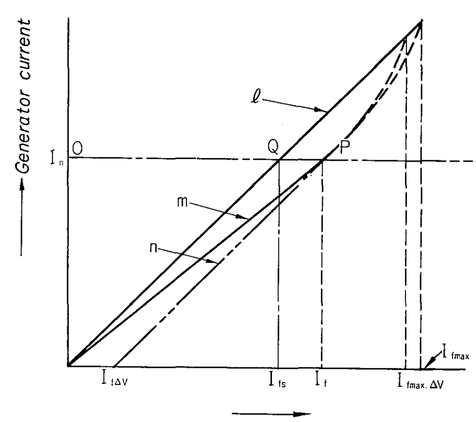


Fig. 11 Short-circuit curve and thyristor output

1. Excitation Transformer

Condition :

> When the thyristor firing angle α is a minimum during no-load conditions, $V_{f\max}$, which requires V_F, must be provided.

From equations (4) and (14), $\dot{V}_V$ can be obtained by $V_{f\max}$, $\alpha_{\min}$, R_F and X_F.

The relation between the thyristor output current and the generator no load voltage when the thyristor firing angle α is at a minimum is shown in *Fig. 10.*

The line *n* shows the relation between the thyristor output current and the generator voltage when the firing angle is fixed at $\alpha_{\min}$. The point *P* shows the field ceiling voltage for no load conditions when parallel with the system. The point 0 is obtained in accordance with the control angle α when the excitation transformer primary voltage is a constant (V_0). $I_{f\max}$.—I_{f0} is the amount of forced excitation under no load conditions.

2. Excitation Current Transformer

Condition :

> The required field current must be maintained even when a 3-phase short-circuit occurs in the system bus line of the generator.

The voltage component V_V for the residual voltage in the system is first obtained from equations (4) and (14) and the current component V_I required to maintain the first current is then worked out.

Fig. 11 shows the relation between the generator short-circuit curve and the thyristor output current supplied by the excitation current transformer secondary voltage.

The line *l* is the 3-phase short-circuit curve and the curve *m* is the thyristor output current when the thyristor firing angle becomes $\alpha_{\min}$ during a 3-phase short-circuit. When there is residual voltage in the bus line, there is an output $I_{f\Delta v}$ in accordance with this residual voltage which means that an excitation

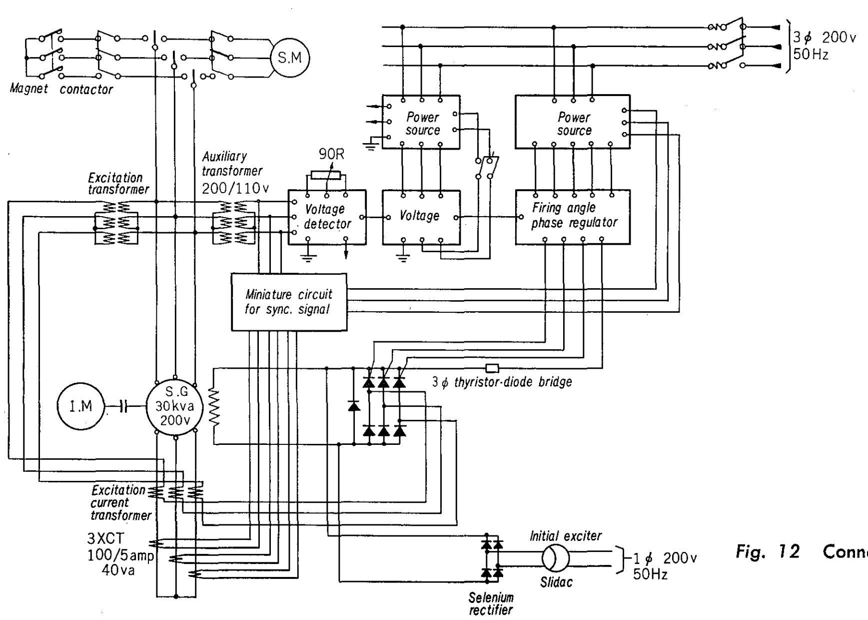


Fig. 12 Connection diagram for fundamental test

current transformer with output characteristics like those shown by curve n is suitable.

With curve m, the permanent short-circuit field current becomes $I_{f\max}$ and with curve n, it becomes $I_{f\max(\Delta v)}$.

To get the required permanent short-circuit field current or generator short-circuit current during short circuit faults in the generator output bus line system, it is essential to determine the current/voltage conversion ratio, i.e. the secondary output voltage of the excitation current transformer, under the condition to get the relation of $OP \geqq OQ$ based on the field resistance R_f of rated operation.

When considering the amount of $I_{f\Delta v}$ in accordance with the residual voltage ΔV in the bus line, the ratio and the capacity of the excitation current transformer is decreased.

The secondary equivalent impedance of the excitation current transformer should be as low as possible on the basis of the current/voltage conversion ratio. This will contribute to shortening the commutation time.

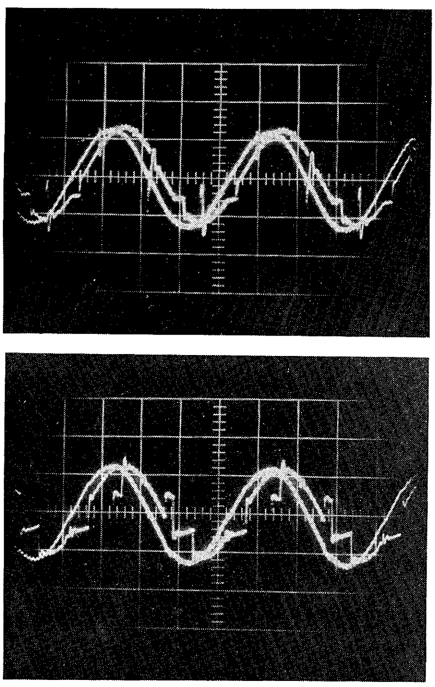
V. TEST RESULTS

Fig. 12 shows the circuit diagram for the basic tests.

Main tests:

1) Open loop test

In the open loop of the excitation system, the waveforms of the thyristor input voltage (U_F) and the output voltage of the special power source for synchronous signal detection (U_{syn}) were compared and the phase checked for the firing angle α. The results are shown in *Fig. 13*. The phase of U_{syn} is leading U_f by 30° because of connection difference.



(a) $\alpha=120°$

(b) $\alpha=30°$

Fig. 13 Waveform of U_F and U_{syn} and phase difference

2) Closed loop test

(1) A motor starting test was performed as the closed loop test for the system shown in *Fig. 12*. (Refer to *Fig. 14*).

(2) Operation characteristics were investigated under the same conditions during a sudden three phase short-circuit and the time at which the short-circuit was cleared. (Refer to *Fig. 15*).

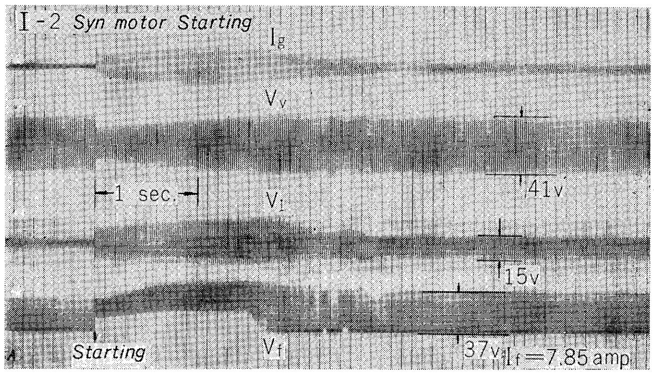


Fig. 14 Motor starting test

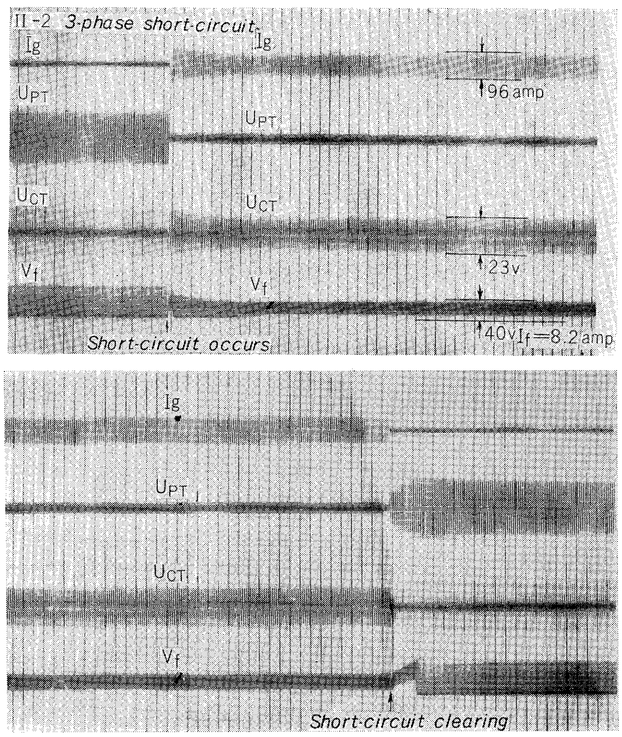


Fig. 15 Sudden 3-phase short-circuit

From the results of these tests it was evident that control of the firing is always possible with the special power source for detection of the synchronous signal in the small miniature circuit even if transient phenomena arise in the thyristor input source. These test results also agreed well with the theoretical results obtained from vector analysis and the equations given previously.

Factory tests conducted with the 6500 kva unit delivered to the Takayama Power Station revealed that the open loop characteristics were exactly the same as those found in the basic tests. The maintenance of the field current during a short-circuit was also confirmed by an indirect method. As shown in *Fig. 16*, excellent voltage recovery characteristics are also obtained during transient phenomena when the short circuit is being cleared.

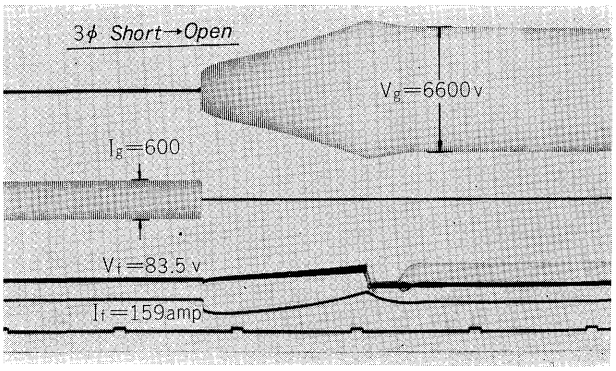


Fig. 16 **Self build-up test of 3-phase short-circuit clearing**

The specifications of the generator delivered to the Takayama Power Station are as given in section I. The specifications of other main components in this system are as follows.

1) Excitation transformer
   Number of phases : 3 phases
   Primary voltage : 6600 v
   Secondary voltage : 240 v
   Capacity : 100 kva
2) Excitation current transformer
   Number of phases : 3 phases
   Primary current : 569 amp
   Secondary voltage : 37.8 v
   Capacity : Primary 57.5 kva, secondary 49.3 kva
3) Rectifier
   Connections : 3-phase thyristor-diode bridge
   Dc output : 220 v, 330 amp
4) AVR
   Standard TRANSIDYN type AVR :

VI. CONCLUSION

The excitation system has been explained above. An article is planned for the near future concerning the results of the tests on site of the Takayama Power Station.

Even when used in a very large capacity generator of the 100,000 kva class, this system saves considerable space when compared to the conventional compound-type static excitation system. The system is also very economical in comparison with the rotating excitation system and the authors consider that it will become standard in large capacity generators in the future.