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ELECTRICAL EQUIPMENT FOR HOT SKIN PASS MILL

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I. FOREWORD

Fuji Electric delivered electrical equipment to the Nagoya Iron and Steel Works of the Fuji Iron and Steel Corporation. This equipment was placed into operation in June of last year and is exhibiting top performance. In addition to the use of a thyristorized Leonard system for main d-c motors, this all-new installation includes control devices and instruments such as an X-ray thickness gauge, center line position control device extension meter and ton counter (automatic stopping device). This article gives a brief introduction of the equipment and covers the associated high-capacity power thyristors.

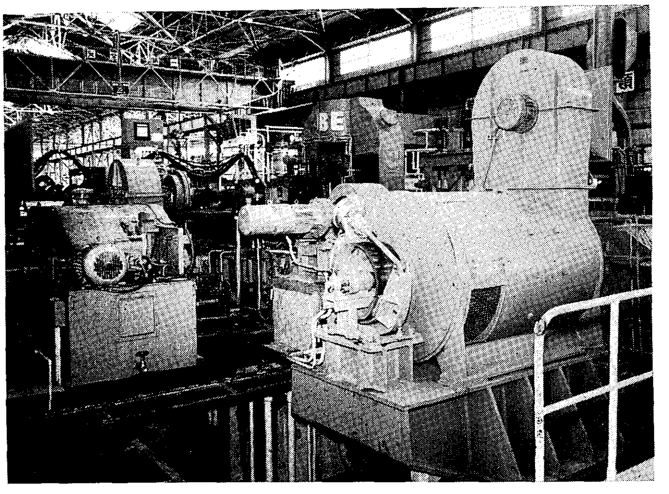


Fig. 1 Pay off reel motor (dc)

II. EQUIPMENT INTRODUCTION

This equipment serves to temper and recoil material which has been hot-rolled and pickled. Salient specifications are given below.

Processed material:
- Thickness: 1.0~6.35 mm
- Width: 500~1570 mm
- Coil diameter: Inside: 610 or 762 mm
  Outside: 1330~2032 mm
- Weight: 3.4~27.8 tons

Line speed:
- 300 mpm

Tension:
- Uncoiling side: 230~3500 kg-m
- Coiling side: 600~9000 kg-m

Equipment of the entry side consists of a conveyor, coil car, cradle roll, and other items. The coil on the coil conveyor is, for all practical purposes, placed over the mandrel automatically by means of automatic control equipment, and stops at a position which corresponds to the center of the line.

The pay off reel, along with the speed reduction device and drive motor, is designed to slide on the base through action of the electrically operated edge position control device. This control functions to shift the pay off reel in such a manner that one edge of the coil being fed is always aligned. However, the other edge will not be aligned in the case of this equipment unless the hot-rolled material is passed through a side trimmer. Thus, a detector is located at both edges, enabling the center position control to maintain the center of the material on a reference line.

The upper and lower rolls of the mill are driven only threading. The upper roll is separated by the magnetic clutch when its speed exceeds the threading speed, and the lower roll is driven independently. When recoiling, the lower roll is dropped and the tension reel is switched to the "speed-master".

The mill is loaded by hydraulic cylinders. With ordinary screw down systems which use electric motors, rolling is accomplished by establishing a fixed clearance between rolls. This hydraulic system offers an additional feature: Rolling can be made while holding pressure applied to rolls at a constant value.

The tension reel is a stationary type which permits coiling in either direction.

Equipment of the delivery side includes a coil car, scaler, strapping machine, and coil conveyor. As in the case of the entry side, the maximum degree of automation is applied.

III. ELECTRICAL EQUIPMENT

Table 1 gives specifications of main drive components. A thyristorized Leonard system is used for all d-c motors in this equipment. There are no motor-generator sets in the electrical room. Instead, transformers, reactors, and thyristor cubicles are arranged in neat rows. High tension cubicles, thyristor transformers, reactors, and high-speed air circuit breakers are located in the first floor electrical room. This room is divided and includes the air filter and intake fan (turbo fan). The control center, TRANSIDYN cubicles, d-c control panels, and thyristor cubicles are located in the second floor electrical room.

1. Main Drive Motors (dc)

The main drive motors conform to JEM–1157. Insulation is Class-B and the temperature rise is 40 deg (40°C ambient temperature). These motors will withstand a 115% overload continuously, 125% overload for two hours, and 200% overload for one minute (all field ranges). The ventilating system is a separate type (fan mount). Mill and tension reel motors have a laminated yoke designed to improve commutating characteristics. Roller bearings are used in the pay off reel and mill motors, and natural-cooled sleeve bearings (with cooling fins) for the tension reel. The generator for speed detection projects from one end of the mill motor. The pilot generator for no-load loss compensation and the pulse generator for automatic stopping are directly coupled to one end of the pay off reel motor.

2. Thyristors

Two GTN 01–10 thyristors are used in series. Both have unit construction (to be described).

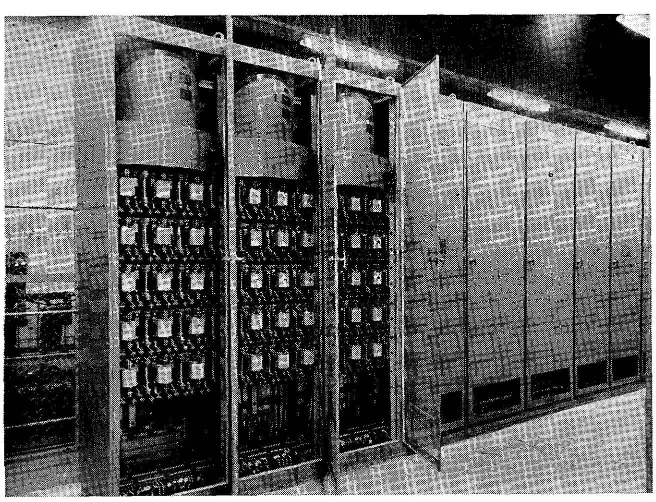


Fig. 2 Thyristor cubicles

Thyristor elements are accomodated in a standard thyristor cubicle. Cross connections are used, and the arrangement is that shown in *Table 1*. The number of parallel elements is determined by: Continuous 100% overload on converter side for pay off reel and continuous 200% overload on inverter side ; continuous 200% overload on converter side direction for mill and continuous 100% overload in inverter side and continuous 200% overload on both converter and inverter side for tension reel.

3. Thyristor Transformers and Reactors

The transformers are indoor oil immersed self-cooling types, and the reactors are dry types with Class-H insulation. Reactors are selected to realize five-percent cross current control.

4. Ventilating Equipment

One 13 m^3/sec, 35 mmAq silocco fan is installed in the fan room. After passing through an air filter air is forced to the first and second floor of electrical rooms. Air replacement in the electrical rooms is accomplished by eight propeller fans which force interior air outside.

5. Measuring Instruments

An X-ray thickness meter is used which has a measuring range of 1.0∼7.99 mm and difference indicating ranges of $+500\,\mu\sim-450\,\mu$ and $+100\,\mu\sim-90\,\mu$.

6. Automatic Stopping Device (ton counter)

This functions to stop the line automatically after a set weight of material has been coiled on the tension reel (coiling stop) or material remaining on the pay off reel diminishes to a set length (tail end stop). The first case improves operating efficiency in respect to product control and the second operating efficiency and safety.

Fig. 3 is a block diagram of the system. The following description begins with coiling stop. In general, when decelerating and stopping the line, deceleration is made at a constant rate as shown in *Fig. 4*. Coiling length L from the start of deceleration until speed V is reached (when decelerating from line speed V_0 at constant rate α) is represented by:

$$L = 1/2\alpha(V_0^2 - V^2) \quad \text{..................(1)}$$

Coiling length l_0 until full stop is represented by:

Table 1 Specifications of Main Drive

Application	Motor				Thyristor Arrangement		Transformer		
	Qty	Output (kw)	Voltage (v)	Speed (rpm)	Convert	Invert	Capacity (kva)	2ry voltage (v)	Connection
Pay Off Reel	1	150	600	300/1050	2S 1P 6 amp	2S 1P 6 amp	217	610	△/人人
Skin Pass Mill	1	300	600	500/1500	2S 3P 6 amp	2S 2P 6 amp	480	610	△/人人
Tension Reel	1	500	600	300/1050	2S 5P 6 amp	2S 3P 6 amp	795	610	△/人人

$$l_0 = \frac{V_0^2}{2\alpha} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

By letting l_R represent the remaining length and incorporating equations (1) and (2):

$$l_R = l_0 - L$$
$$= V^2/2\alpha$$
$$\therefore \quad V = \sqrt{2\alpha l_R} \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Thus, the line can be brought to a full stop under a constant rate of deceleration if line speed V satisfies equation (3) in respect to remaining length l_R. By letting l_s represent the desired winding length and V_M the actual speed determined by MRH, the relationship shown in *Fig. 5* is obtained.

With this equipment, control is made by converting all set weights to lengths. In other words, the desired winding weight (ton count setting) *Wh*, thickness *h*, and width *w* are set, the desired winding length l_s is operated and "$i_s - l_0$" is preset in the preset counter. The winding length is counted after passage through the roll diameter compensating circuit, by means of pulse generator PG1 directly connected to the pinch roll at the entry side. As shown in *Fig. 5*, remaining length l_R is made a variable by means of the function generating circuit when the winding length reaches "$l_s - l_0$" (point-C) and speed command "V" (deceleration pattern CDE) from equation (3) is generated. Speed command V is A/D converted and compared to actual line speed V_M. V decreases in step with the decrease of l_R. At point-D ($V_M \geqq V$), switching is made from line speed control by MRH to control by output V of the deceleration pattern. The line advances from *D* to *E* and stops.

The next phase is tail end stop. Coil length l remaining on the pay off reel is represented by the following equation when number of pay-off turns n, coil diameter D, and thickness h are included.

$$l = D_0\pi n + n^2 h\pi \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

The first step is comparison of pulses from pulse

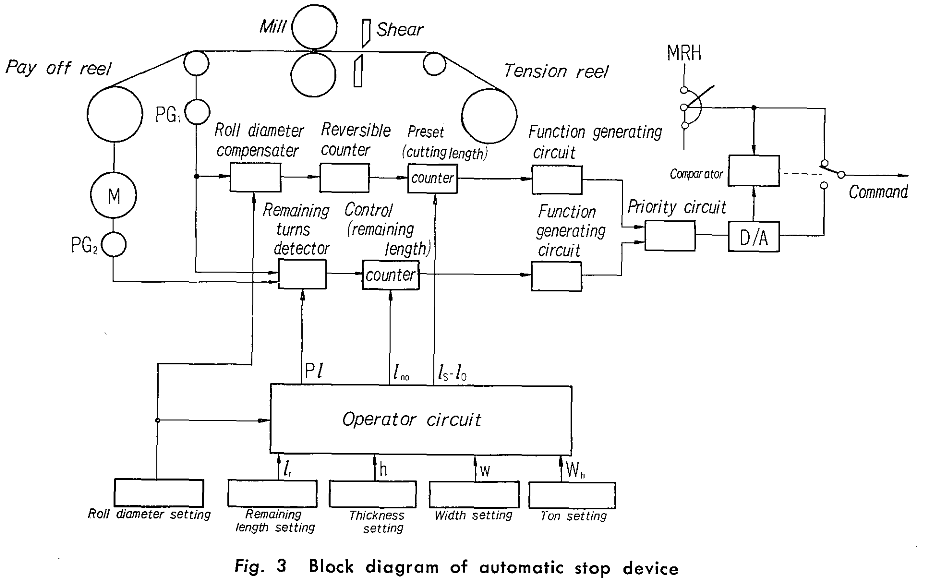


Fig. 3 Block diagram of automatic stop device

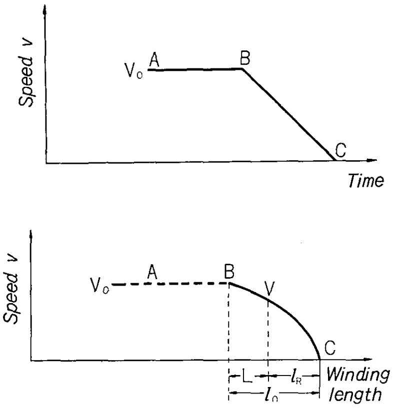


Fig. 4 Speed relation ships

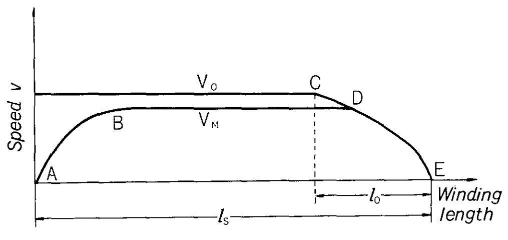


Fig. 5 Winding relationship

generator PG1 attached to the pinch roll at the entry side and pulse generator PG2 attached to the pay-off reel motor. In other words, the number of winding turns N is determined by counting the number of PG2 pulses before the pulse count *Pl* (determined by operation) of PG1 is reached.

The number of winding turns N is established to give:

$$D_0\pi N = l_0 + l_r \cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

The term l_r represents the set winding length. Uncoiling is made to the extent "$l_{n0} = N^2\pi h$" preset in the remaining length counter. When this has been completed, the deceleration pattern is generated. The remaining procedure is identical to that for coiling stop. When the stopped state is reached, only the set length remains on the pay off reel.

Fuji Electric has already produced many automatic stop devices of this type and all are giving excellent service.

IV. MAIN DRIVE CONTROL

1. Mill Control System

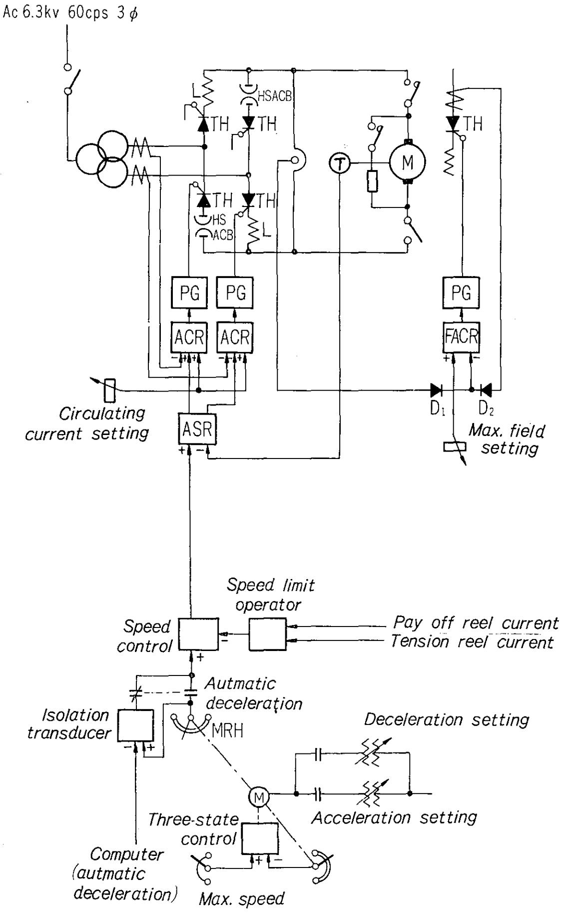
The mill control system is illustrated in *Fig. 6*. A cross connection formed from a three phase bridge is used for the main circuit, giving constant control of cross current.

TRANSIDYN equipment is used for all controls. Speed control having a minor current loop is applied, giving automatic control of motor fields by means of a single command.

There are several types of speed command signal systems for this mill, and these are described in the following.

Desired speed can be set at the control desk. Maximum speed can also be set and automatic deceleration control described previously applied. This arrangement boosts efficiency and improves safety aspects. Another item is maximum acceleration control which conforms to the overall installation.

This arrangement controls equipment speed in accordance with the individual load states of the pay off and tension reels. Thus, maximum acceleration which can be considered applicable for the overall installation is set by MRH (set to approximately five seconds from starting to maximum speed due to equipment strength limitations). The resultant speed signal becomes input for speed control. This control is a unit integrator which functions to convert a rapidly changing signal to an appropriate speed signal. Quite naturally, however, setting must



FG: Thyristor gate shifter
ACR: Armature current control
FACR: Field current control
MRH: Motor operated speed control
TH: Thyristor
HSACB: High-speed air circuit breaker
L: Reactor

Fig. 6 Block diagram of mill control system

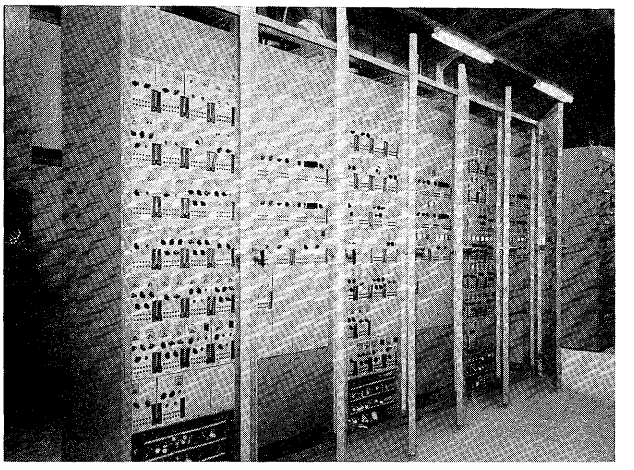


Fig. 7 TRANSIDYN cubicle

be made to an integrating time which is less than the MRH speed setting. The resultant output becomes input for the speed control.

When starting is made under maximum speed as established by MRH, acceleration is applied at that rate if individual units are lightly loaded. If, for example, tension of the tension reel is set to a very high value, however, the sum of accelerating current of the motor and tension current will exceed the capacity of tension reel power source facilities (equal to 200% of motor capacity). In this case, the tension reel current is detected, the acceleration limit computer immediately provides output, adjustment is made by the speed control, and acceleration is continued at a (reduced) rate which falls within the permissible capacity. In other words, maximum acceleration is that governed by the permissible capacity limit of the pay off and tension reels in this instal lation.

This type of control presents problems in respect to tension variation and control stability among components when the installation is considered as a whole. Various conditions were assumed and analysis made by electronic computer, revealing that this type of control is more than adequate in actual applications.

2. Pay Off Reel Control System

The pay off reel control system is illustrated in *Fig. 8*. As in the case of the mill control system, a cross connection formed from a three-phase thristor bridge is used for the main circuit. Constant tension control by counter emf control through current and motor field control is realized. An automatic tension-speed switching circuit is incorporated which eliminates the possibility of overspeed from tension current when cutting the material. This circuit enables automatic switching from tension control to speed control or operation in the reverse direction, by output limit control derived from high TRANSIDYN gain. Further description is not given in this article, as various information concerning this circuit has already been published.

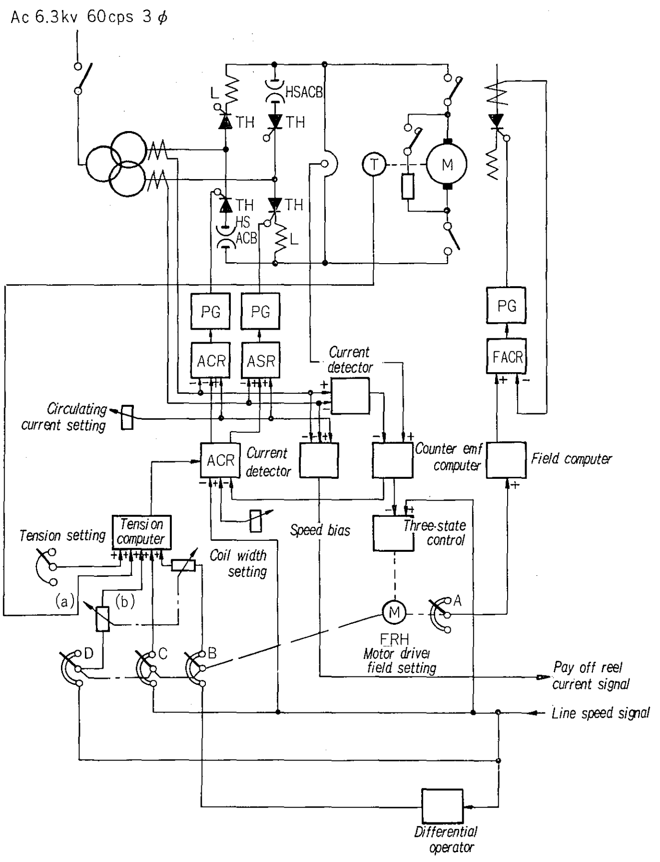


Fig. 8 **Block diagram of pay off reel control system**

There are many instances when material on the pay off reel is loose at this installation. If a large tension setting is applied, coils will be pulled taut, causing scratches. Therefore, a small tension setting is usually used. In this case, no-load loss compensation must be very exact. In other words, when the tension setting is small, current is applied to effect uncoiling of the pay-off reel.

In general, the no-load loss for this type of reel can be considered as shown in the following.

$$L=(C+W)\alpha n \quad \ldots\ldots(6)$$

$$W=\left(\frac{D^2}{4}-\frac{D_0{}^2}{4}\right)\pi\rho t \quad \ldots\ldots(7)$$

- L: Wear loss
- W: Coil weight
- α: Coefficient of friction
- D_0: Coil inside diameter
- t: Coil width
- C: Stationary weight
- n: Motor speed (rpm)
- D: Coil outside diameter
- ρ: Specific weight

From equations (1) and (2):

$$L=\left\{ C+\left(\frac{D^2}{4}-\frac{D_0^2}{4}\right)\pi\rho t \right\}\alpha n \quad \ldots\ldots(8)$$

Relationship between line speed and coil diameter:

$$V=k\pi n D \quad \ldots\ldots(9)$$

- V: Line speed
- k: Gear ratio

From equations (3) and (4) by considering " $D^2 \gg D_0{}^2$ ":

$$L=\left\{ C+\frac{D^2}{4}\pi\rho t \right\}\alpha n = C\alpha n+\frac{\rho\alpha}{4k}\cdot DtV \quad \ldots\ldots(10)$$

In other words, friction loss from equation (10) is represented by the sum of the motor speed function and coil diameter, coil width, and line speed functions. In this installation, as shown in *Fig. 8*, no-load loss compensation input (*a*) to the tension computer is obtained from output of the tachogenerator (corresponds to motor speed), and (*b*) from coil width (from coil width setting control located at the operating desk) and coil diameter (from line speed signal and D-dial of FRH), effecting compensation. At this installation, (a) at maximum speed is max. 5.9% and all items related to (B) are max. 5.0% under maximum conditions.

3. Tension Reel Control System

As in the case of the mill control system, a cross connection formed from a three-phase thyristor bridge is used for the main circuit, and tension control identical to that for the pay off reel is applied.

However, the tension setting of the tension reel differs from that of the pay off reel insomuch as it is always large and a comparison of tension currents reveals that no-load loss current may be disregarded. Thus, no-load loss compensation is not applied.

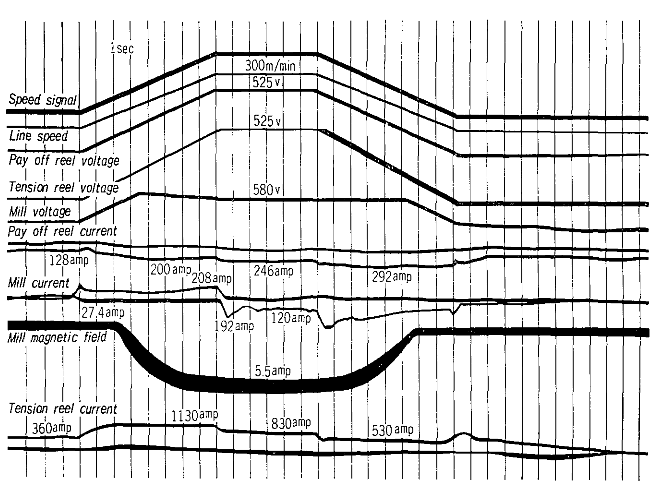


Fig. 9 **Oscillogram**

The tension reel becomes the "speed-master" of this installation during recoiling operation. In other words, constant speed control consisting of feedback of the line speed detector (tachogenerator) is applied to the tension reel. Back tension is applied by the pay off reel.

Switching between tension and speed control of tension reel (between skin pass and recoil) is easily accomplished by means of the automatic tension-speed switching circuit previously described.

Switching between tension reel winding directions can be freely made.

Fig. 9 depicts an oscillogram showing operating conditions of pay off and tension reels.

V. THYRISTOR RECTIFIER EQUIPMENT

1. Thyristor Firing and Extinction, and Duty of Rectifier Equipment

There are several problem points relating to three-phase bridge-connected rectifiers. The following items pertain to conditions in each arm at the time of firing and extinction.

1) Firing

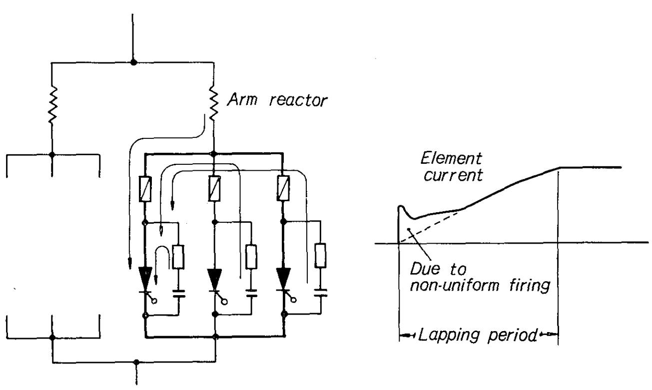
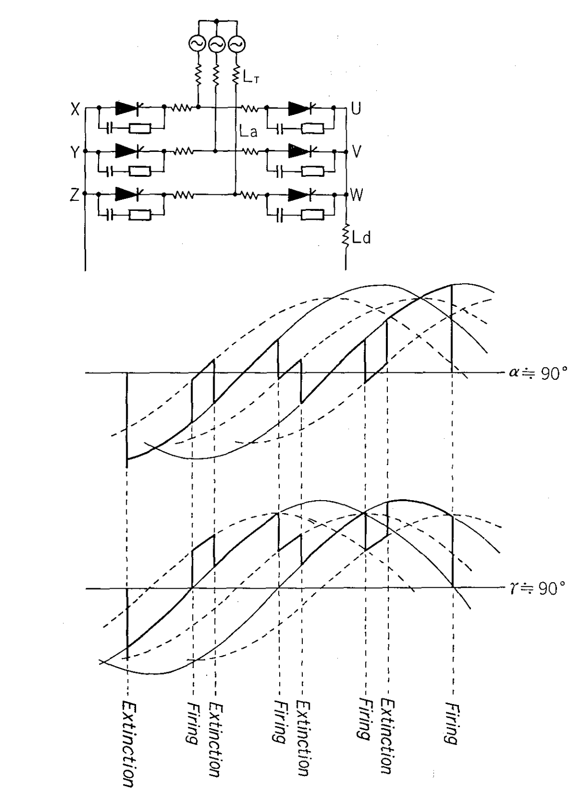


Fig. 10 Thyristor current at the time of firing



L_T: Transformer reactance
La: Arm reactor
C_1 R: Filter between anode and cathode
U, V, W, X, Y, Z: Main thyristors
Ld: D-c smoothing reactor

Fig. 11 Blocking voltage in three-phase bridge connection

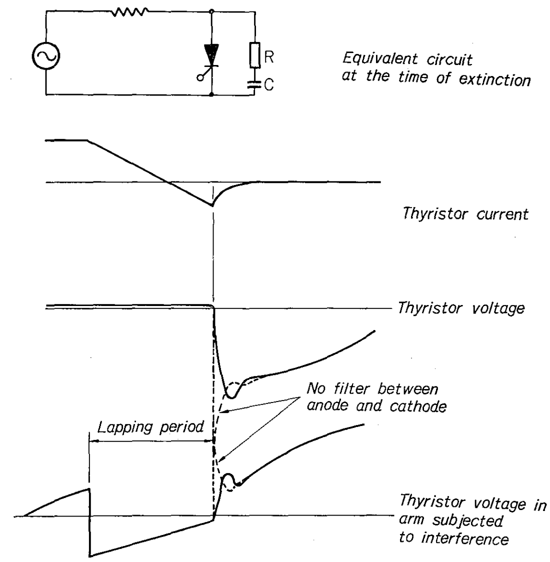


Fig. 12 Transient waveforms at the time of extinction

(1) Magnitude of discharge current (from the r-c filter) which flows in the element which fires first in a particular arm (due to non-uniform firing characteristics of elements connected in parallel). (Refer to *Fig. 10.*)

(2) Rise time "di/dt" of main circuit current in the above case.

(3) Positive "dV/dt" magnitude caused by interference in an arm which is blocked. (Refer to *Fig. 11.*)

2) Extinction

(1) Magnitude of initial inverse voltage caused by Hall-storage effect in element which has fired. (Refer to *Fig. 12.*)

(2) Magnitude of "dV/dt" caused by interference in an arm which is blocked. (Refer to *Fig. 10.*)

If permissible values of thyristors in any of these cases are exceeded, breakdown (flashback) or break-through will occur, causing commutation failure during inversion and excessive rectifier current.

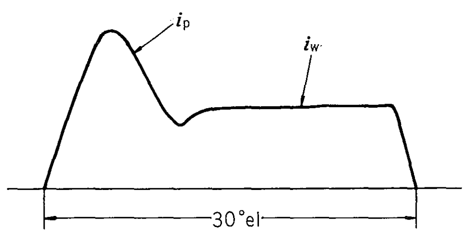
In general, the R-C filter between the anode and cathode of applied thyristor elements determines the element withstand voltage, a-c reactance, and inverse current (caused by the Hall-storage effect).

This filter is effective in suppressing dV/dt and the initial inverse voltage at the time of extinction. However, an anode reactor is connected as there is no suppression of dV/dt at the time of firing.

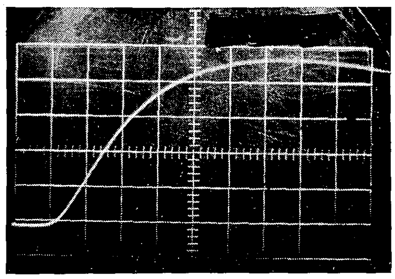
When the number of parallel connected elements is increased, the magnitude of discharge current of the R-C filter at the time of firing becomes large. In this equipment, an arm reactor is connected for each set of three elements when there are three or more elements connected in parallel, and serves to provide a suppression effect for discharge current. (Refer to *Fig. 10.*)

2. Gate Current Duty

Firing of thyristors in series-parallel connection:



(a) Standard gate pulse current



(b) Peak rise current (gate)
Current axis: 1 amp/div
Time axis: 1μs/div

Fig. 13 Gate current

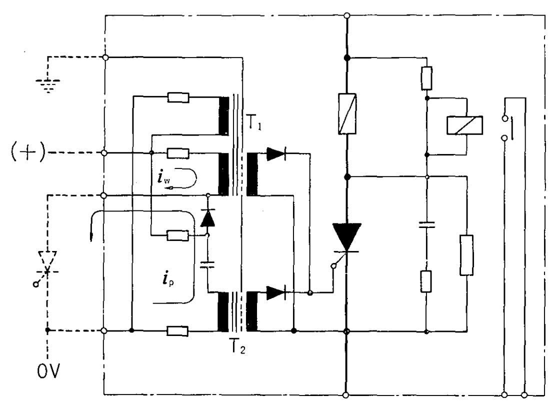


Fig. 14 Thyristor unit connections

1) Positive firing
2) No unbalance in switching loss at "turn-on" time

These two items present problems. As the methods of firing, however:

1) Cascade triggering method which utilizes the firing of one element to effect firing of the remaining elements.
2) Direct triggering method which applies gate current to all elements at the same time.

Fuji Electric uses the direct triggering method, since non-uniform firing readily occurs in the cascade triggering system, leading to unbalancing of switching losses.

There are two types of direct triggering systems: one which has independent pulse transformers for each thyristor and the other which has a single pulse transformer with split secondary winding for connection to each thyristor. In the interest of improving reliability, Fuji Electric employs (as standard) the type which has individual transformers.

Fig. 13 depicts gate current. Narrow and wide pulses are superimposed.

Amplitude at the wave peak is approximately ten times the static triggering gate current. Positive triggering is effected by applying current with a short rise time (better than one ampere per microsecond). At the same time, "turn-on" loss is reduced by eliminating non-uniformity of firing.

The continuation of current flow guarantees positive equipment operation by providing an amplitude which is approximately double the static triggering current.

The pulse width is determined by considering positive holding of the conducting state (by means of local anode current). Rise characteristics of current flowing in thyristors which fire when starting or switching main circuit current are more than adequate.

As shown in *Fig. 14,* these gate currents are obtained by superimposing the output of two transformers.

3. Thyristor Unit

When one thyristor is used, a heat sink, fuse, r-c filter, pulse transformer, and alarm device for fusing are required as accessories.

Fuji Electric combines these items into a single standardized unit for each thyristor. Connections are shown in *Fig. 14.*

The primaries of the gate pulse transformers are connected to the phase shifter. As wiring in this circuit affects gate current rise time, each item is individually connected by coaxial cable. Special wiring procedures are used to exclude external noise interference.

4. Overvoltage and Overcurrent Protection

Procedures pertaining to overvoltage protection are listed in *Table 2.* A special problem in the case of thyristor rectifiers is that of surges in the a-c power source.

Filters such as those shown in *Fig. 15* can be installed to suppress surges. However, the circuit in (a) of this figure is not suitable for large capacity rectifiers since filter discharge current surges into conducting thyristors because of rectifier firing effects. Fuji Electric employs the discharge blocking filter arrangement shown in (b) of *Fig. 15.*

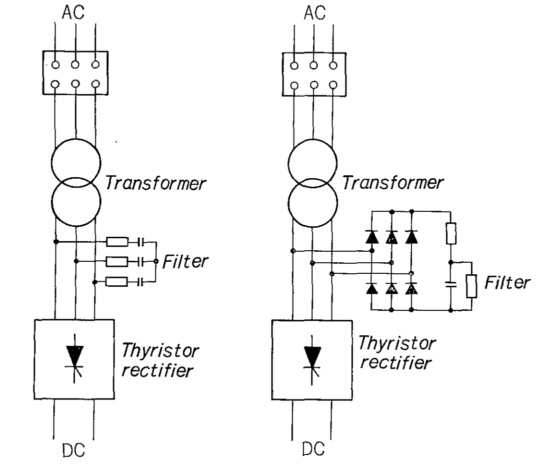
Fig. 16 is an oscillogram which shows the surge suppression effect in respect to primary interruption of the rectifier transformer, the major source of a-c surges.

If the primary of the transformer is interrupted when the rectifier is unloaded, abnormal voltage will be produced since there is no circuit to absorb magnetic energy stored in the transformer core. If a filter is connected, this energy is absorbed in the filter, suppressing the generation of abnormal voltage.

Overcurrent protection is described in the follow-

Table 2 **Overvoltage Protection**

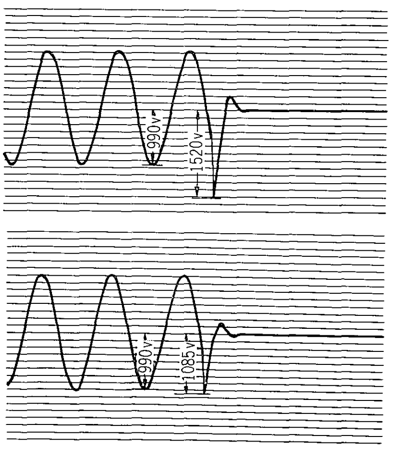
Fault	Protection
Oscillatory voltage due to Hall-storage effect	Filter between thyristor anode and cathode
Surge voltage at make and break on a-c side breaker	R-c filter on secondary side of transformer
Surge voltage at make and break on d-c side breaker	D-c circuit filter (thyristor element filter)
Source overvoltage	Overvoltage protective relay
Lightning stroke	Incoming circuit arrester



(a) Standard gate pulse current (b) Filter without discharging current

Fig. 15 Ac surge absorbing filters

ing. The permissible thyristor overcurrent curve is divided into two areas in the form of permissible



(a) No ac filter

(b) With ac filter

Fig. 16 Surge voltage at opening of circuit breaker on primary side of transformer

continuous overcurrent time, the area above one cycle and that below one cycle. Protection (gate interruption) can be made for overcurrent within the permissible value which continues for more than one cycle by means of gate pulse phase control. This means that protection must be made by such items as a fuse or circuit breaker since phase control is not possible for overcurrent with duration less than this.

In this equipment, overcurrent limit control and gate interruption are made in the case of overload current, but fuses and circuit breakers are used for protection in the case of overcurrent arising from a short-term short-circuit.

Table 3 covers phenomena related to overcurrent for various faults and the operation of protective and control equipment.

VI. CONCLUSION

Practical usage of thyristors is not new. However, engineering problems remain as before, since demands of the present age have become more severe. Engineering experience realized from the completion of this equipment has given those at Fuji Electric a great sense of accomplishment.

We wish to thank the personnel of Fuji Iron and Steel Corporation for their invaluable guidance and extensive cooperation.

Table 3 **Overcurrent Protection**

	Fault	Overcurrent	Protection	Control
Power Rectifier	Backfire (Breakdown)	One phase short-circuit, overcurrent in good arm	Fuse	Gate pulse shift
	Element breakthrough	Element overcurrent	Fuse	Gate pulse shift
	Element misfire	Overcurrent in good element of arm which includes misfire element	Fuse	Gate pulse shift
	D-c side short-circuit	One phase or three phase short-circuit	Circuit breaker	Gate pulse shift
	A-c interruption	Increase in conducting angle (increase in average current) of arm conducting immediately before ac interruption	—	—
Power Inverter	Element backfire	1. Phase short-circuit, overcurrent in good arm 2. Commutating failure	Fuse, Circuit breaker	Gate pulse shift
	Element break through	1. Element overcurrent 2. Commutating failure	Fuse, Circuit breaker	Gate pulse shift
	Elementmisfire	1. All elements in one arm: Commutating failure 2. One or more elements in one arm: Overcurrent in good elements	Fuse, Circuit breaker	Gate pulse shift
	Interruption of a-c power	Commutating failure	Circuit breaker	—
	Controller fault (abnormal phase controll angle)	Commutating failure	Circuit breaker	Pulse shift