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ELECTRICAL EQUIPMENT FOR NEW WIRE ROD MILL

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I. FOREWORD

Fuji Electric Co., Ltd. delivered a complete set of electrical equipment for the new wire rod mill at the Kobe Factory, Kobe Steel Works, Nadahama, Japan. A few weeks after installation, the equipment was put into operation very successfully with maximum rolling speed.

The products manufactured by this mill are mainly 5 mm ϕ and 7 mm ϕ wire rod. The maximum delivery speed reaches 6700 fpm and the most modern techniques have been employed for the electrical equipment combined with the rolling machines. The mechanical equipment in the mill was manufactured by the Kobe Steel Works, and a complete set of electrical equipment for use therewith was manufactured by Fuji Electric Co., Ltd.

II. MILL OUTLINE

Fig. 1 shows the schematic layout arrangement of the mill consisted of roughing mill train (No. 0 through No. 4 stands), intermediate mill train (No. 5 through No. 15 stand), and the finishing mill train (No. 16 through No. 21 stands). Although two lines A and B were designed for the intermediate mill train and the finishing mill train, only line A has been installed for the moment.

A steel billet from the furnace is forwarded to the No. 0 stand and then the No. 1 stand by roller table. A tilting table is provided on each stand to perform several return rollings. The billet passed through the roughing mill train is led into the intermediate mill train which consists of 11 roll stands. The finishing mill train consists of six roll stands, three of them are vertical and the other three are horizontal. They are alternately arranged in a straight line. As the result of this way, it is fully expected to increase output and to improve the precision of the products. Single strand loop rolling under no-pull condition is employed at the finisher, and each stand is equipped with individual motor. For the little loop between each finishing stand, quite efficient automatic constant loop control is performed. In addition, the rolling stands are appropriately by-passed in accordance with the desired finishing diameter of the products, and any one of the stands Nos. 17, 19, and 21 can be accordingly selected as the final stand. The wire forwarded from the final stand is wound alternately with laying reel, and then transferred to the coil yard by means of coil conveyor and hook conveyor.

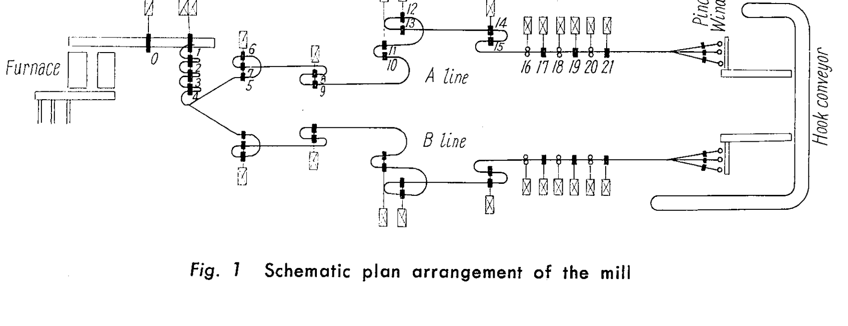


Fig. 1 Schematic plan arrangement of the mill

III. MAIN ELECTRICAL DRIVE EQUIPMENT

The major specifications of the main electrical drive equipment are shown in *Table 1*. As well known, for continuous wire rod mill, static Leonard system is used for the purposes of speeding up the rolling speed, precision product development, and required electric power reduction. Also for this mill, mill drive motor, except No. 1 roughing mill, dc motors are used and the static Leonard feeding systems with mercury-arc rectifiers are used. In the automatic speed regulators, Transidyn control system equipped with transistorized controller and computer is employed in order to provide fast speed of response and the best steady state speed regulation. To be more specific, the advantages of the Transidyn control system are mainly ① in the roughing mill with good current control operation. Main circuit interruption due to overload does not

Table 1. Main Drive Specifications

Machine		Motor					Mercury-arc Rectifier			
Machine	Stand No.	Output (kw)	Time Rating	Speed (rpm)	Voltage (v)	No. of Machines	Type	Output (kw)	Voltage (v)	No. of Machines
No. 1 roughing mill	0	950	Continuous	600	3300 60 cps	1	—	—	—	—
No. 2 roughing mill	1, 2, 3, 4	750	Continuous	650/900	375	2	Multianode PSL 2011 Type	825	750	2
A line, No. 1 intermediate mill	5, 6, 7	660	Continuous	750/1200	750	1				
A line, No. 2 intermediate mill	8, 9	450	Continuous	750/1200	750	1				
A line, No. 3 intermediate mill	10, 11	550	Continuous	750/1200	750	1	Multianode PSL 2011 Type	900	750	3
A line, No. 4 intermediate mill	12, 13	450	Continuous	750/1200	750	1				
A line, No. 5 intermediate mill	14, 15	450	Continuous	750/1200	750	1				
A line, No. 1 finishing mill	16	225	Continuous	900/1800	440	1	Multianode PSL 1211 Type	260	440	1
A line, No. 2 finishing mill	17	225	Continuous	900/1800	440	1	Multianode PSL 1211 Type	260	440	1
A line, No. 3 finishing mill	18	225	Continuous	900/1800	440	1	Multianode PSL 1211 Type	260	440	1
A line, No. 4 finishing mill	19	200	Continuous	1200/2400	440	1	Multianode PSL 1211 Type	260	440	1
A line, No. 5 finishing mill	20	200	Continuous	1200/2400	440	1	Multianode PSL 1211 Type	260	440	1
A line, No. 6 finishing mill	21	200	Continuous	1200/2400	440	1	Multianode PSL 1211 Type	260	440	1
A line, pinch rool	—	20	Continuous	2600	440	3	Single-anode PEL 0212 Type, 3-phase half wave connection	24.2	440	3
A line, reel	—	30	Continuous	2000	440	3	Single-anode PEL 0212 Type, 3-phase half wave back-to-back connection	35.2	440	3

occur and the operating efficiency is developed, and ② in the intermediate and the finishing mills. By improving the transient impact speed drop characteristics higher speed rolling can be easily performed.

1. Main Drive Motors

Except for the No. 1 roughing mill, all rolling stands are driven by dc motors, having overload capacities of 125% load (2 hours) and 200% load (1 minute.) Roughing mill motors are installed in the electric room, hence, they are designed for pipe ventilation. All other motors located outside the electric room are made as up-draft forced ventilation. Cooling air is fed to the motors by several variable pitch propeller fans installed in the fan room through the underground common air duct. No. 2 roughing mill motors are tied mechanically with reduction gears, and the armatures of both motors are electrically connected in series. For the roughing and the finishing mill motors, considering impact loading, design improves the transient characteristics for commutation by laminating yokes. Especially the finishing mill motor is a high speed motor operated through mercury arc rectifier power feeding and

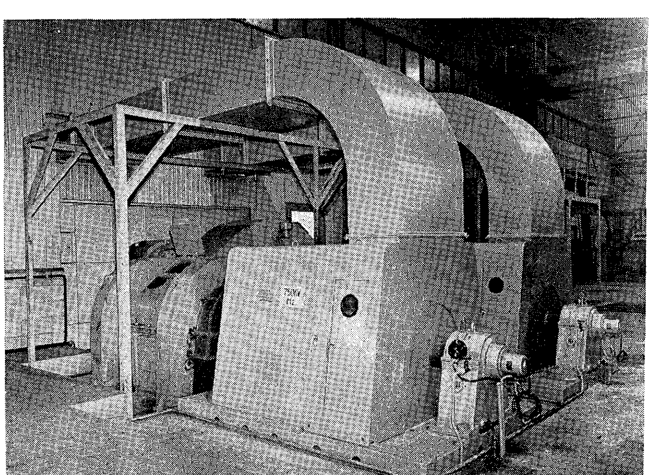


Fig. 2 Two 750 kw dc motors for four stand roughing mill

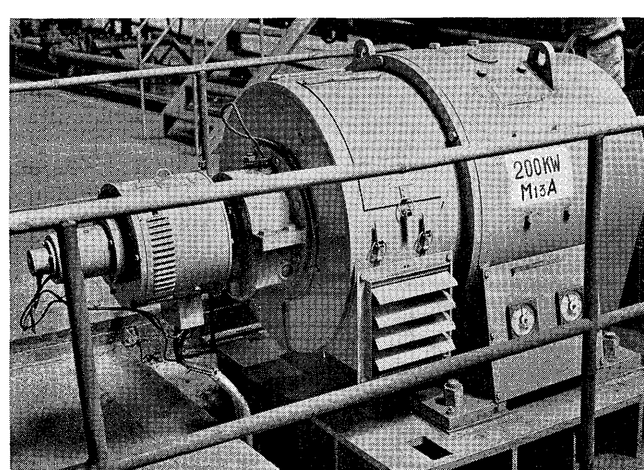


Fig. 3 Dc motor for finishing mill

Rectifier Transformer				Remarks
Capacity (kva)	Voltage (v) (60 cycles)	Connection	No. of Machines	
—	—	—	—	Wound rotor
2300	33,000/848	Delta/ double star	1	Individual feeding
3520	33,000/796	Star/ double star	1	Common bus feeding
369	3300/508	Delta/ double star	1	Individual feeding
369	3300/508	Delta/ double star	1	Individual feeding
369	3300/508	Delta/ double star	1	Individual feeding
369	3300/508	Delta/ double star	1	Individual feeding
369	3300/508	Delta/ double star	1	Individual feeding
369	3300/508	Delta/ double star	1	Individual feeding
43	440/542	Delta/ zig-zag star	3	Individual feeding
62	440/542	Delta/ zig-zag star	3	Indiviudal feeding

relatively wide field-control range. Thus particular consideration is taken to the commutation, and the brush is carefully selected. The bearings used in the finisher motor are sleeve bearings using forced oil circulating cooling. In the automatic speed control system applied to the intermediate and finishing mill motors, it is quite necessary to lower the level of the low frequency voltage ripple of the tacho-generator as much as possible, by which great effects influences may be caused to this system as a disturbance.

For this reason, the tacho-generator is overhung on the shaft end of the motor in order to eliminate voltage ripples due to the mechanical vibration of the motor shaft and the speed up gear mechanism between the motor and the tacho-generator successfully. It is ideal to select a constant current power source for tacho-generator exciting, economical consideration, however make it use constant voltage powersource. For the roughing mill motor, pinch-roll motor, and reel motor, permanent magnet type tacho-generators are used, and these tacho-generators are directly coupled to the motor shaft end.

2. Mercury-arc Rectifier

For the main drive motors multi-anode air-cooled sealed type mercury-arc rectifiers are used. The overload capacities are 125% load 2 hours, and 200% load 1 minute. For the roughing mill and the finishing mill motors, individual feeding method is employed, and for the intermediate mill motor,

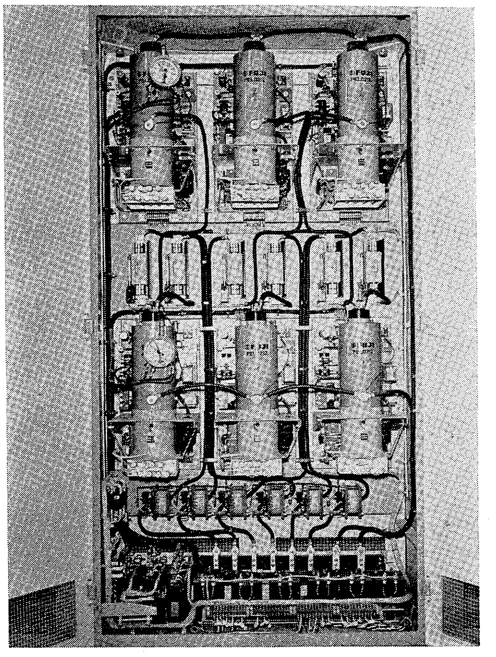


Fig. 4 Mercury-arc rectifier to provide armature current of the reel motor

common bus feeding method is employed. When the billet is bit, the roughing mill performs size reduction by utilizing the flywheel effects, hence it is necessary to provide an armature current limiting regulator to control the armature voltage so that an excessive load current does not flow in the motor. For this reason, individual feeding is provided for the roughing mill motors. For the finishing mill, a highly precise constant speed control is required, and at the same time, the response in the speed control system has also to be fast, so the individual feeding method is adopted. For the intermediate mill, the rolling speed is comparatively low and the permissible loop length is long, so the common bus feeding is employed, and with adjusting the exciting current of the motor, constant speed control is performed. The mercury-arc rectifier is contained in a special rectifier room. Ventilation hole is provided in the lower portion of the rectifier room side wall, and the cooling air is fed from the electric room through that ventilation hole. Beneath the rectifier room ceiling, some propeller fans automatically operated according to the room temperature are provided in order to exhaust heated air to the outside. As explained above, cold air fed from a forced draft fan is not drawn into the rectifier room directly, but through the electric room, so that anode units of the rectifier do not become too cold. In the control of the rectifier tank cooling fan, transistor type temperature controller (provided with proportional actions) is used.

For the static Leonard power sources to provide armature current of the pinch roll and reel motors, small capacity single-pole mercury-arc rectifiers are used. For the individual motors for the pinch rolls, three single-pole rectifying tanks adopting three-phase zig-zag star connection are contained in one cubicle, and for the individual reel motors, six single-pole rectifying tanks adopting three-phage zig-zag back-to-back connection are contained in one cubicle. The reel rotating direction is decided to one direction; however, it is necessary to perform so-called "wave control" so that the produced wire is wound on the reel drum with a proper width. For the load applied to the reel is light, it is necessary to effect both accelertating and braking current alternately. For this reason, the rectifier is provided with the converter and the inverter. In the rectifier cubicle ignition exciters, grid bias devices, anode fuses, anode current transformers, and automatic temperature controlling devices are contained with the rectifier. The mercury-arc rectifiers for mill motors are installed in the special room, but this rectifier cubicles are not required to install in a special rectifier room, and are located in the electric room where other control panels are installed.

3. Rectifier Power Transformer

Rectifier power transformers and smoothing reactors are located in the transformer room. Both are nitrogen-sealed, oil-insulated, self-cooling types. In the rectifier transformers, interphase reactors are self-contained. In the primary side of the each rectifier transformer equipped with the roughing mill and the intermediate mill motors, motor-operated no-load tap changer is provided to change the rectifier nominal d-c out from 560 to 750 v for the roughing mill and from 510–750 v for intermediate mill in several steps in equal percentage. The voltage between those steps can be continuously obtained by comparatively little phase control. It is also possible to obtain a wide range d-c voltage only by the phase control; however, it is not advantageous in case of a large capacity rectifier transformer because the power-factor drops in accordance with the control-factor and duty of the mercury-arc rectifier increases. In the finishing mills the capacity is comparatively small, the tap switch is not provided, and the voltage range is obtained only by the phase control. The rectifier power transformers and the smoothing reactors for the pinch roll and reel motors are dry type, and located in the electric room.

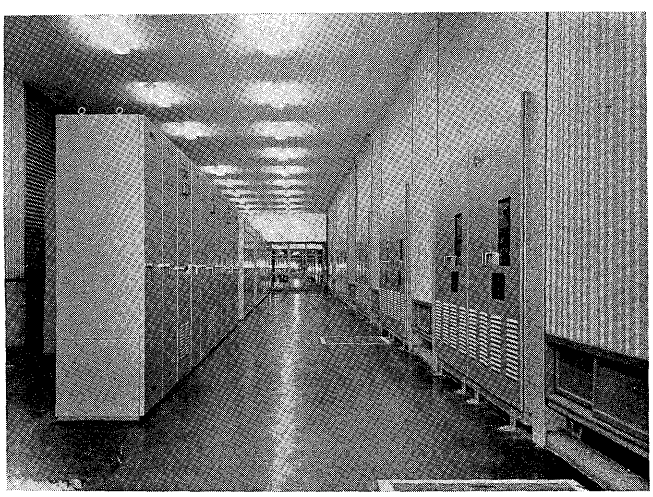


Fig. 5 Electric room

IV. AUXILIARY DRIVES

A total of 76 ac auxiliary motors are arranged from the furnace front table to the coil unloader, and many solenoid valves are used in the reel selecting devices, snap shear, etc. Almost all of these may be automatically controlled.

V. MAIN DRIVES AUTOMATIC CONTROL

1. Roughing Mill Control System

The control system for roughing mill motors are shown in *Fig. 6,* in which the Transidyn control system is employed. Each controller and computer is contained in an independent plug-in type unit so as to be convenient for testing, adjusting, maintenance, and inspection.

Unit integrator controls the rate of change of speed reference signal below a proper limit. On the unit integrator, output limit is interlocked with the selected tap of the rectifier transformer (MR. Tr). Therefore, even if the speed setter is set at a higher speed, the speed reference to the speed controller never exceeds a proper value which is limited by the selected MR. Tr tap.

For the speed controller is a PI-controller, and its output is the reference to the minor loop which controls the armature current, the maximum output is limited according to the armature current value to be limited. The current controller is also a PI controller, and its output controls pulse phase of grid control device. The armature current detector is provided with a circuit which obtains a voltage signal from the secondary current of anode current transformer in a level suitable for the current controller input.

CEMF-computer obtains an output which is proportional to the counterelectromotive force of the motor by means of substracting the voltage which is proportional to the armature current from the voltage which is proportional to the armature voltage. This is as described below, provided to control the motor speed by single speed reference both in the voltage control range and in the field control range. The field current controller is a PID type the output of which controls the field exciting current through the thyristor.

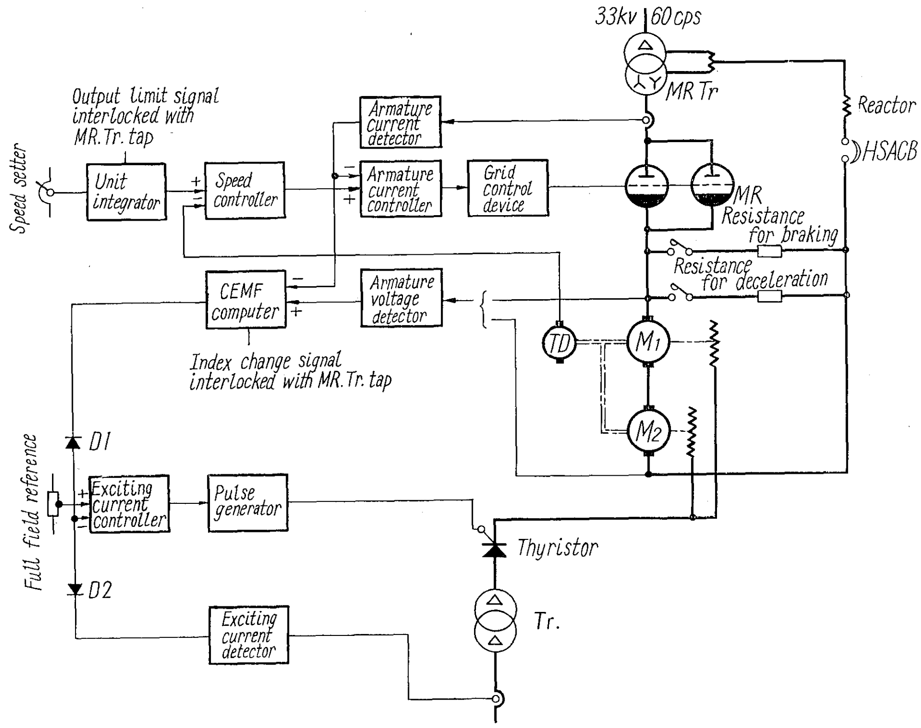


Fig. 6 Control system block diagram for roughing stand motors

As the reference to the field current controller the reference signal corresponding to the full field current signal is applied. And when the setting speed is low, exciting current feed back signal passes through the diode D_2 and counterelectromotive force feedback signal in blocked by diode D_1 so that the exciting current is kept at the maximum value. It is so designed that, when the counterelectromotive force is increased up to the voltage with which the motor gets into the field control range, the voltage of the CEMF-computer output becomes equal to the exciting current detector output. Therefore, the diode D_1 conduct, and the diode D_2 is blocked when the counterelectromotive force tends to increase due to the increase of speed reference. As the result, the field current controller controls the exciting current so as to make the counterelectromotive force a constant value combined with the selected MR transfomer tap, so the field is weakened by maintaining the counterelectromotive force as constant, and increases motor speed up to the setting speed. *Fig. 7* shows the oscillogram of changing the speed reference from zero to the maximum and from the maximum to zero in the unit step.

2. Intermediate Mill Control System

The intermediate mill motor control system is shown in *Fig. 8* of which consists bus voltage control and speed control.

The bus bar voltage adjustment is given by motor operating setter. The power amplifier only amplifies the current, and its output is limited to prevent the voltage setting exceeding proper bus voltage decided by the MR. Tr. tap.

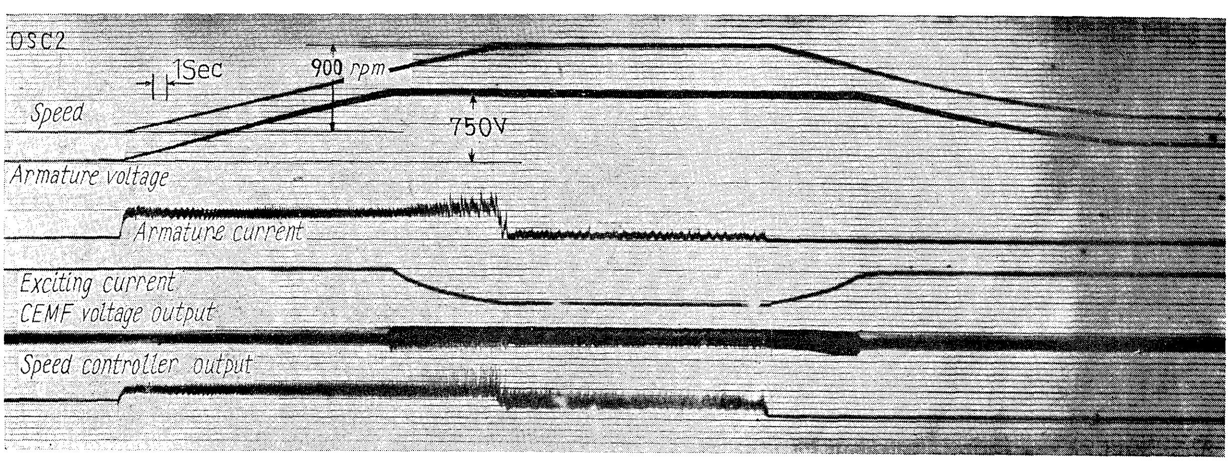


Fig. 7 Oscillogram shows acceleration and deceleration of roughing stand motors

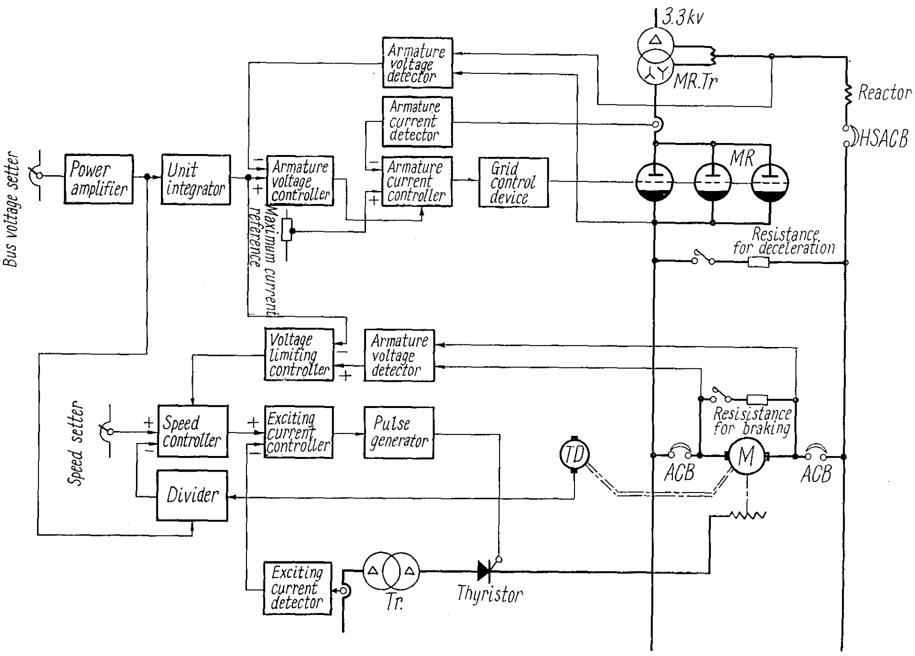


Fig. 8 Control system block diagram for intermediote stand motor

Unit integrator controls the rate of change of bus bar voltage reference signal below a proper limit.

The output of the unit integrator is the reference to the voltage controller. The voltage controller is a PI controller, and when the bus current does not come up to maximum, this output is directly sent to the grid control device. For the above purpose signal selecting circuit is provided in the current limiting controller. The bus bar voltage is detected by a voltage detector, insulated from the main circuit, and fed back to the voltage controller.

The current limiting regulator, when the rectifier current is about to exceed the maximum value, switches the grid control device input from the voltage controller output to the current limiting regulator output to limit the rectifier current.

The speed reference to the speed control system is also given by the motor operating setter. This speed reference is applied to the speed controller. Since the speed reference is given in a form of ratio of speed range in time of proper bus voltage, the tacho-generator output is divided by the bus voltage reference and is fed back to the speed controller. With this method, even if the bus voltage is altered, the loop gain of the speed control system remains steady.

The speed controller output is sent to the field current controller as the field current reference. In the reference circuit of the field current controller, non-linear element is used in which diode layer voltage is provided in order to compensate the change of the loop gain due to the field saturation. The field current controller output is applied to the pulse generator for the thyristor gate. The exciting current, detected by the current transformer and the field current detector, fed back to the field current controller.

In order to prevent armature voltage exceeding the nominal voltage in case that, immediately after a rolled wire rod is passed out, the voltage limit regulator compares the bus bar voltage reference and the actual armature voltage, and when the latter rises, the voltage limiting controller initiates to weaken ing of the field prior to controlling the speed. This signal selecting circuit is provided in the speed controller.

For the transfer function of the field control system, it can be expressed as depicted in *Fig. 9*.

In the figure, to obtain $dN/d\Phi$, the following equations apply:

Assuming,

$$\frac{1}{\{(1+ST_a)R_a\cdot SJ\}}\equiv G_1 \quad\cdots\cdots(1)$$

the following equations (2) and (3) are established

$$(1-N\Phi)\Phi G_1=N \quad\cdots\cdots(2)$$

$$\therefore\ N-\Phi G_1+NG_1\Phi^2=0 \quad\cdots\cdots(3)$$

thus, differentiating this equation with Φ

$$\left(\frac{dN}{d\Phi}\right)-G_1+G_1\left\{\left(\frac{\Phi^2 dN}{d\Phi}\right)+N2\Phi\right\}=0 \quad\cdots(4)$$

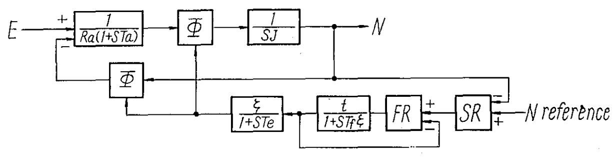
$$\therefore\ \frac{dN}{d\Phi}=\frac{\{G_1(1-2N\Phi)\}}{(1+G_1\Phi^2)} \quad\cdots\cdots(5)$$

Assuming that $N\Phi=1$ is almost satisfied:

$$\frac{dN}{d\Phi}\doteqdot\frac{(-G_1)}{(1+G_1\Phi^2)} \quad\cdots\cdots(6)$$

$$\therefore\ \frac{dN}{d\Phi}\doteqdot\frac{-\frac{1}{\Phi^2}}{1+\frac{R_aSJ}{\Phi^2}+\frac{R_aJT_aS^2}{\Phi^2}} \quad\cdots\cdots(7)$$

The equation (7) is in a form of quadratic equation; however, if the following equation (8) can be established, the equation (7) can be approximated as equation (9).



E: Armature voltage....Rated as 1 (constant)
Ra: Armature resistance (ratio to 100% resistance)
Ta: Armature time constant
J: Inertia constant (time required in reaching the base speed from zero when $\Phi=1$ under the rated current)
N: Speed....1 at the base speed
ζ: Field saturation factor (1 when it is not saturated, but when saturated, it becomes smaller than 1)
Te: Field eddy-current delay time constant
Tf: Field time constant
FR: Field controller
SR: Speed controller

Fig. 9 Block diagram for field control

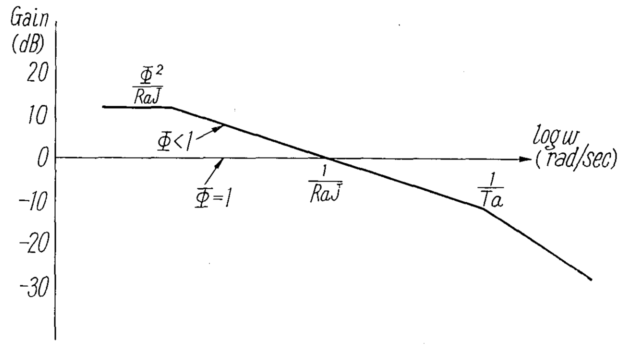


Fig. 10 Frequency response for $dN/d\Phi$

$$\left(\frac{R_a J}{\Phi^2}\right) \gg T_a \quad \cdots\cdots(8)$$

$$\frac{dN}{d\Phi} \doteqdot \frac{-\dfrac{1}{\Phi^2}}{\left(1+\dfrac{R_a JS}{\Phi^2}\right)(1+T_a S)} \quad \cdots\cdots(9)$$

Thus, the frequency response is changed in accordance with Φ as indicated in *Fig. 10*. If the cut-off frequency in the speed control system is taken as "ω" in a smaller value than $1/RaJ$, the system stability can be made not to change even if Φ is changed. In the event that the condition of the equation (8) is insufficient, the response in high frequency is also influenced by the value of Φ. Especially, when the denominator of the equation (7) cannot be separated into an equation of the first degree, differential compensation is performed at the speed controller, and the stability is studied further, considering the changing of the Φ. As explained above, if $dN/d\Phi$ can be obtained, the stability and response time can be studied as a simplified loop.

Fig. 11 is an oscillogram of actual rolling operations performed by the 5th intermediate mill. Since the 5th intermediate mill bites the billet two times, the impact speed drop is duplicated. During rolling, the loop control signal is applied, and just before passing out the wire rod, the signal to minimize the loop is initiated to drop the speed.

3. Finishing Mill Control System

The finishing mill control system is depicted in *Fig. 12* which is very similar to that of the roughing mill control system. The different points are that no tap is provided in the MR. Tr, and the control method in shifting into the field control range. The field current negative feedback is not applicable to the finishing mill. The CEMF reference is made to correspond to the nominal CEMF, when the field weakening begins. For this reason, the field current controller is saturated when the CEMF computer output, i.e., the actual CEMF value is smaller than the reference. This saturated output is limited by the field current controller output limiting circuit so that the phase control angle from the pulse generator corresponds to the full field current. When the output of the CEMF computer becomes equal to the reference and is about to rise further, the field current controller is actuated to maintain the CEMF in a constant voltage, weakens the field, and raises the speed.

Especially for finishing mill, the speed stability must be improved, the impact speed drop must be minimized, and be recovered quickly. As to the stability of the speed, Transidyn system which is provided with high gain and excellent response time is employed. With the Transidyn system, stability is confirmed to stay within $\pm 0.1\%$.

Fig. 11 Oscillogram shows control characteristics of intermediate stand motor under operation

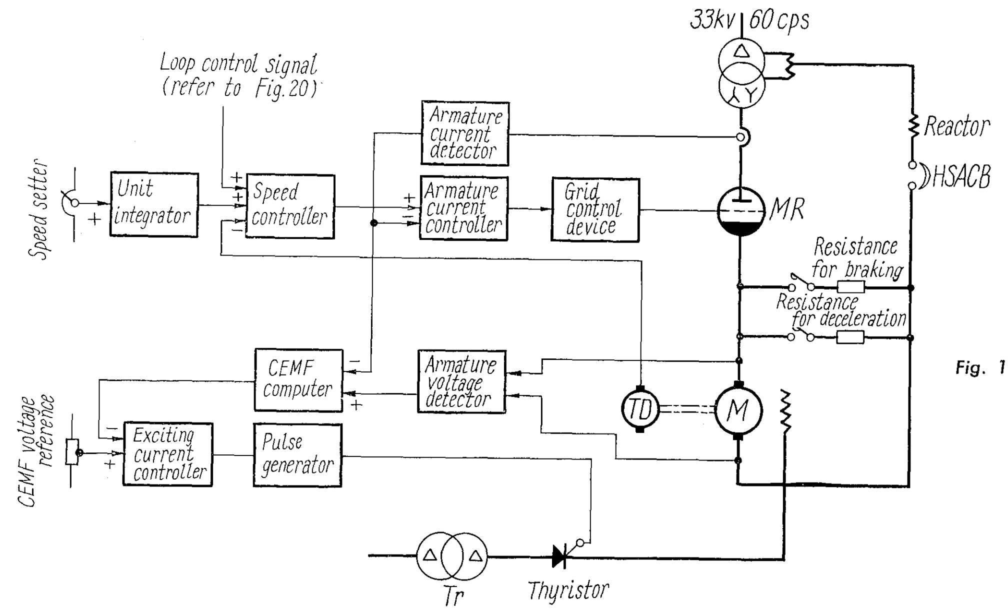


Fig. 12 Control system block diagram for finishing stand motor

For the impact speed drop, it can be theoretically computed as explained below. In the control system of *Fig. 12*, normally response of the field current control system may be delayed from that of the armature voltage control system even if the operating condition enters into the field control range. Therefore the armature voltage immediately actuates to compensate a rapid disturbance such as the impact speed drop. In *Fig. 13*, "Tm" is the time constant which is the approximated first order time delay of the dead time influence due to the firing interval. When the control angle α is constant, and if the power source is 60 cycles and 6-phase rectifying, the firing interval will be approximately 2.8 ms ($1/60 \times 6 = 0.0028$). As the averaged value, this interval can be considered to be a half of 2.8 ms; thus, the "Tm" will be 1.4 ms. Further, in order to protect from inductive interference, a 1 ms-filter is provided in the current detector. Therefore the total 2.4 ms is considered to be the minimum time constant which cannot be compensated with the regulator. Since the influence from the CEMF can be disregarded, the armature current minor loop regulates the open loop transfer function as depicted in *Fig. 14*. The reason why the integral action is provided to the regulator in its low frequency is to improve the recoverability against disturbances. Normally the armature time constant "Ta" is sufficiently separated from the cut-off frequency, so this is negligible. Then the closed loop transfer function of this minor loop $Gc(s)$ becomes as expressed by the following equation:

$$G_c = \frac{\dfrac{1+4ST_u}{8(ST_u)^2(1+ST_u)}}{1+\dfrac{1+4ST_u}{8(ST_u)^2(1+ST_u)}} = \frac{1+4ST_u}{1+4ST_u+8(ST_u)^2+8(ST_u)^3} \quad \text{............(10)}$$

The indicial response of this closed loop transfer function becomes as follows:

$$L^{-1}G_c(s)\frac{1}{S} = 1 + e^{-\frac{t}{2T_u}} - 2e^{-\frac{t}{4T_u}} \cdot \cos\frac{\sqrt{3}}{4T_u}t \quad \text{......(11)}$$

When this drawn in a curve, this will be as curve 1 in *Fig. 15* which has approximately 43% overshoot. This way of compensation is satisfactory for disturbances, however, for a change in reference, it is not acceptable because the armature current overshoot appears. For this reason, the filter having the transfer function $1/(1+4Tu)$ is inserted in the

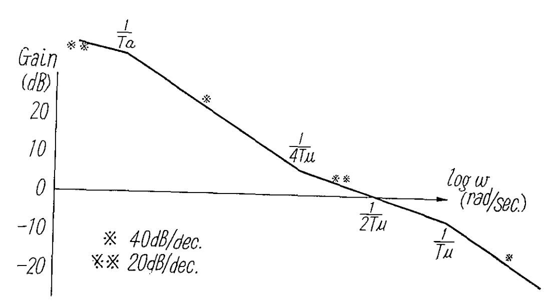
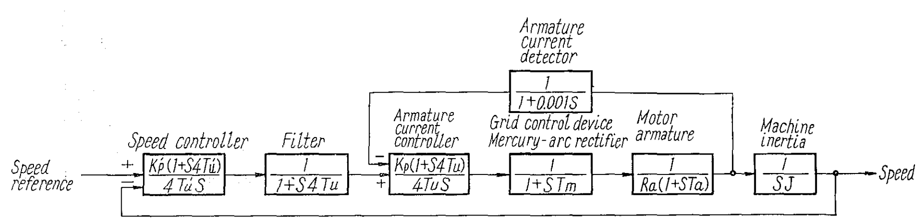


Fig. 14 Open loop frequency response for current minor loop



$T_u = T_m + 0.001$, $4T_m = T_u'$ K_p, $K_p' = P$-gain

Fig. 13 Block diagram for speed control

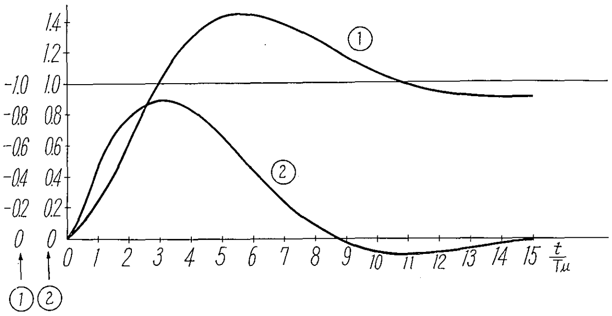


Fig. 15 Theoretical wave shapes of motor current (1) and speed (2) in impact speed drop

reference input circuit of armature controller. Thus, the outward transfer function of the armature current minor loop becomes as follows and the overshoot becomes small:

$$G_c'(s)=\frac{1}{1+4ST_u+8(ST_u)^2+8(ST_u)^3} \quad \cdots\cdots\cdots(12)$$

This is approximated as expressed by the following equation about the speed controlling system:

$$G_c' \doteqdot \frac{1}{1+4ST_u} \quad \cdots\cdots\cdots(13)$$

As to the speed control system, an 8 ms time lag of first order filter is provided in the speed feedback circuit, so the addition of the 8 ms to the above $4Tu=8.6$ ms is considered to be the minimum time constant ($=Tu'$), and $2Tu'$ is taken as the cut-off frequency. For this reason, the practical purpose, there are no objections to omit the S^2 term and S^3 term in the equation (12).

The speed control system sets the open loop transfer function such as the Tu is transferred to Tu' on the frequency response in *Fig. 14*, in the same manner as that of the current minor loop setting. In this case, however, there is no time constant corresponding to Ta; thus, dB/dec for the lower frequency is left at $60dB/dec$ as is. Accordingly, the indecial response of the closed loop transfer function of the speed control system becomes what can be obtained by placing the Tu as Tu' in the equation (11). Considering the impact speed drop when a step function is applied as a torque disturbance, the torque disturbance will be as indicated by the following equation:

$$D(s)=\frac{-K}{S} \quad \cdots\cdots\cdots(14)$$

where, K is disturbance value and assumed to be one per unit torque.

The speed response due to this torque disturbance becomes:

$$I(\mathrm{s})=\frac{-K}{T_j S}\cdot\left(\frac{1}{S}-\frac{1+4T_u'S}{1+4ST_u'+8(ST_u')^2+8(ST_u')^3}\right) \quad \cdots\cdots(15)$$

$$L^{-1}(s)=\frac{-2KT_u'}{T_j}\cdot\left\{e^{-\frac{t}{2T_u'}}+2e^{-\frac{t}{4T_u'}}\cdot\sin\left(\frac{\sqrt{3}\,t}{4T_u'}-\frac{\pi}{6}\right)\right\} \quad \cdots\cdots(16)$$

where: $I(s)$: Impact speed drop

From the equation (16), it can be understood that, in order to minimize the impact speed drop, it is necessary to either increase Tj by increasing both motor inertia and machine inertia or minimize Tu' by quickening the response, and unless Tu' is minimized, the recovery time cannot be quickened.

In equation (16), the curve 2 in *Fig. 15* is the graph, which was drawn by assuming $2KT_u'/T_j=1$. With this graph, the maximum speed drop becomes approximately 0.9; thus, when the control system is regulated as explained in the above, the impact drop becomes as follows:

$$I_{\max}\doteqdot\frac{2T_u'K\times 0.9}{T_j}=\frac{1.8T_u'K}{T_j} \quad \cdots\cdots\cdots(17)$$

where, $I_{\max}$=Impact speed drop maximum value

Now, when the disturbance is in 100%, if K and Tj are assumed to be respectively 1 and 3, Tu' becomes to 17.6 ms; thus, the maximum impact speed drop becomes appproximately 1.1% from the following equation:

$$I_{\max}\doteqdot\frac{1.8\times 0.0176\times 1}{3}=0.0106 \quad \cdots\cdots\cdots(18)$$

Further, the time required in recovering the speed error within 5% in case of the $I_{\max}$ becomes approximately $140ms$. (approximately $8Tu'$ from *Fig. 15*.)

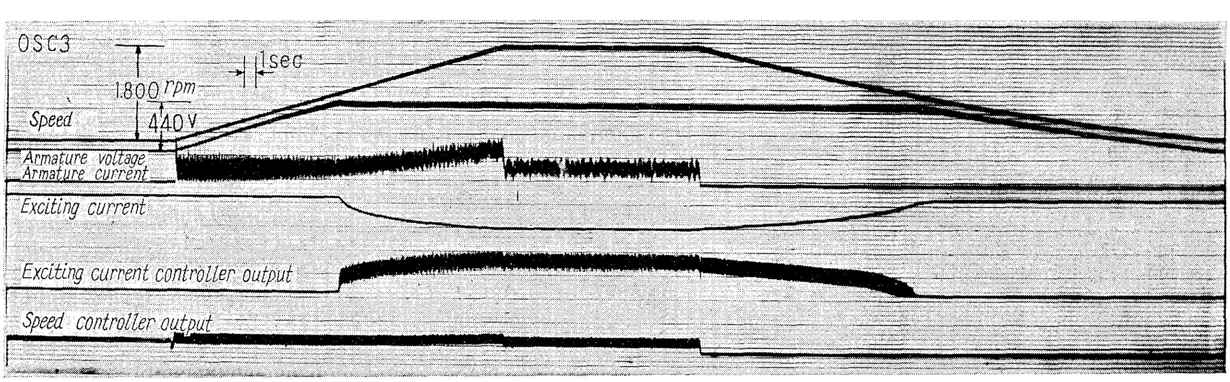


Fig. 16 Oscillogram shows acceleration and deceleration of finishing stand motor

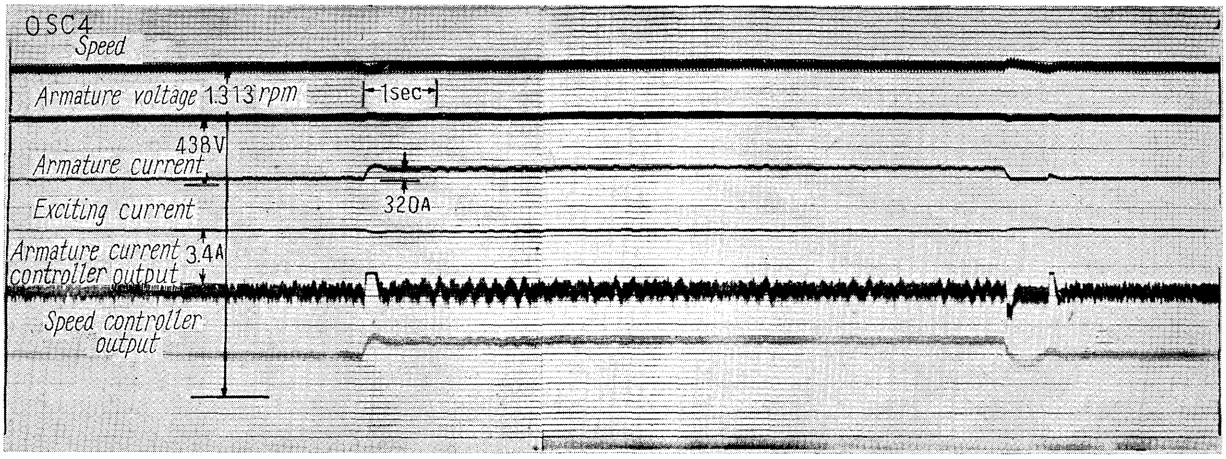


Fig. 17 Oscillogram shows control characteristics of No. 1 finishing stand motor under operation

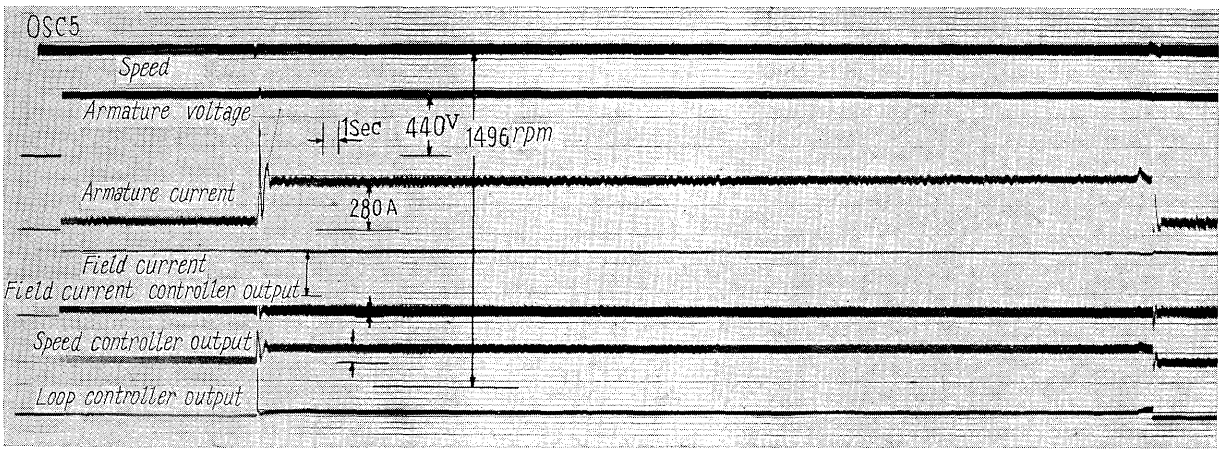


Fig. 18 Oscillogram shows control characteristics No. 3 finishing stand motor under operation

Fig. 16 shows the oscillogram of changing the finishing mill speed setting from zero to the maximum and again from the maximum to zero in a unit step. *Fig. 17* shows the oscillogram of the 1st finishing mill during actual operation.

Fig. 18 is for 3rd finishing mill, in which the influence from the loop control signal appear on the armature current. In addition, in this oscillogram, the speed is increased to reduce the wire rod about to pass from the mill.

4. Loop Control System

In the finishing mill and a part of the intermediate mill train, a loop which is controlled by the loop regulator is provided. In the finishing mill, the distance between the stands is approximately 13 feet and the height of loop is 8 to 12 inches, and the loop length is comparatively short. The individual speed control system for each stand in so regulated that the merit of each control unit can be utilized in the full extent, as previously explained. And also the devices for detection and control of the loop should sufficiently correspond to these. The loop detector is imported from Siemens-Schuckertwerke AG (Germany).

The height of the loop is detected from the phase relation between the power source and the electrically converted infrared rays pulse from a wire rod which is obtained through a lens rotating synchronously with the power source.

The principle of this method is explained as follows: preparing two transistorized integrators, integration and reset are operated by the power source and the pulse signal as shown in *Fig. 19.* The starting of the integration is synchronized with

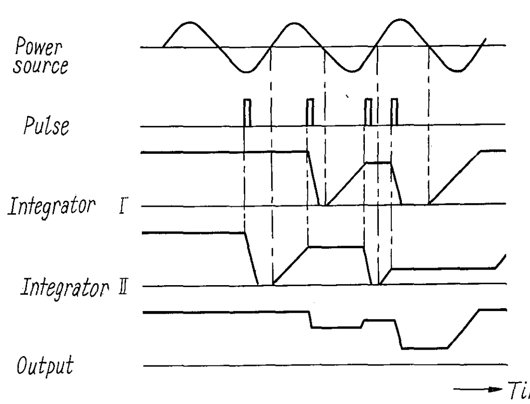


Fig. 19 Time chart showing the way of loop detecting

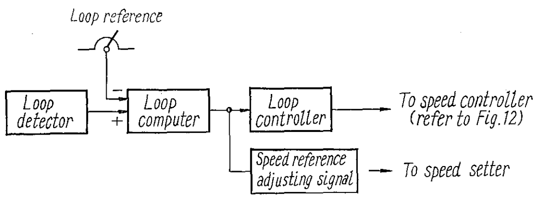


Fig. 20 **Simplified diagram of loop control**

the power source, the pulse is used alternately for integration stopping and resetting, and the larger one of these two integrators output is selected by the diode as the output. Thus, the detected signal can be obtained as ripple free and fast response.

The outline of the loop control system is indicated in *Fig. 20.* The speed setter adjusting signal is a signal which adjusts the speed setting for the speed control system in a certain period during the wire rod is forming a loop and is being stably rolled so that the loop regulator output becomes zero.

Fig. 21 shows the speed of the individual finishing mill when the finishing mill is rolling at delivery speeds of 5100 fpm and 6700 fpm and the loop regulator output is zero. In the figure, it can be seen that the loop regulator is largely operated when the speed becomes fast.

5. Pinch Rolls and Winding Reels

The pinch roll and reel control systems are shown in *Fig. 24.* Both speed are synchronized to that of the finishing delivery mill stand.

The converter receives the synchronizing signal by magnetic amplifier to prevent inductive noise, since the distances from the finishing mill to the pinch roll and winding reel are long. The magnetic amplifier lower input impedance and has the feature with which the output signal can be electrically isolated from the input.

The pinch roll speed controller is a low gain P controller and the input error singnal accordingly with the armature current increase. Thus, the speed becomes a compound characteristics. The output of this speed controller is the reference to the armature current controller, and controls the armature current through with the firing circuit of the mercury arc recti fier.

For the winding reel, the synchronizing signal is applied also to the wave controller from the converter. The wave controller has been provided to superimpose wave signal having the proper frequency and amplitude in proportion to synchronizing signal. For this reason, the speed reference of the controller alters in a wave shape. With this wave signal, the acceleration and deceleration of the reel are repeated during the operation, so the mercury arc rectifier is made in back-to-back connection for the regenerative braking.

The speed controller is a PI type, and this output is applied to two armature current controllers for converting and inverting. In the armature current controller, cross current reference is also applied in order to keep the cross current constant. The

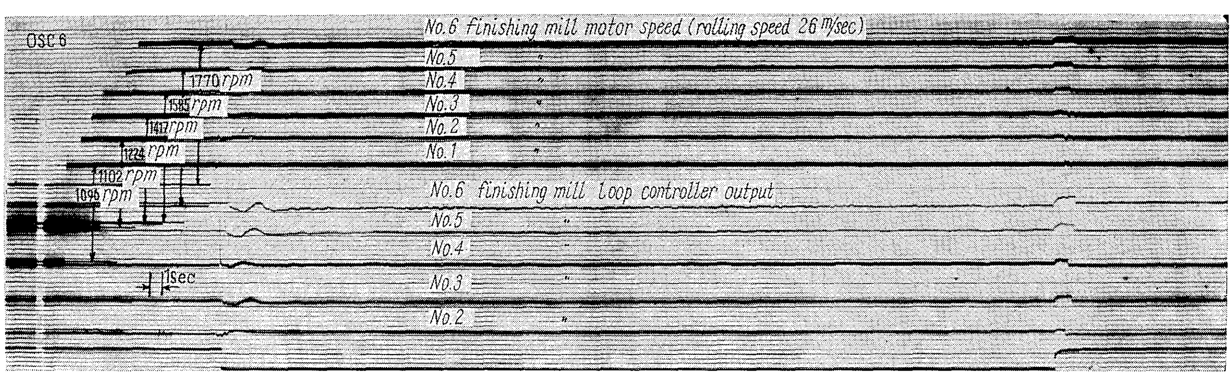


Fig. 21 **Recording of speed and loop controller output for low line speed (5100 fpm)**

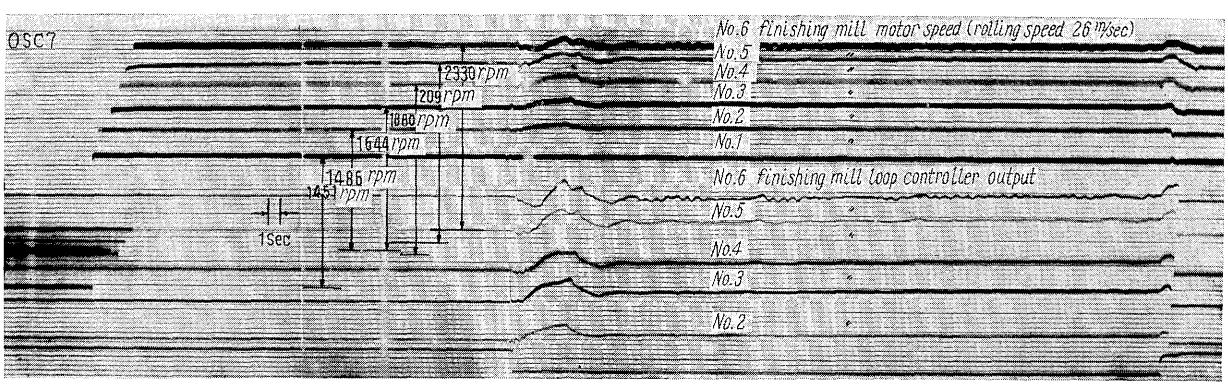


Fig. 22 **Recording of speed and loop controller output for maximum line speed (6700 fpm)**

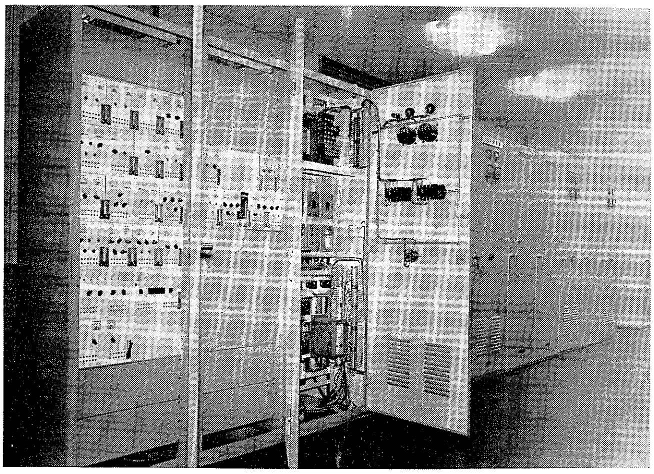


Fig. 23 Automatic control cubicle with TRANSIDYN control devices

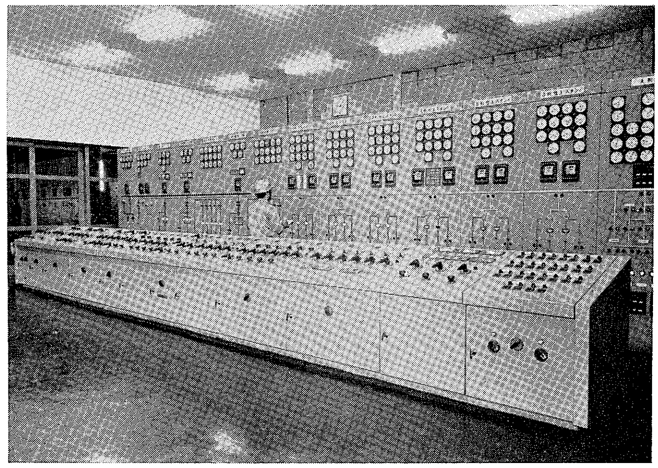


Fig. 25 Main control board in the electric room

negative feedback signal of the armature current is detected from anode current transformers of both the converter and inverter.

VI. OPERATION PANEL

The supervision and operation of electrical equipment located in the electric room are performed on the main control board also installed in the electric room.

Operator rooms consist of No. 1 roughing mill, No. 2 roughing mill, intermediate mill, finishing mill, and winding reel operation room, and all of these rooms are installed in the mezzanine. On the operator finishing mill control desk, digital speed-meters the finishing mill motors are prepared. These speed meters are used to adjust the each roll speed precisely at a proper value prior to rolling.

Fig. 26 Operator finishing mill control desk

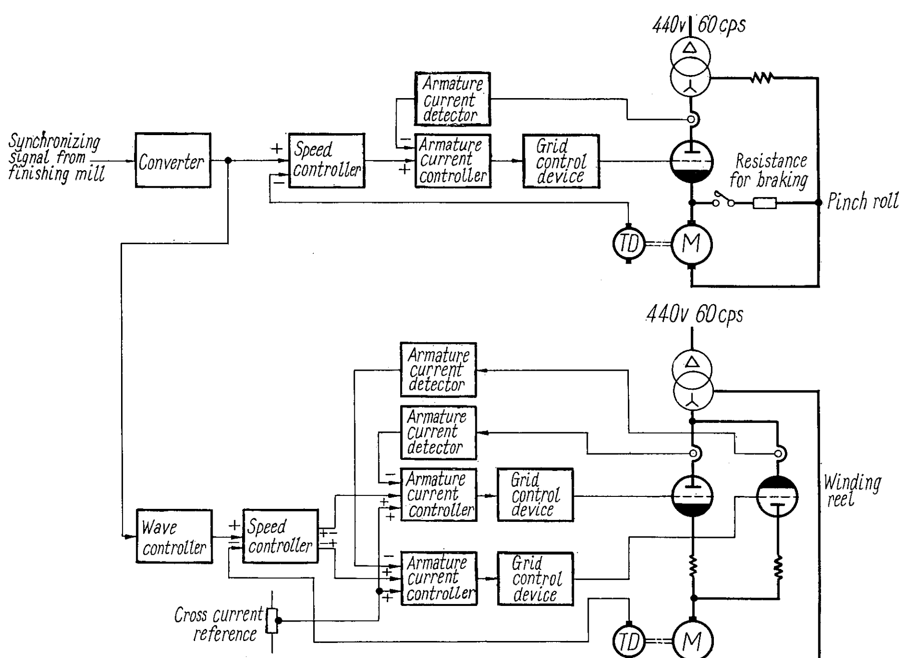


Fig. 24 Control systems for pinch roll and reel

VII. COOLING AND VENTILATION

A common fan room is installed for the electric room and the main motor ventilating. For the air feeding to the electric room, Silocco fans are used, and for ventilation of the motors, variable pitch propeller fans are used. For the air filter, JAF multi-duty type is adopted. The air required for ventilating the electric room is 84,000 cu.ft/min. Separately from this ventilation system, one Silocco fan of the capacity of 31,800 cu.ft/min is installed near the trans former room for its ventilating. For the finishing mill motor bearings, the forced oil circulating cooling system is adopted and lubrication pump, oil tank, and recooler are installed in the basement of the mill yard.