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OPERATING RESULTS OF COMPOUND-TYPE THYRISTOR EXCITATION SYSTEM FOR KANSAI ELECTRIC POWER CO.

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I. INTRODUCTION

A compound type thyristor static excitation system has been developed for ac synchronous generators, and the first system was delivered to the Takayama Power Station of the Kansai Electric Power Co. Before delivery the system was checked through the various basic tests using the generator in our model transmission equipment. After tests at both the factory and site, the system went into operation in December, 1968.

In order to confirm various problems, characteristic tests including 3-phase short-circuit were carried out in the middle of February this year. The excellent results obtained will be outlined in this report.

II. OUTLINE OF THE COMPOUND TYPE THYRISTOR EXCITATION SYSTEM

In order to achieve compound characteristics in the thyristor excitation system for synchronous machines, the voltage component related to the generator terminal voltage ($\dot{V}_V$) and the component related to the generator output current ($\dot{V}_I$) are composed vectorically and the resulting vector sum becomes the thyristor input source. In order to control the thyristor firing angle, this power is fed via a current/voltage converter (hereafter referred to as an excitation current transformer) such as a gap *CT* or a *CT+L*. *Fig. 1* is an outline of this system.

The relation between the voltage component $\dot{V}_V$ and the current component $\dot{V}_I$ in *Fig. 1*, is shown in *Fig. 2*. The vector sum of $\dot{V}_V$ (voltage component) and $\dot{V}_I$ (current component) becomes the thyristor input voltage. However, vector $\dot{V}_I$ is leading the generator output current vector by 90°. With this vector relation, the thyristor input voltage can be maintained at the required value even if generator terminal voltage is low during bus line shorts or generator overloads. When the generator terminal voltage $\dot{V}_V$ in *Fig. 2* is decreased to $\dot{V}_V'$, the generator output current increases by $\Delta\dot{I}_Q$, the excitation transformer secondary output voltage changes from $\dot{V}_I$ to $\dot{V}_I'$, and $\dot{V}_E$ becomes $\dot{V}_E'$.

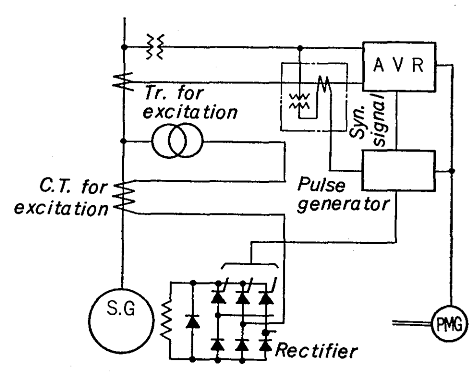


Fig. 1 Thyristor type excitation system with compound performance

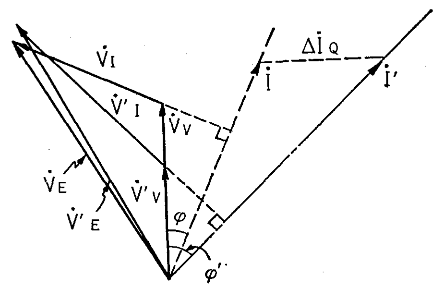


Fig. 2 Vector of thyristor input voltage

If the bus line voltage drops to zero, the vector sum of V_I due to the corresponding generator output current and the residual voltage V_V' due to the impedance drop in the generator transformer becomes V_E' (at this time, the vectors of V_I' and V_V' are in almost the same phase).

It is possible to achieve compound characteristics for the thyristor input voltage, with the aforementioned construction. The synchronized signal for thyristor firing angle control must naturally be based on $\dot{V}_E$ because of the synchronizing between thyristor input voltage and its firing device input voltage. However, the thyristor input voltage waveform is badly distorted due to the impedance of the excitation current and the voltage transformers and the commutation phenomenon in the rectification equipment. For this reason, it is impossible to use thyristor input voltage $\dot{V}_E$ directly as a synchronized signal for stable firing angle control. This fact made all previous compound type thyristor excitation system impractical.

This defect was overcome as follows. For the excitation current and voltage transformers in the thyristor input source, small model voltage and current transformers with the same conversion ratios and saturation characteristics were connected to a PT and CT respectively for metering or AVR. The vector sum of the secondary output voltages of these models become the synchronized signal (Refer to *Fig. 1*).

In this method, the model circuit contains no rectifiers so that there is no distortion in the voltage waveform. Also there is absolutely no trouble of firing angle control since the phases of the voltage vector for the synchronized signal from the model circuit and of the thyristor input basic voltage for main excitation circuit are remained in the same phase under transient conditions during voltage fluctuation as well as during line faults.

III. FUNDAMENTAL PRINCIPLES

If the ac side equivalent impedance of the generator field circuit resistor is used as a parameter of the thyristor firing phase α, the following equation can be applied the excitation circuit shown in *Fig. 1*.

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

where $\dot{V}_F$: Vector of thyristor input voltage or field voltage ac side reduced phase voltage

$\dot{I}_F$: Field current ac side reduced phase current

Z_F: Field reistance ac side reduced impedance per phase, (— coefficient of α —)

$\dot{V}_V$: Secondary phase voltage of excitation voltage transformer

$\dot{V}_I$: Secondary phase voltage of excitation current transformer

X_V: Secondary reduced reactance of excitation voltage transformer

X_I: Secondary reduced reactance of excitation current transformer

$$\dot{V}_I=j\,X_I\frac{\dot{I}_1}{b} \quad\cdots\cdots\cdots\cdots (2)$$

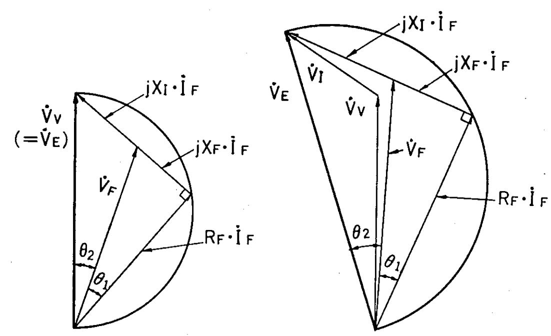
where $\dot{I}_1$: Generator output current

b: Winding ratio of excitation current transformer

If Z_F is divided into a resistance component R_F and a reactance component X_F, equation 3 results. R_F and X_F are both coefficients of the firing angle α.

$$\dot{V}_F=\dot{I}_F Z_F$$
$$=\dot{I}_F(R_F+j\,X_F) \quad\cdots\cdots\cdots\cdots (3)$$

The vector relations of equations (1), (2) and (3) are shown in *Fig. 3*. For the relations between R_F and X_F and the firing angle α, please refer to Vol. 15, No. 3 of the Fuji Electric Review.



(a) No-load condition (b) On-load condition

Fig. 3 Vector diagram of exciting circuit

IV. FEATURES OF THE COMPOUND TYPE THYRISTOR EXCITATION SYSTEM

This system has the following features

(1) Compound characteristics can be obtained for the thyristor input voltage. This compound input vector $\dot{V}_E$ is the vector sum of the voltage component $\dot{V}_V$ and the secondary output voltage $\dot{V}_I$ of the current/voltage converter.

(2) In the previous compound type self-excitation systems, overcompensation was difficult, but in this system it is possible whenever required. Excitation is also maintained even with large voltage drops due to some fault for long periods.
During the boosting operation for generator field from the excitation current transformer, there is current division via the reactor, but if the thyristor firing angle α is under full gate position ($\alpha_{\min}$), the field input is maintained in more than 100% if necessary.

(3) Field overcurrent limitting equipment is provided in the transistor type AVR, so that optional short-circuit current output of generator can be maintained during 3-phase short-circuits. Furthermore transient response characteristics are ideal and the generator voltage can maintain itself after faults are being eliminated no matter how long the interruption.

(4) By overcompensation characteristics of the excitation current transformer, an armature winding heating test of generator is possible with the self-excitation circuit only.

(5) There is no problem during opening of the secondary circuit of excitation current transformer.

(6) The excitation current transformer is effective in decreasing the amount of waveform distortion in the generator voltage which occurs during thyristor commutation.

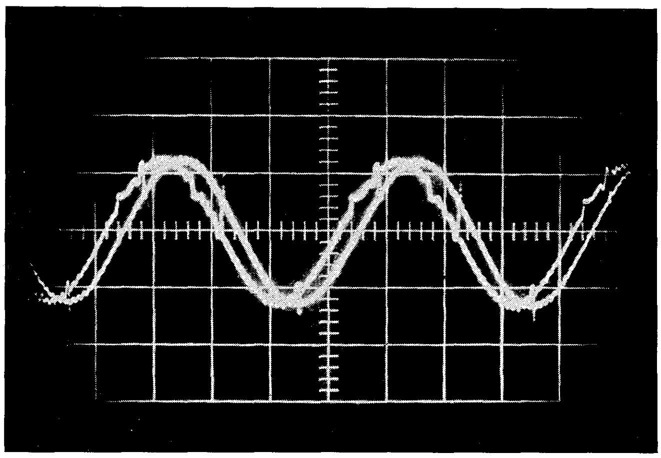
(7) This method is convenient for line charge operation or leading operation of generator, because the firing angle never inclines to $\alpha_{\max}$.

(8) Compared with previous compound type self-excitation system, this system is much more compact.

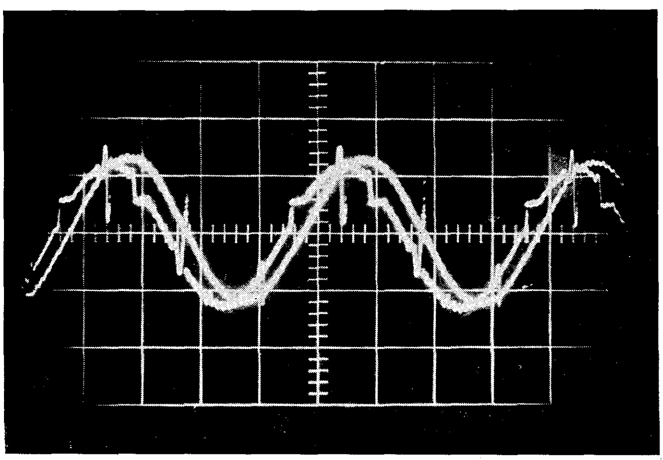
V. RESULTS OF MEASUREMENTS

The methods of eliminating the aforementioned problems were confirmed experimentally. An outline will be given here of data obtained from experiments carried out on the acutal equipment at the Takayama Station of Kansai Electric Power Co. as well as on models. The purpose of these experiments was to back up technical planning work concerning the various features, especially voltage establishment during or after the elimination 3-phase short-circuits.

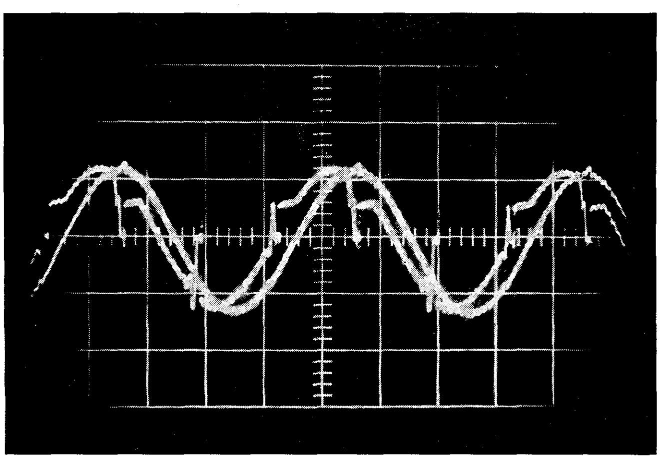
The specifications for the equipment used in these tests are as follows.



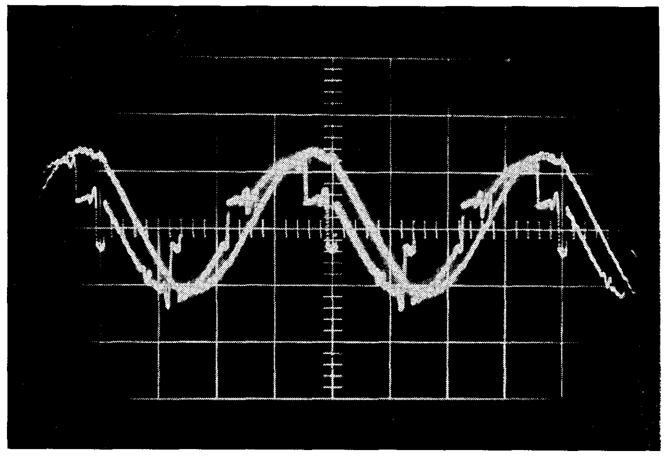
(a) $\alpha=150°$



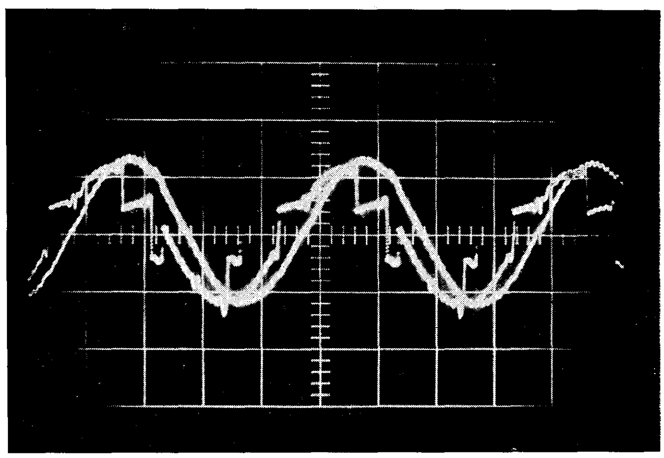
(b) $\alpha=120°$



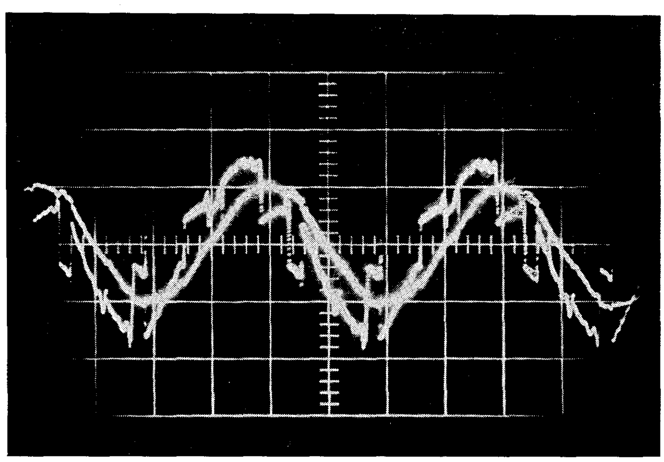
(c) $\alpha=190°$



(d) $\alpha=60°$



(e) $\alpha=30°$



(f) 3-phase short-circuit

Fig. 4 Waveforms of V_F and V_{syn}

1) Generator
   Rated output : 6500 kva
   Rated voltage : 6.6 kv
   Frequency : 60 Hz
   No. of phases : 3
   Rated power factor : 0.9
   Speed : 450 rpm
2) Excitation transformer
   Primary voltage : 6600 v
   Secondary voltage : 181 v (with 290,245,209 and and 154 v taps) (using 181 v tap)
   Capacity : 140 kva
   No. of phases : 3
   (Note : 140 kva is based on the 290 v tap)
3) Exciatation current transformer
   Primary current: : 569 amp
   Secondary voltage : 59 v/phase (with $59\times 9/14$ and $59\times 5/4$ taps) (using the 59 v tap)
   Capacity : Primary 57.5 kva, secondary 49.3 kva
   No. of phase : 3
4) Rectifier equipment
   Connection : 3-phase thyrister-diode mixed bridge
   Dc output : 220 v 330 amp
5) AVR
   Type : Standard TRANSIDYN PI type AVR with field overcurrent limitting equipment
6) Generator field specifications
   No-load field voltage : $V_{f0}=95$ v
   No-load field current : $I_{f0}=137$ amp
   Field voltage during rated output : $V_{fn}=181$ v
   Field current during rated output : $I_{fn}=260$ amp
   Field current during 3-phase short-circuit : $I_{fs}=133$ amp
   Field resistance : $R_f=0.65\ \Omega$ (75°C)

1. Voltage Waveforms in Thyristor Circuit

Fig. 4 shows the voltage waveforms of the thyristor input phase voltage $\dot{V}_F$ and the synchronized signal voltage $\dot{V}_{syn}$ at various firing angles, which are obtained in factory tests. *Fig. 4 (f)* shows the waveforms during a 3-phase short-circuit at the generator terminal. When the output of the excitation current transformer alone serves as the thyristor input souce,r the synchronized signal is also obtained only from the output voltage of a model current transformer via a CT for AVR. Phase discrepancies between $\dot{V}_F$ and $\dot{V}_{syn}$ are according to phase discrepancies at the measuring points (30°), and it is evident that under all the conditions shown below, the basic wave phase difference between $\dot{V}_F$ and $\dot{V}_{syn}$ was almost zero.

Fig. 5 shows the vectors obtained during generator heating operation (factory test) to confirm the vectors in *Fig. 3*.

Measured values : $\dot{I}_1=729$ amp
$\dot{V}_F=43.8$ v/phase (ac)

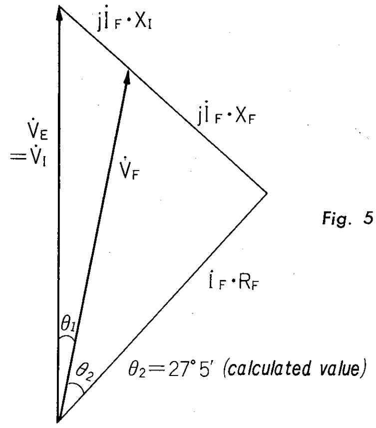


Fig. 5 Vector diagram of 3-phase short-circuit

$I_f=169.2$ amp (dc)
$V_f=88$ v (dc)
$\dot{V}_F=41.9$ v/phase (ac)

Excitation voltages transformer : 181 v tap
Excitation current transformer :
569 amp/37.8 v, $X_I=0.75\ \Omega$/phase
(569 amp/59 v......using 14 T tap $59\times 9/14$ v using 9 T tap)

The firing angle at this time was $\alpha_{min}=30°$. From the above measured values, the secondary voltage $\dot{V}_I$ of the excitation current transformer is obtained as follows :

$$\dot{V}_I=\frac{37.8}{569}\times 729$$
$$=48.4 \text{ v} \quad \cdots\cdots (4)$$

And the field resistance :

$$R_f=\frac{88}{169.2}$$
$$=0.52\ (\Omega) \quad \cdots\cdots (5)$$

Since $\alpha=30°$, the equivalent resistance (R_F) of R_f is as follows :

$$R_F=\frac{1}{0.954\,(1+\cos 30)}\times 0.52$$
$$=0.292\ (\Omega) \quad \cdots\cdots (6)^{*1}$$

The equivalent power factor of Z_F at $\alpha=30°$ is

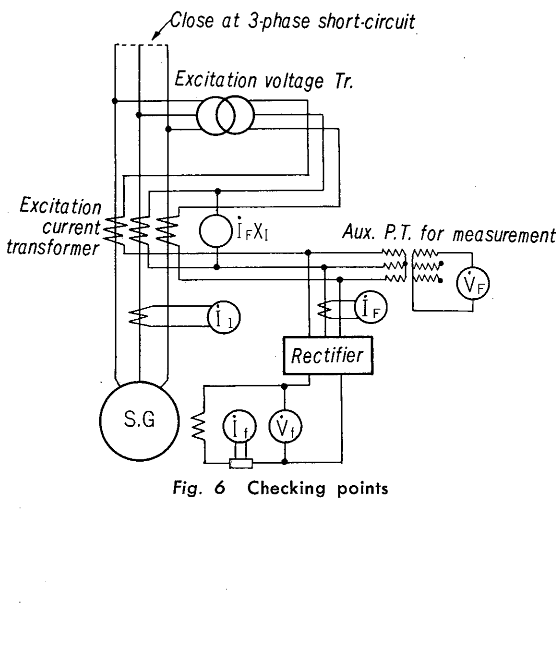
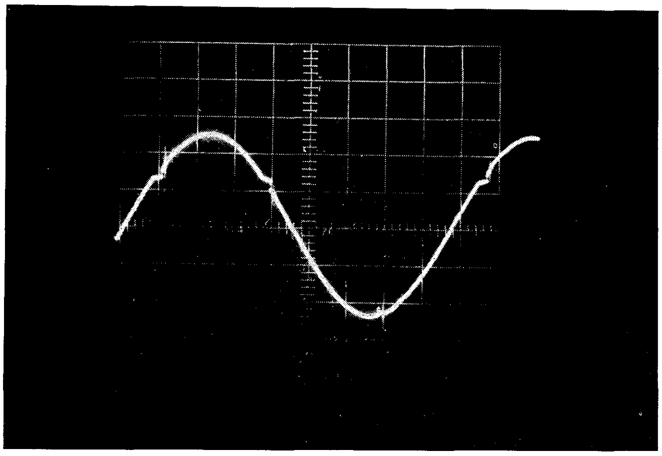
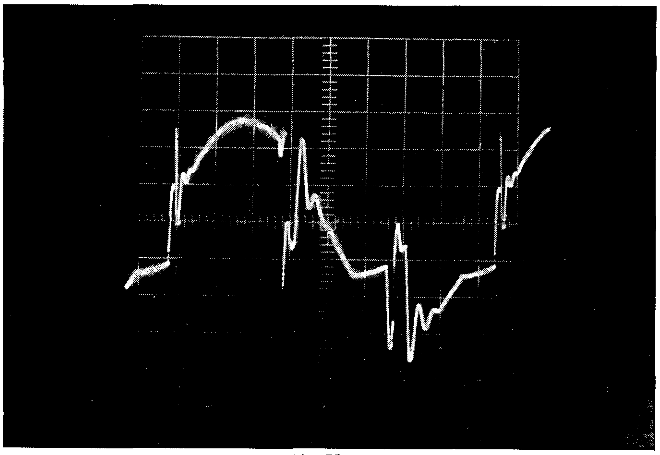


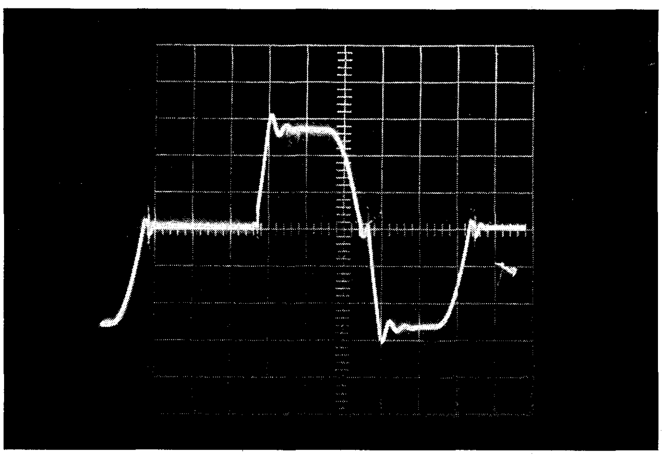
Fig. 6 Checking points



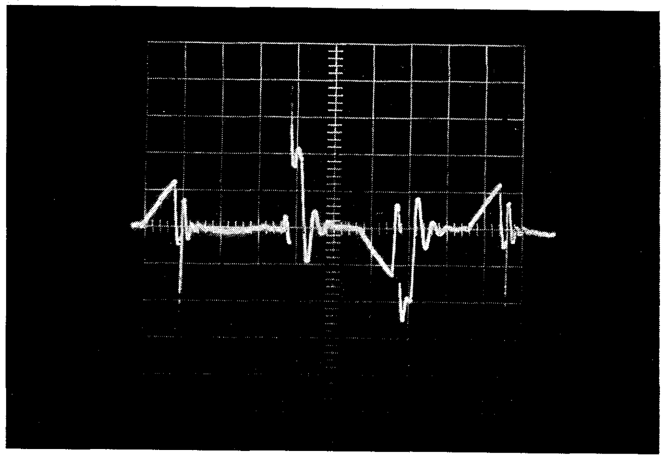
(a) V_{syn}



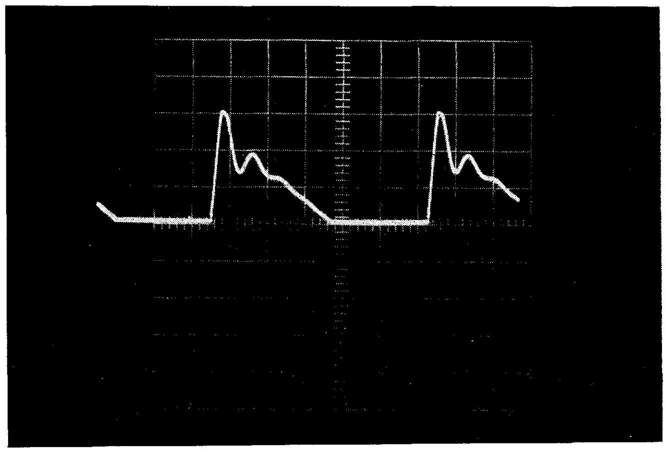
(b) V_F



(c) I_F (ac)



(d) $I_F \cdot X_I$



(e) V_f (dc)

Fig. 7 Waveforms under no-load conditions

given approximately by equation 7.

$$\cos\theta = 0.477\,(1+\cos 30)$$
$$= 0.89 \quad \cdots\cdots (7)^{*1}$$

From equation 7, $\dot{X}_F$ is:

$$\dot{X}_F = R_F \times \tan\theta$$
$$= 0.292 \times 0.511$$
$$= 0.149\ (\Omega) \quad \cdots\cdots (8)^{*1}$$

The equivalent effective value ($|\dot{I}_F|$) of I_f can be obtained as a parameter of the firing angle α as follows.

$$|\dot{I}_F| = I_f \times \sqrt{\frac{2}{3}}$$
$$= 169.2 \times 0.82$$
$$= 139\ (\text{amp}) \quad \cdots\cdots (9)^{*1}$$

*1 (Note: Refer to Fuji Electric Review Vol. 15, No. 3)

From equations 7, 8 and 9,

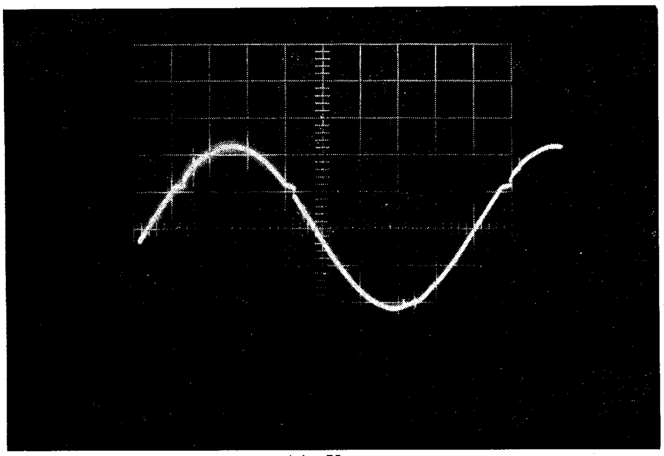
$$\left.\begin{array}{l} |\dot{I}_F \cdot R_F| = 40.5\ (\text{v}) \\ |\dot{I}_F\, X_F| = 20.7\ (\text{v}) \\ |\dot{I}_F\, X_I| = 10.4\ (\text{v}) \end{array}\right\} \quad \cdots\cdots (10)$$

Fig. 5 was obtained from equation 10. The value of $|\dot{V}_I|$ obtained from *Fig. 5* coincides with that of equation 4, as well as $|\dot{V}_F|$ and measured value. *Fig. 6* shows the measuring points.

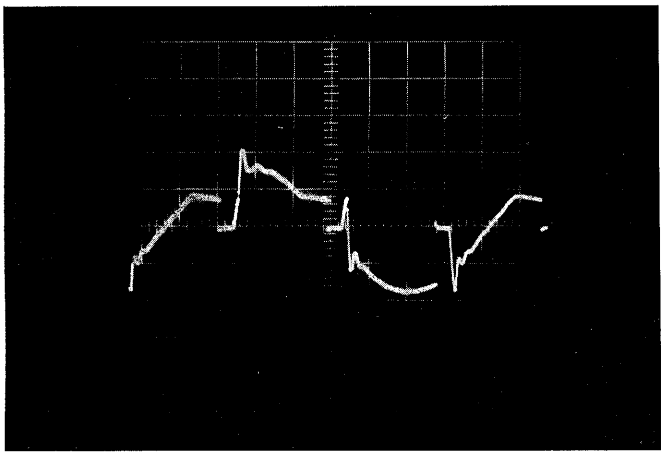
Figs. 7, 8 and *9* show the waveforms at each of the points when the generator is connected in parallel as in *Table 1*. The generator power output was kept at zero.

2. Synchronizing Operation with Voltage Difference

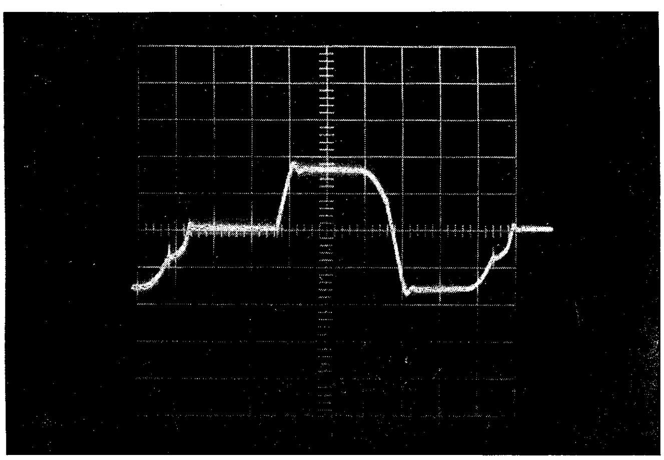
The synchronizing operation test with some voltage difference between generator terminal voltage and



(a) V_{syn}



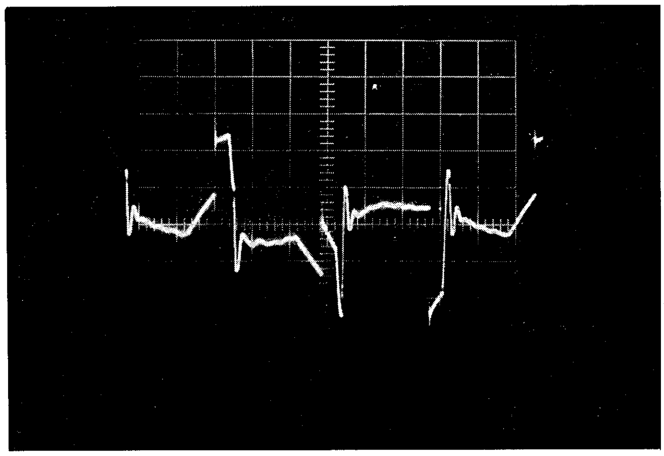
(b) $\doteqdot V_F$



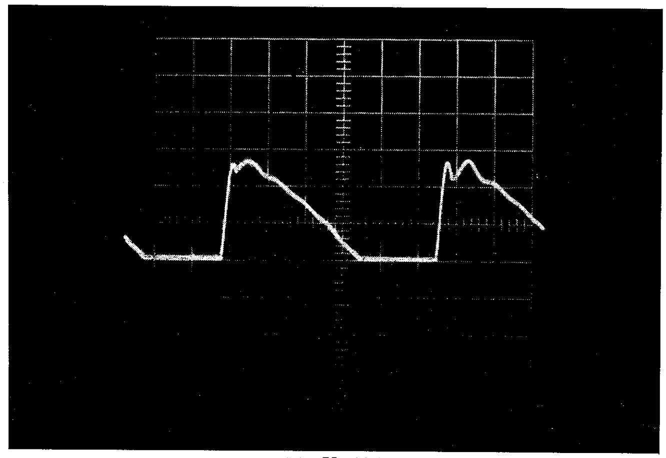
(c) I_F (ac)

Table 1 **Conditions of Waveform Checking under Parallel Running**

Condition \ Measuring Point	Generator Voltage	Generator Current	Oscillogram
No-Load Parallel	6120	0	Fig. 7
Lagging Reaction Power (2 MVAR)	6450	184	Fig. 8
Leading Reactive Power (1.2 MVAR)	5940	116	Fig. 9



(d) $I_F \cdot X_I$



(e) V_f (dc)

Fig. 8 Waveforms at lagging (2 MVAR lag)

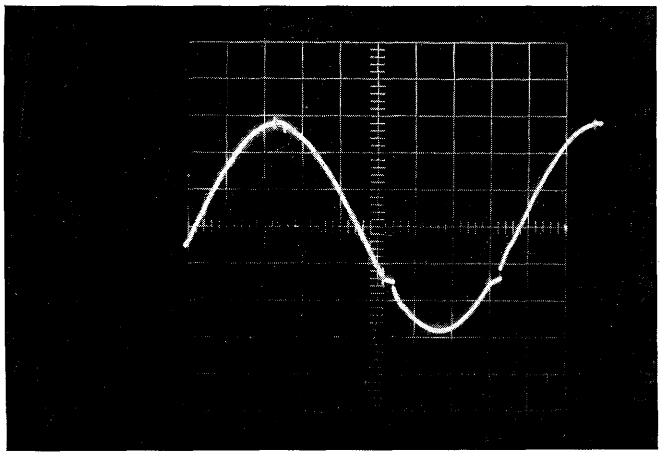
line voltage was done, so as to confirm firing angle control of AVR and to check transient output voltage of the excitation current transformer.

Unlike previous compound type static excitation equipment, voltage source of thyristor is an summation of two voltage vector ($_V+$ $_I$). In this condition it was confirmed that the firing angle control at transient condition is never disturbed by any noise, for instance dc component of generator output current at short-circuit fault or the time delay of AVR being caused by a filter of voltage detector circuit.

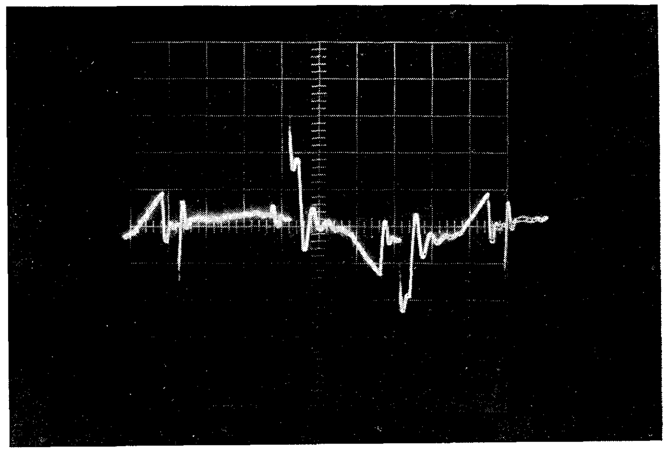
The test conditions are as shown in *Table 2*, and the oscillograms are shown in *Figs. 10, 11,* and *12.* In *Fig. 12,* the oscillograph speed was increased to show V_{syn}, V_f and I_f under transient conditions.

3. Three-Phase Short-Circuit and the Elimination

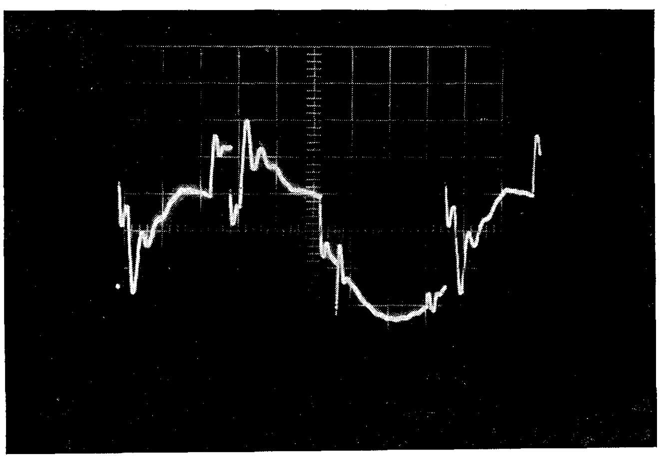
One of the main features of compound type thyristor excitation system is that it is possible to establish the voltage itself even after long periods of interruption due to 3-phase short-circuit. However, in order to achieve this requirement, a choice is made for overcompensation of the excitation current transformer on account of the internal voltage drop in the current transformer unit. This means that



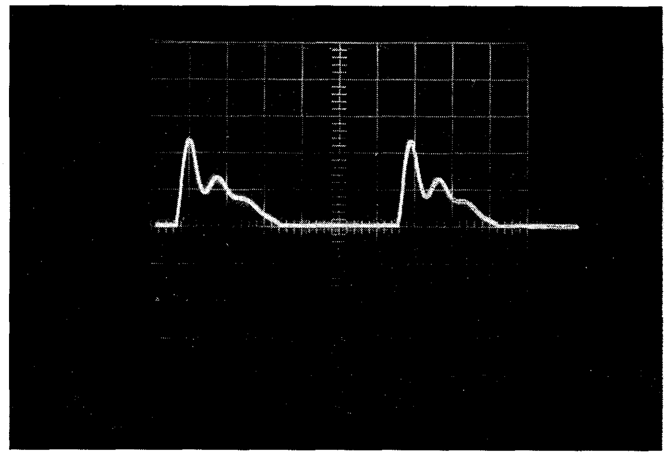
(a) V_{syn}



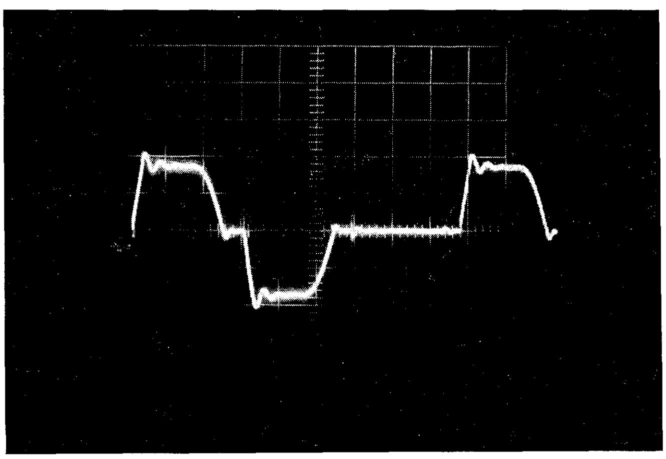
(d) $I_F \cdot X_I$



(b) V_F (ac)



(e) V_f (dc)



(c) I_F (ac)

Fig. 9 Waveforms at leading (1.2 MVAR lead)

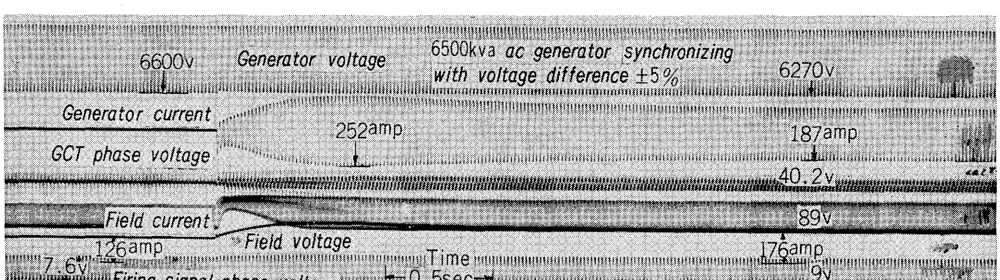


Fig. 10 Synchronizing with voltage difference $V_g > V_L$

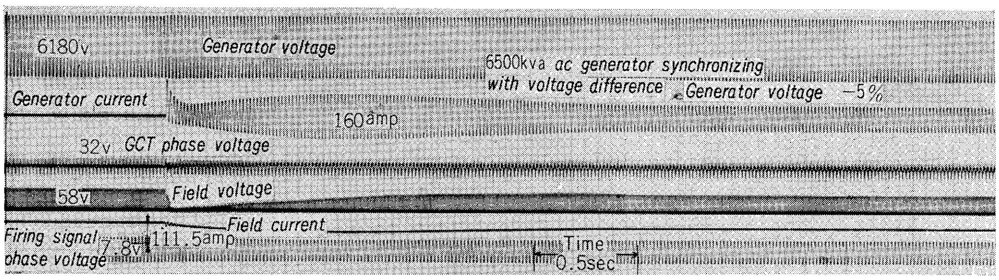


Fig. 11 Synchronizing with voltage difference $V_g > V_L$

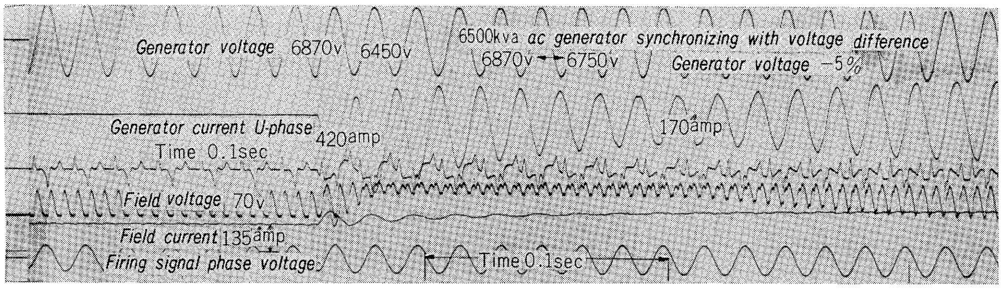


Fig. 12 Synchronizing with voltage difference $V_g > V_L$

***Table 2* Data at Synchronizing with Different Voltage**

Condition \ Measured Value		V_L* (v)	V_g* (v)	$\dot{I}_1$ (amp)	$\dot{V}_V$ (v)人	$\dot{I}_F X_I$ (v)人	V_F (v)人	I_F ac	I_f dc
+5% (10 cm/s)	Before	104.5	110.0	0	92.0	34.0	82.0	92.0	126.0
	After	107.5	108.0	187	90.0	40.2	98.5	132	176.0
−5% (10 cm/s)	Before	108.5	103.0	0	94.0	32.0	86.9	80.0	111.5
	After	107.0	105.2	88	92.0	31.0	79.0	60.0	91.3
+5% (100 cm/s)	Before	109.0	114.5	0	94.0	36.0	84.0	89.5	134.5
	After	111.8	112.5	208	98.0	43.0	103.0	144.0	191.0

*) 6600/110 v PT secondary voltage

the short-circuit current during a 3-phase short-circuit is at least maintained at a value above that of the rated generator output current. For overcompensation, the thyristor output current curve " *m* ", in relation to the generator output current obtained only by the excitation current transformer at α_{min} must be below the 3-phase short-circuit curve " *n* " as shown in *Fig. 13.* However, the generator output current and field current during a 3-phase short-circuit increase until the two curves *m* and *n* intersect at the point *P* as shown in *Fig. 13.* But it is very difficult to determine the point *P* beforehand, because it differs greatly according to the saturation characteristics of the excitation current transformer and the generator field resistance. To solve this problem, the AVR has field overcurrent suppression properties ACR, and any field limiting current can be controlled according to set value. In this manner, the generator output current can be suppressed indirectly. *Fig. 14* shows I_{1max} and I_{fACR} as the maximum current values for the generator and field respectively. For these

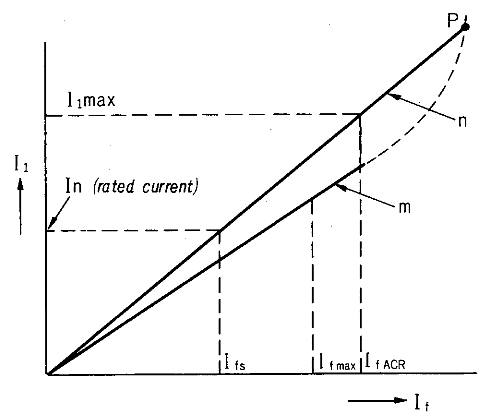


Fig. 13 ACR characteristics

ACR characteristics, it is not necessary to use special manufacturing conditions concerning the saturation characteristics of the excitation current/voltage converter. The set value I_{fACR} for suppression of field current must be set slightly more than I_{fmax} which

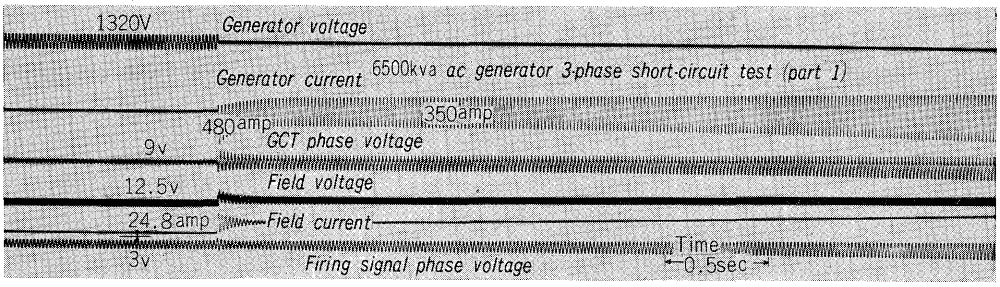


Fig. 14 Oscillogram of 3-phase short-circuit

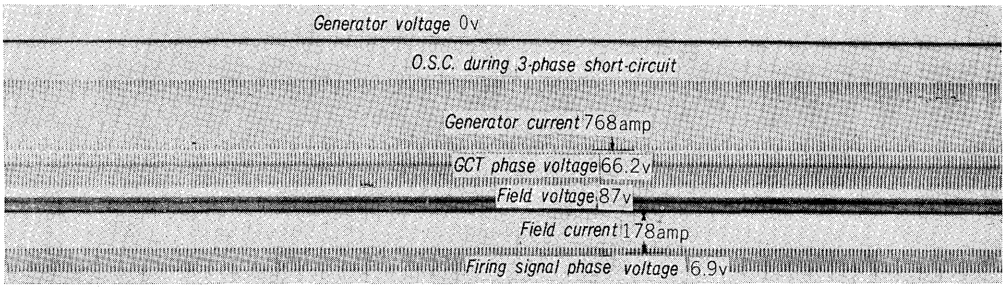


Fig. 15 Oscillogram under short-circuit conditions

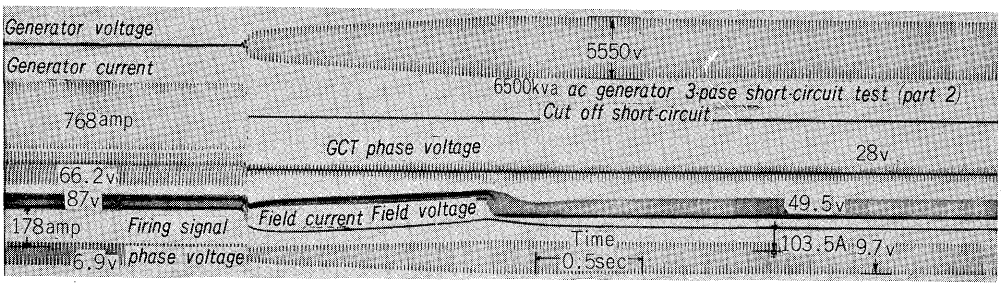


Fig. 16 Oscillogram at cut-out of short-circuit

Table 3 **Data of 3-phase Short-Circuit Tests**

Measurement Point / Time of Measurement	* V_g (v)	I_g (amp)	$I_F \cdot X_I$ (v)人	V_F (v)人	I_F ac (amp)	I_f (amp)
Before Closing	22.0	—	9	16.2	8	24.8
After Closing Setting	—	768	66.2	51.0	156	178
After Elimination Setting	89.0	—	28	65.0	67.8	104

* 6600/110 v PT secondary voltage

is required during emergencies. During a normal condition, the ACR has no relation to field exciting control. After the field current increases because of an AVR signal during bus line voltage drop, this value reaches the set I_{fACR} value, after the characteristic *PI* response time, the operation mode is switched over from the AVR to the ACR. This switching is not dependent on any external changeover signal, which means that very smooth switching between the AVR and ACR is possible. *Table 3* shows the data obtained from 3-phase short-circuit tests. *Figs. 14*, *15* and *16* show oscillograms at the time of the 3-phase short-circuit, during the short-circuit and at the time the short-circuit is cut out respectively. The pre-set value of the generator voltage for the short-circuit tests was 20% before the short-circuit, and imediately after short-circuit the setting voltage is changed over to 80% before cutting out of the short-circuit. I_{fACR} was 115% of I_{fs}.

VI. CONCLUSION

This article has given an outline of the results of tests carried out in the factory and at the site on the compound type thyristor excitation system which was introduced in the Fuji Electric Review Vol. 15, No. 3. This excitation equipment can maintain all its functions even during line faults and is more economical than other systems. We expect that this system will be used widely as main excitation equipment to improve the power supply reliability and quality in ever-expanding power systems.

In this article excitation system is explained using thyristor-diode mixed bridge construction for the thyristor bridge. If full bridge thyristors are used, by inverter operation, energy of field current will be fed back to ac network through excitation current transformer.

Reference

(1) Kaneda, Moriyasu, Yokokawa: Compound Type Thyristor Excitation System for Large Capacity Generators, Fuji Electric Review, Vol. 15, No. 3