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THYRISTOR-TYPE EXCITATION EQUIPMENT FOR WATER AND STEAM TURBINE GENERATORS

By Masaomi Nagae

Takehito Inoue

Development Dept.

I. PREFACE

Because of recent increase in electric power needs, the generating capacity of both steam and water power stations has been stepped up. Since generators are of prime importance in this case, static excitation equipment, noted for the high response ratio has been used rather frequently in place of rotary exciters.

In accordance with the remarkable progress made lately in semiconductor techniques, the reliability of various kinds of semiconductors such as thyristors and transistors has increased so much that effective application of such semiconductor characteristics as:

(1) Small and light weight,
(2) High mechanical strength,
(3) Low forward loss and high efficiency,
(4) Rapid operating and short response time,
(5) Small input and gate signals,
(6) Expansion of permissible operating temperature range.

has made it possible to manufacture static excitation equipment which is small and sturdy, useful with small power sources, and above all equivalent in response to self compound excitation equipment. Thus static excitation equipment is now being used in place of customary static-type self compound excitation equipment composed mainly of magnetic amplifiers, saturable current transformer.

Generally speaking, the response in generator excitation systems can be considered in relation to two major factors: time lag existing in all sections of the closed loop, and regulator characteristics. The open-circuit time-constant is most important when considering the former.

For instance, when it is necessary to intensify the magnetic field because of some disturbance, the amount of intensification of the magnetic field current is directly proportional to the time integral of the voltage that is induced in magnetic field by the action of the excitation equipment during the disturbance.

Therefore, it is absolutely necessary to intensify the field current by inducing a large voltage in the field as rapidly as possible during the disturbance.

The magnitude of voltage induced in the field is generally limited to 1.5~2.0 times the nominal slipring voltage according to the insulation level or excitation equipment capacity. The response ratio of various excitation equipment depends on how fast field voltage can be supplied during a disturbance.

Of course, in connection with the capacity to supply the necessary reactive power to the system and the synchronizing power, generator impedance and short-circuit ratio play a large role.

Although static excitation equipment with magnetic amplifiers and amplidynes has always been very common, there was a time lag in their control devices and they were accordingly limited in use as excitation equipment.

Self compound excitation equipment has solved the problem of time lag in the control device by supplying the necessary voltage directly to the field via a current transformer.

Progress in the manufacturing techniques of semiconductors, especially transistors and thyristors, has led to both reliability and low prices. It is now possible to manufacture control devices without time lag. This, in turn, has allowed for the fabrication of thyristor-type excitation equipment equivalent to self compound excitation equipment in response ratio and superior to it in price and size.

For generators used in atmospheres containing reactive particles, brushless excitation equipment with simple maintenance and inspection has been developed using toyristers for control.

II. APPLICATIONS OF VARIOUS KINDS OF THYRISTOR-TYPE EXCITATION EQUIPMENT

In comparison with rotary exciters, the usual self compound excitation equipment consists of a reactor with shunt winding characteristics, a current transformer with series winding characteristics, and a semiconductor rectifier for ac-dc conversion. The effective blending of the former two factors has resulted in compound characteristics and a high response ratio.

Even in the thyristor-type excitation equipment however, use of a transistor as detector and regulator allows time lag factors to be reduced to dead time with detector filter and thyristor controls (this time lag can be kept as low as 20 msecs at maximum by useing a detector filter with a high response ratio). If the excitation equipment source is maintained satisfactorily, the equivalent charcteristics can be kept high in response to disturbances such as voltage and load fluctuations with the customary self compound excitation equipment.

Principles in "Thyristor-Type Excitation Equipment for Water and Steam Turbine Generators" should be applied in practice according to several basic methods which differ as follows:

(1) Type of exciter
(2) Type of thyristor connection (hybrid bridge connection)
(3) Type of thyristor input source, and
(4) Type of AVR device and other detailed specifications for application.

Each method has merits and demerits; practical applications should be decided considering various characteristics such as excited generator capacity, rotational frequency, short-circuit ratio; system response; required excitation capacity at line short-circuits; excitation system response ratio; and the surroundings. (Comparison of each method is referred to in *Table 1.*)

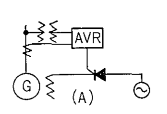
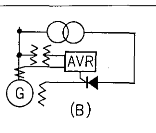
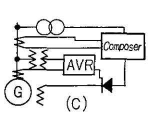
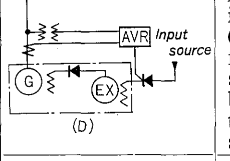
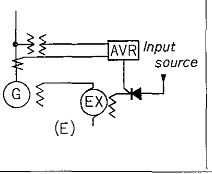
In order to maintain a stable excitation source, an ac source generator for thyristors must be placed coaxially with the main generator as is shown in *Table 1* (*a*).

Although there is no particular problem in turbine generators with a high rotational frequency, there is a problem in turbine generators with a low rotational frequency—i.e., application of source generators with high enough ceiling voltages to cope with disturbances would result in very large devices and costs. Because of this with water wheel generators, it is generally desirable to use the self-excitation type to remove the thyristor source from the main circuit via a source transformer. *Table 1* (*b*) shows this source transformer method, which is extremely effective in the response to system disturbances under normal operation.

However, this method has one defect—loss of excitation source during an overall short-circuit makes forced excitation impossible. However, this method can be adopted for medium and small capacity generators which have no particular importance in the system, or for generators which are to be aligned in a single system and designed to stop during short-circuit result in no line cuts.

That is, when a short-circuit occurs in the system,

Table 1 Various Types of Thyristor-Type Excitation Equipment

Excitation system		Thyristor Input Source	Connection Method	Regenerating Brake with Pure-Bridge Connection of Thyristor	Response	Excitation Capacity during a Short-circuit	Brush Maintenance	Economic Application
Thyristor Type Excitation Equipment	Static excitation equipment	a) Ac source generator (direct coupling or separate insertion)		Effective	Highly effective	Highly effective	Necessary	Direct coupling source generator is more economical for high speed device (ex. steam power)
		b) Source transformer		Inferior during source disturbance	Inferior	Inferior	Necessary	Simpler and more economical than (a) or (c); possible with medium and small capacity generator
		c) Source transformer and source current transformer		Effective	Highly effective	Highly effective	Necessary	Profitable with water wheel generators. Rather expensive in high speed machine with a small short-circuit ratio (ex. steam power)
	Ac excitor (direct coupling brushless generator)	Same as in static excitation equipment		Effective when input source is (a) or (c); inferior during source disturbance when the input source is (b)	Slightly inferior	Highly effective when the input source is (a) or (c); inferior during source disturbance when the input source is (b)	Not necessary	Applied in unsatisfactory environments; economical when used in high speed machines (ex. steam power)
	Dc excitor (direct-coupling or separate insertion	Same as in static excitation equipment		Effective when input source is (a) or (c); inferior during source disturbance when the input source is (b)	Slightly inferior	Highly effective when the input source is (a) or (c); inferior during source disturbance when the input source is (b)	Necessary	Used for reformation of existing excitation equipment

even if the line is cut by the last breaker, it does not take more than 2 seconds. In the case of generators with a big *Td'* and small *xd'* and *xd* such as water wheel generators, it is even possible for the field current to maintain the necessary voltage for reestablishment of the voltage after the line is cut.

In case of turbine generators, however, there is a slight disadvantage, but line cutting in generators is possible when the thyristor source is not taken from the power take-off side of the generators, but from the same bus line with the important auxiliary machine in the boiler system, since the turbine must be stopped when this source fails.

For generators that are important in the system, thyristor supply by combining components is derived from the supply transformer (voltage) and current transformer (current) as shown in *Table 1* (*c*).

Since the current part is meant for field maintenance during short-circuits, economical design is possible if the current transformer capacity can be made as small as possible by making the induced voltage and time as low as possible.

Therefore, the method is not economical when applied to generators that can be coupled directly at low cost with high speed machines, and have a big *xd* value like turbine generators.

The excitation equipment of brushless ac excitors and dc exciters with thyristors—(cf. *Table 1* (*b*) and (*c*)—is slightly different in comparison with the above-mentioned equipment, and is slightly inferior to them in response since it requires the help of excitors.

The brushless method, in particular, aims at simplifying maintenance by decreasing the brushes, slip-rings, and commutators. Since rotational frequency is particularly high, it is the most suitable excitation equipment for turbine generators in which brush wear is high.

III. EXCITATION EQUIPMENT WITH SOURCE TRANSFORMERS

A generator with a source transformer in which the thyristor is supplied from the main circuit through a source transformer has been delivered to the Sumise Power Plant of the Nippon Light Metal Co., Ltd. Presently it is operating well. Several more are now under production to be delivered to various plants.

Excitation equipment with a source transformer in general will be discussed later, based on actual data from the Sumise Plant.

Specifications of machines and devices in the Sumise Plant are as follows: (As to the circuit of this type of excitation equipment and its excitation cubicle, see *Figs. 1* and *2* respectively.)

Generator:	14,500 kva
	6.6 kv
AVR equipment:	Transidyn AVR
AVR source:	4000 va
Thyristor:	3 phase hybrid-bridge connection

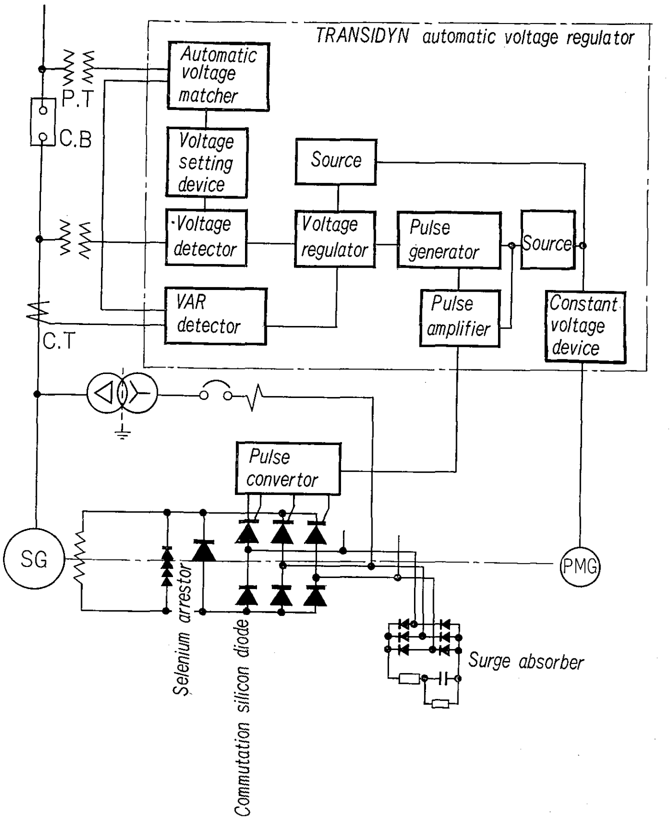


Fig. 1 Thyristor-type excitation equipment with source transformer

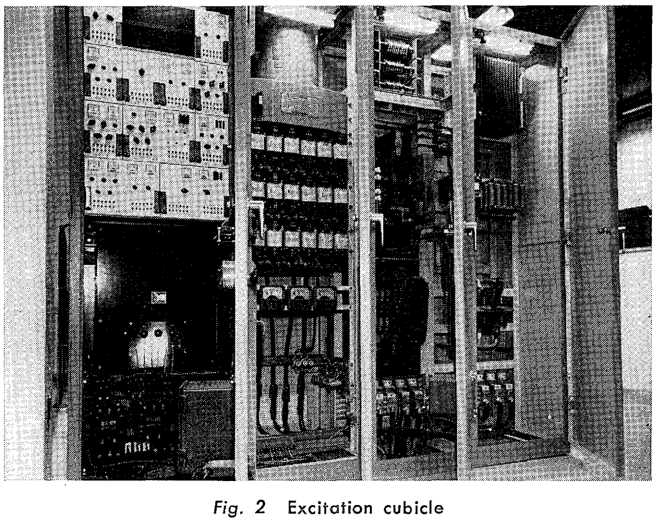


Fig. 2 Excitation cubicle

Characteristics of excitation equipment with source transformers are: high response ratio to overall disturbances such as voltage and load fluctutations during normal operation, simplicity of control since a large time lag occurs only in the generator field system, and ease of maintenance since the circuit is very simple.

Effective application of a TRANSIDYN device with semiconductors such as transistors and diodes developed by Fuji has resulted in the production of very high quality excitation equipment.

1. TRANSIDYN AVR Device

TRANSIDYN AVR device consists of detecting units, setting units, regulating units, and pulse generator units, as shown *Fig. 1.* Its characteristics are as follows:

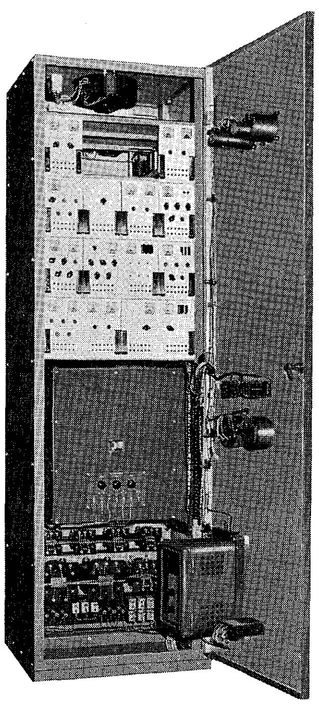
(1) Easy operation identification and maintenance inspection since all parts are based on the standard TRANSIDYN sizes with draw-out type construction. The regulating cock, meter, and test jack are arranged in the front of each panel (see *Fig. 3*).

(2) High reliability since all transistors, diodes, resistors, condensers, etc. have been selected carefully for the rated values with sufficient margins.

(3) High static gain since a PI regulator is used in the regulating unit; the equipment is capable of full-range regulation with a transistor optimum regulation system.

(4) Low time lag, which occurs only at the detection filter and is limited to around 20 msecs maximum since the detection filter has a high response ratio.

(5) Power can be supplied from an ordinary permanent-magnet generator with an electric governor since power requirements are low.



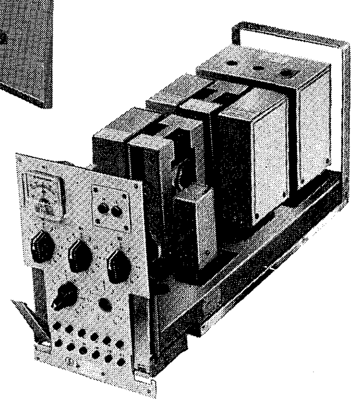


Fig. 3 TRANSIDYN cucicle and TRANSIDYN unit

2. Thyristor-Type Converter

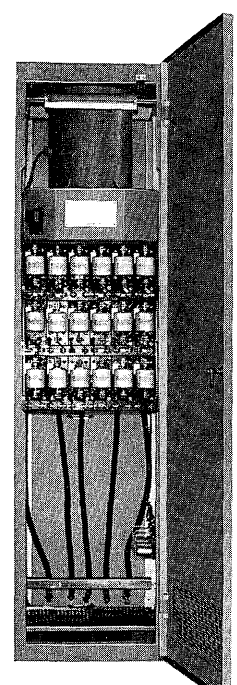
The thyristor-type converter contains a 3-phase hybrid-bridge connection of thyristor and silicon diode.

The most prominent feature of this 3-phase hybrid-bridge connection is that it enables perfect voltage maintenance by means of a commutating diode. There is no fear of abnormal voltages caused by open fields even when the gate pulse signal misfires since the commutating silicon diode short-circuits the field circuit.

There is another thyristor-type converter the 3-phase pure-bridge connection consisting solely of thyristor diodes. This system features rapid field current reduction when compared with the hybrid-bridge connection, inverter action when the thyristor source operates normally and quick demagnetization during some disturbance inside the generator. There is, however, a danger that the thyristor will misfire. This system is not effective in excitation equipment with a source transformer, since the thyristor source is always cut out when there is a short-circuit inside the generator.

Both the thyristor and silicon diodes are single units consisting of cooling fins, fuses, fuse alarm relays, resistance for potential dividing resistors, connection condensers, and pulse converters (only in the case of thyristor diodes). They are arranged in sequence in a cubicle of the draw-out type.

With this type of construction, it is easy to arrange a spontaneous commutation circuit. The circuit is compact and interchangeable since each unit can be drawn independently. Individual units can be replaced separately when there is some trouble in the diode or other parts. Maintenance inspection is therefore facilitated.



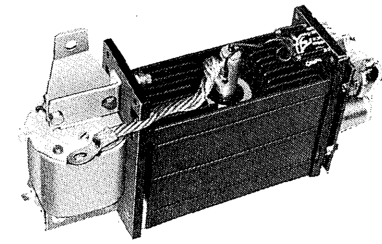


Fig. 4 Thyristor cubicle and structural unit

The pulse converter shapes the gate pulse signal fed to the thyristor. It converts the signal into two pulses; a hair pulse which is rapid at the beginning and wideband pulse to supply sufficient ignition energy. These are superimposed and sent to the thyristor gate.

Thus, it is possible to do away with overloading which occasionally occurs because of spreading out of the start-up time, even when there is an increase of registration with thyristors in series or parallel.

The thyristor can be used even in high capacity excitation equipment without worry.

When choosing a diode, it is necessary to select a rating with a sufficient margin for continuous resistance at maximum current during normal operation. A short time rating is also necessary in order to protect against large overcurrents occasionally induced in the field when a 3-phase short-circuit occurs in the main circuit.

3. Connection of the Source Transformer

As shown in *Fig. 5* there are two possible locations for the thyristor source. One is the power output side of the generator (A), and the other is the transmission line (B). Each point has merits and demerits and choice must be made after carefully considering the situation in the individual power station of the transmission system.

With self-excitation equipment, the former point (power output side of the generator) is generally used since it is possible to utilize the mains as a supply source during short-circuits in the system. In this case the generator voltage is maintained by the self exciting source when the line is cut.

However, there is one disadvantage: the field system requires a separate excitation source (ex. battery) at the beginning until the AVR equipment begins to operate. In this case, if the source voltage is supplied by TRANSIDYN AVR excitation equipment from a permanent magnet generator, the supply can be continued until the synchronizing signal of the phase regulator takes affect and the 50% voltage is sufficient for safety purposes.

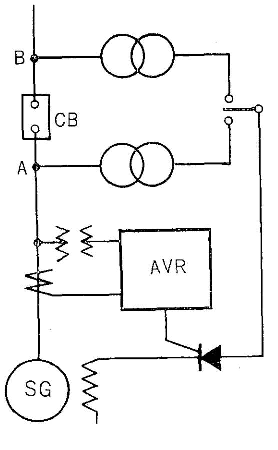


Fig. 5 Supply points of source transformer

When the thyristor source voltage is supplied from the transmission line, initial excitation is unnecessary at generator start-up, since a parallel generator breaker is opened—i.e., it is the same as if the voltage were supplied by a separate excitation source from the transmission line. In other words, the system voltage is required before the generator will start; only when the generator is connected in parallel with the system will the self excitation circuit be formed.

With this method, there is no need to form a special circuit even during drying when the generator is shut down for a long time as long as the transmission line maintains the voltage. A test is very easy even when the generator is shut off. The AVR device source voltage can be obtained from a source transformer.

4. Field Circuit Protection

Generally speaking, semiconductor diodes have such disadvantages as small overload capacities and limited inverse voltages (almost zero during a time excess).

For this reason, it is necessary to consider protecting the semiconductor diode against abnormal phenomena which sometimes occur in the excitation circuit during operation.

(1) Overvoltage protection

It has always been considered that abnormal voltage sometimes occurs during load interruption, short-circuits, lightning strikes, and commutation in excitation circuits which include ac circuits.

Although during load interruptions there is sometimes a decrease in field current in order to resist excessive magnetomotive force that has been reducing the armature reaction, no abnormal field voltage occurs since the field current can not flow in the inverse direction. Depending on the power factor, there is a voltage increase equal to the synchronous reactance drop in the generator caused by the load current on the main circuit side. However, this can be considered as negligible since it is only 20% maximum and is added in the direction of easy flow in the thyristor and silicon diode; it can also be inhibited immediately by AVR device with a high response ratio.

With a 3-phase short-circuit, generator flux drops at the beginning of the short-circuit, and therefore, field current increases in the direction of increasing flux—i.e., the direction of easy flow. Even if the thyristor accidentally misfires at this moment, abnormal voltage never occurs in the field since current flows through the commutating silicon diode. With a single phase short-circuit, the field current includes a double harmonic factor, although it never becomes strong enough to invert the field current.

During a lightning strike in the transmission line, abnormal voltage could be transferred to the excitation circuit via stray-capacitance between the primary and secondary coils of the source transformer or between the generator stator and rotor.

This can be avoided by placing a static shield between the primary and secondary coils of the source transformer so as to avoid a static connection. For utmost safety, an isolation transformer should be inserted in all input and power circuits of the TRANSIDYN. A selenium arrester is placed in the field circuit in order to absorb transfer voltage by utilizing the inverse characteristics of the selenium rectifier.

The magnitude of the selenium arrester voltage is fixed so that " silicon inverse voltage > selenium arrester voltage > ceiling voltage."

In order to measure the magnitude of the transfer voltage fed to the excitation circuit when a lightning strike or the like occurs in the main circuit, impulses from impulse analyzing equipment are supplied to the stator output terminals. As shown in *Fig. 6*, effects were negligible.

Abnormal voltage sometimes occurs during thyristor commutation when controlling induction voltage with the thyristor. This can be avoided by placing a surge absorber on the ac side.

(2) Overcurrent protection

Protection against short-circuits and overloads in the excitation circuit can be divided into two cases: ac circuits and dc circuits.

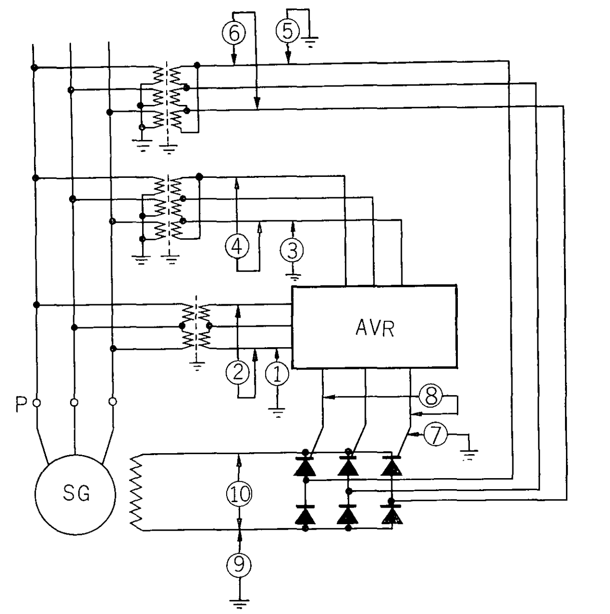
When there is a short-circuit in the ac excitation circuit, it is necessary to protect the source transformer. The common method is to insert a no-fuse breaker or air circuit breaker, with an overcurrent tripping device, on the secondary side of the source transformer. Another method is to place an overcurrent protection relay on the secondary side.

When there is a short-circuit or overload in a dc excitation circuit, immediate protection is necessary, since a thyristor diode with a small short-time capacity will soon be destroyed. Immediate protection on such occasions is possible by attaching super-rapid fuses to each element depending on their overcurrent characteristics.

The super-rapid fuse is attached with an alarm relay, which gives a signal on fusing in order to avoid spreading of damage.

5. Excitation Characteristics

A series of tests have been carried out at the Sumise Plant of Nippon Light Metal Co. to verify various characteristics of thyristor excitation equipment with a source transformer. The results of tests concerning transient characteristics which affect the excitation system response ratio are as follows:



(a) Observation point

Observation Point	1	2	3	4	5
Transfer Voltage (%)	1.03	1.38	0.73	0.26	1.02
Observation Point	6	7	8	9	10
Transfer Voltage (%)	0.24	1.05	0.19	1.05	0.31

(b) Results

Fig. 6 Transfer voltage of 14,500 kva synchronous generator as per surge test

(1) Initial response

Initial response was tested in the excitation system closed loop, by altering the established voltage by ±10%. A block diagram of the excitation system loop is shown in *Fig. 7*. The

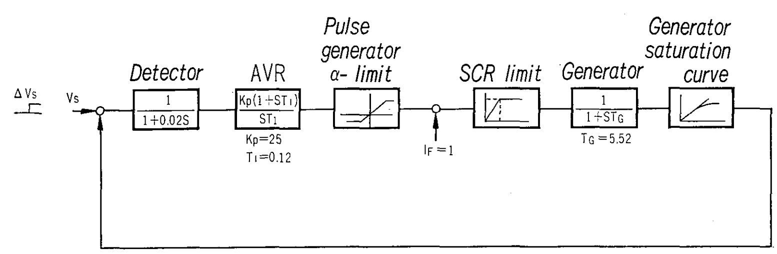


Fig. 7 Block diagram for indicial response

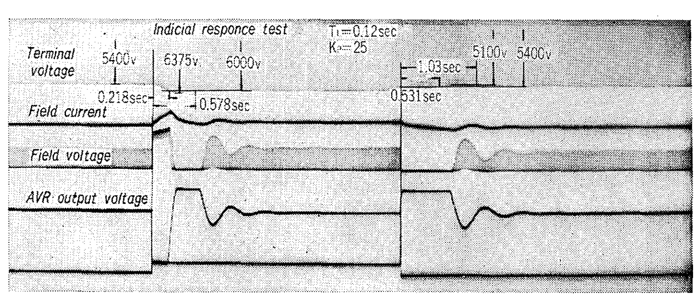


Fig. 8 Indicial response

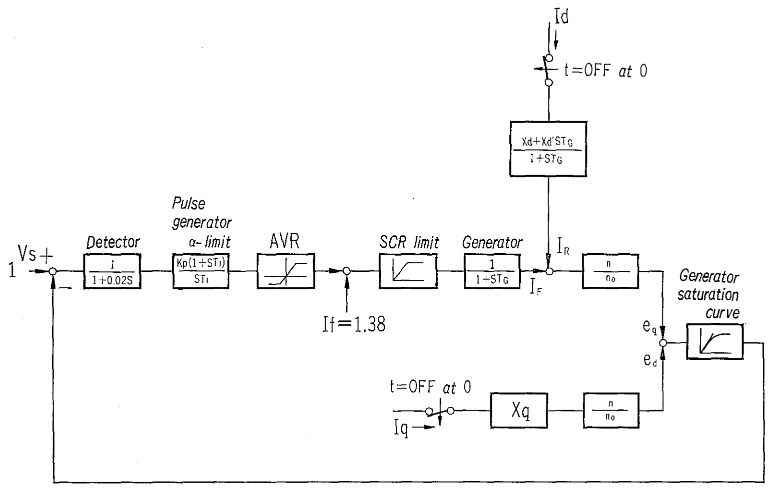
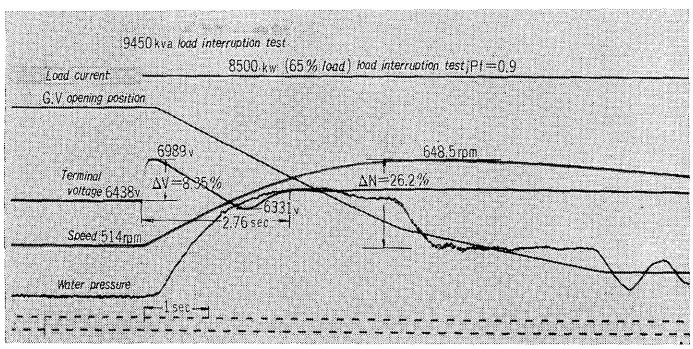
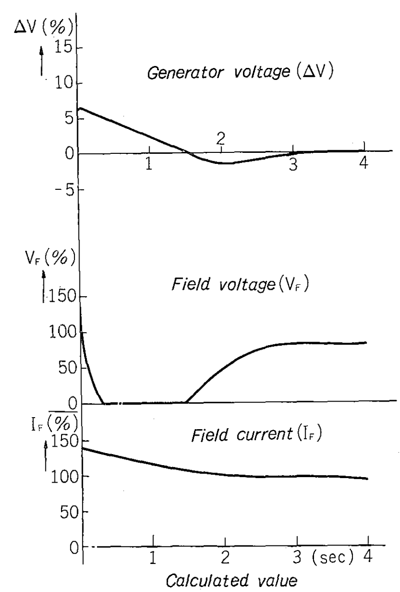


Fig. 9 Block diagram for computation at load interruption



(a)



(b)

Fig. 10 2/4 load interruption characteristics

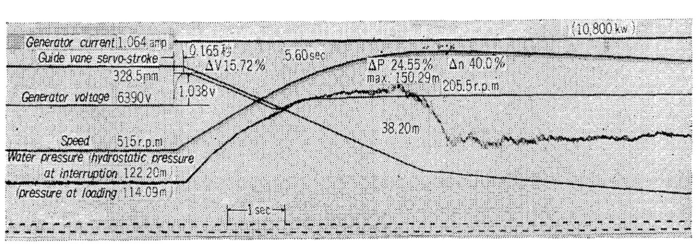


Fig. 11 4/4 load interruption characteristics

response time of one circuit, i.e., the time required to reach the established value for the first time—was only 0.218 seconds in accordance with the TRANSIDYN optimum adjusting theory. Therefore the high response ratio of the system has been established (cf. *Fig. 8*).

(2) Load interruption test

Fig. 9 is a block diagram pertaining to load interruption, with the generator damper effect, internal induced voltage (due to the transformation effect), and armature resistance and speed at constant value.

Load interruption characteristics can be observed by simultaneous interruption at the I_d and I_q pointsin *Fig. 9*. Theoretical figures obtained by a calculator agree well with the results of actual observations as shown in *Fig. 10*.

According to these results, the maximum voltage during load interruption is almost always less than the small transformer voltage caused by transient generator reactance (xd'). This can be explained by the high response ratio of the excitation equipment. Therefore, the maximum voltage during load interruption can be approximated by plotting the voltage characteristics of the generator in a vector diagram, without considering the speed rise of the turbine.

IV. CONCLUSION

Various types of thyristor-type excitation equipment have been introduced and, as a practical example, observation data concerning thyristor-type excitation equipment a source transformer, which was delivered to the Sumise Plant of Nippon Light Metal Co. was given. It is hoped that the excellent response characteristics of thyristor-type excitation equipment are evident from this article.

When using a thyristor excitation system in a generator, choose the most suitable method considering the various conditions discussed in this article.

In conclusion, we'd like to thank the staff of the Nippon Light Metal Co. who have cooperated with us in various fields.