

THE OPERATION OF A LARGE ELECTRICALLY DRIVEN REVERSING ROLLING MILL

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In a paper before this Institute¹ the author referred to the investigations that were made in Europe, preliminary to the installation of the first electrically driven reversing rolling mill, and it is interesting to note that somewhat similar experiments and investigations were made in this country, independently, with the same object in view.

About the middle of 1905, it was decided by the Illinois Steel Company to make inquiries regarding the possibility of installing an electrically driven reversing universal plate mill, and the engineers of that company made some preliminary experiments with a view to determining the power requirements and the probability of the success of such an installation. After sufficient data had been obtained, so that a power curve could be given to the manufacturers of electrical machinery, propositions were invited, and in the spring of 1906 a contract was let for the complete installation. The machines and apparatus were designed in June, 1906, and the complete equipment was delivered by the end of the year, and started in operation at the beginning of 1907.

In the meantime, the first European installation at Hildegrade-huetts was started in operation and before the plant of the Illinois Steel Company was used commercially, a second European plant was started. It is interesting to note, however, that the installation of the Illinois Steel Co. was the second plant of this type to be ready for service. This plant has been in operation for approximately five years, and it is believed that a description of

1. *Electrically Driven Reversing Rolling Mills*, TRANSACTIONS A. I. E. E., 1911, Vol. XXX, II, page 1587.

some of the details of the installation and the results obtained, may be of interest.

The Illinois Steel Company was one of the earliest of the American steel works to utilize the blast furnace gases in gas engines, for supplying power for operating its mills, and the principal reason that led to the installation of this pioneer mill was the realization of the necessity for greater economy in the generation and distribution of power in such works.

The characteristics of the universal plate mill are such that it is necessary to have the greatest flexibility possible in the driving machine, and it was realized that by installing an electric motor, controlled by regulating the field of a special generator supplying it with power, an ideal system would be obtained, enabling all classes of work to be handled in the most desirable manner, the earlier passes being handled at low speeds and the finishing passes at high speeds, it being possible to obtain the maximum output of the mill on account of the flexibility of the speed control.

When the plant was installed, some doubt was felt as to the possibility of quick reversing, but in operation it was soon found that the electric plant was capable of handling material more quickly than similar steam-driven mills and more quickly than the material can be handled by the tables. After the plant had run for some time it was demonstrated that the electric equipment was not the weakest link in the chain. The following brief description of the mill and electrical apparatus will show, to some extent, the nature of the problem involved in the electrification and the methods adopted to insure successful operation.

MILL

The mill is of the two-high universal type, designed for rolling plates up to 30 in. (76 cm.) wide from slabs up to a maximum of 10 in. (25 cm.) thick. The main horizontal rolls are 24 in. (60 cm.) in diameter, and have a face of 34 in. (85 cm.). The vertical rolls, of which there are four, two on either side of the main rolls, are 14 in. (34.6 cm.) in diameter and have a face of 13 in. (32.8 cm.) The mill was designed to roll plates of all thicknesses and, on account of its flexibility, is used to a very great extent for handling small orders. The general layout of the mill is shown in Fig. 1, from which it will be seen that the motor-generator set, for supplying power to the main roll motors, is erected in the same room as the main roll motors. Apart from

the method of driving, the mill is not appreciably different from similar steam-driven installations.

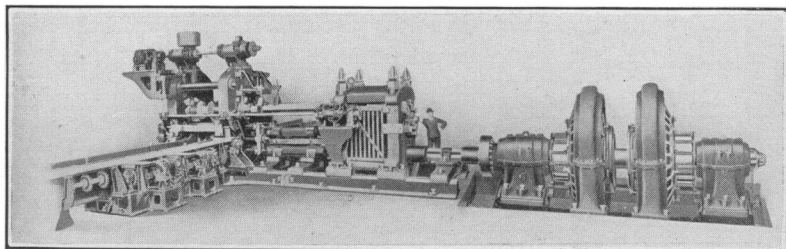
From the general layout drawing, it will be seen that the slabs are heated in two furnaces and carried by an approach table to the mill. When rolled, the plates are taken in two hot beds, and after cooling, to a shearing table, where they are cut to size and are then ready for straightening and shipment. The mill tables are operated by four 50-h.p. mill motors, the control being located at one side of the mill, close to the control for the main motors. The mill and the motor room are spanned by a 30-ton crane, which is capable of handling all parts of the equipment, with the exception of the flywheels of the motor-generator set.

In Fig. 2 a general view of the mill and motors is given, which shows the appearance of the complete equipment. The motors are enclosed in a separate room to protect them from the mill dust. In this view, the mill is shown complete with motor, but from Fig. 1 it will be seen that there is a wall between the pinion housings and the motors. In the illustration the auxiliary motors for the setting of the rolls are shown, that for the horizontal rolls being mounted to the left of the mill housings and that for the vertical rolls to the left of the pinion housings.

The setting of the horizontal rolls is varied by means of an electrically driven screw-down, the screws being operated by a 50-h.p. mill type motor. The setting of the vertical rolls is controlled by means of a 30-h.p. mill type motor, the position of the rolls being shown by the usual micrometer type of indicators. The main rolls are connected to the pinion housing by suitable spindles, arranged to allow a movement of about 12 in. (30 cm.). The lower pinion is driven from the roll motor through a coupling of the usual mill type, arranged to allow for considerable wear in the pinion shaft bearings. No flexibility is allowed for in the drive from the motor to pinions.

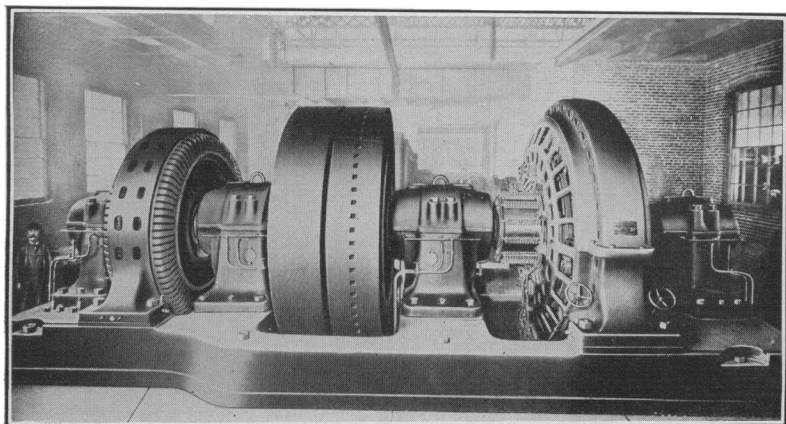
The mill was designed for a maximum speed of 150 rev. per min. but it has been found in practise that about 100 rev. per min. is all that can be conveniently used, on account of the comparatively short plates rolled.

The capacity of the mill varies considerably on account of the material rolled, and depends more on the product required than on its capacity for rolling, and therefore definite figures cannot be given for the output for any particular product. In referring to some of the tests given, an idea of the capacity under various conditions may be obtained. The performance of a mill of this type



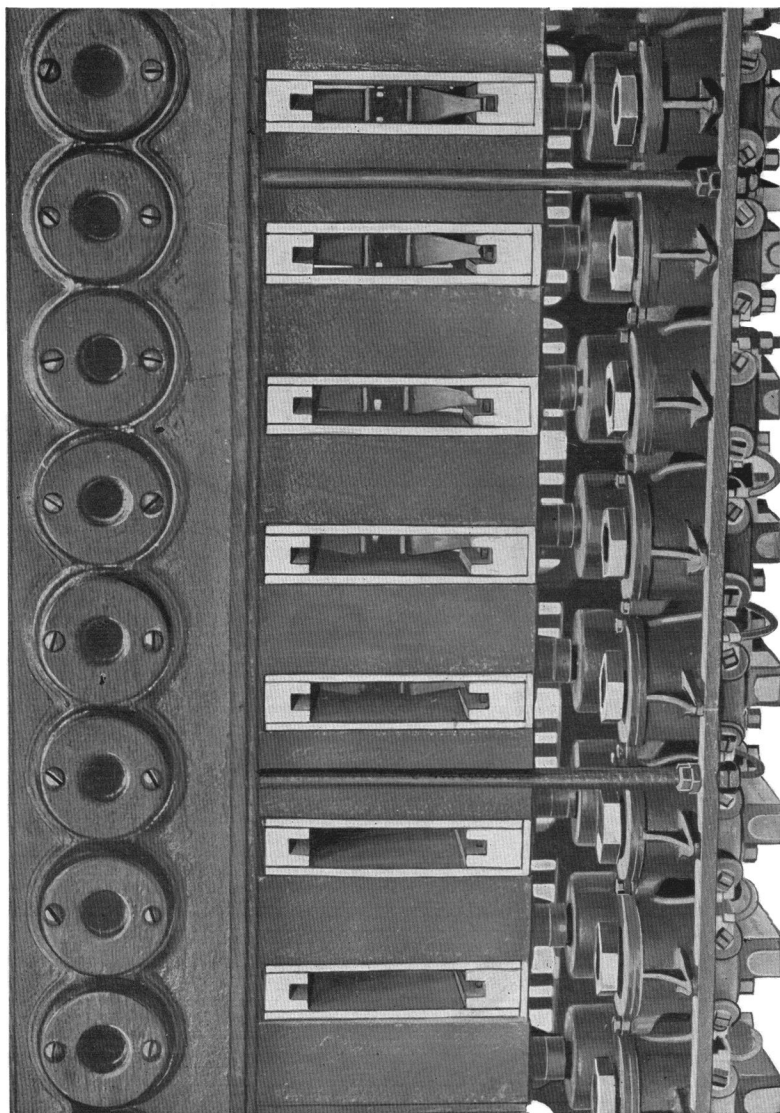
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FIG. 2—UNIVERSAL PLATE MILL AT THE ILLINOIS STEEL COMPANY'S
PLANT, SHOWING THE MOTOR DRIVE



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FIG. 13—MOTOR-GENERATOR SET INSTALLED IN THE PLANT OF THE
ILLINOIS STEEL COMPANY



[SYKES]

FIG. 15—VIEW OF SWITCHES USED FOR REGULATING SLIP

cannot be compared with that of a blooming mill, rolling practically one size of material. The equipment of this mill had to be sufficiently large to handle the heaviest slabs that can be rolled, although the work is comparatively light most of the time and consequently the tonnage suffers.

SYSTEM OF DRIVING

In deciding upon the system to be used for driving the mill, and the control of the motors, the experience that had been gained in the design of large hoisting plants of the Ilgner type was drawn upon. In 1903 experiments had been made to determine the possibility of rapid reversing and the sensitiveness of this system of control, on a large hoisting plant. The results obtained indicated that, from the standpoint of control, this sys-

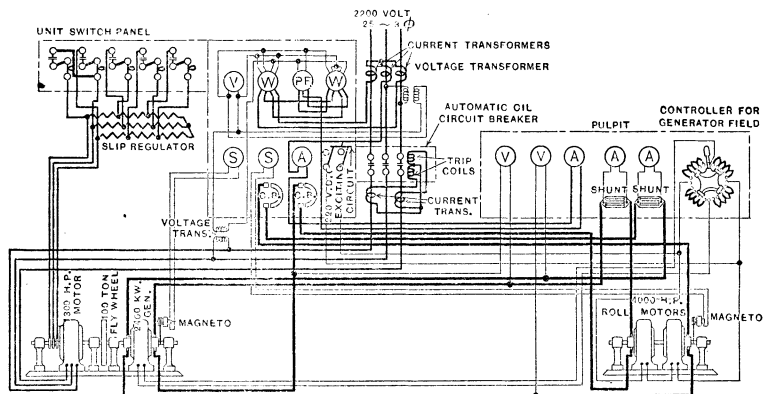


FIG. 3—DIAGRAM OF CONNECTIONS OF ELECTRICAL EQUIPMENT FOR UNIVERSAL REVERSING PLATE MILL OF ILLINOIS STEEL CO., SOUTH CHICAGO.

tem gave all that could be desired, providing the proper provision was made to obtain a rapid change in the generator field. The ordinary solid-field generator cannot follow rapid change in the excitation on account of the eddy currents which are set up and which oppose any change of field strength. It is therefore necessary to design the machine with a completely laminated magnetic circuit so as to overcome this characteristic of the ordinary generator when working under the conditions met with in such service. The importance of having the voltage of the generator follow the changes of excitation quickly is very great from an operating standpoint, and this condition has been very well fulfilled in the Illinois Steel Company's installation.

In Fig. 3 are shown the principal connections of this instal-

lation. It will be seen from this diagram that the roll motors are connected to a double-commutator generator without any starting resistance, each motor being connected to one commutator. This generator is driven by means of a three-phase induction motor, and a 100-ton flywheel is mounted on the same shaft. The roll motors are separately excited, the excitation being constant, with speeds up to 100 rev. per min., and the polarity is not changed. The direction of rotation and speed of the roll motors is controlled by changing the polarity of the generator, and varying its field strength, thereby varying the voltage applied to the armatures of the roll motors. This system avoids rheostatic losses, except in the field circuit, and enables any desired speed to be obtained, independent of the load.

The load on the generator naturally varies rapidly over a large range, the rate of change being at times 3000 to 4000 h.p. per second during acceleration and 8000 to 10,000 h.p. per second when braking. From the standpoint of the power supply, such a load would be highly undesirable, even for a very large power house, and could not be handled at all by gas-engine-driven stations of moderate capacity, such as usually found in steel mills. In order to equalize these fluctuations, the flywheel was provided to deliver energy during the periods of great demand and to store energy during periods of light load, and so that the flywheel may give up some of the energy stored in it, the speed must be reduced, and to store energy the speed must be increased.

To enable the flywheel to assist the three-phase motor in driving the generator, an automatic slip regulator was provided, which introduces resistance into the rotor when the current reaches a certain value, the speed being thereby reduced, and a portion of the energy stored in the flywheel is used for driving the generator. When the load on the generator is reduced, the resistance is automatically cut out, the speed consequently increasing, and energy is thereby stored in the flywheel. In practice, the maximum load on the line due to the reversing set is approximately one-fifth of the maximum load of the generator. By properly setting the regulator in relation to the work to be done, the input to the motor-generator can be maintained practically constant. It will be noted that the driving motor of the set is considerably smaller than the generator, which is due to the fact that the latter must be designed to carry the high peak loads, and as the heating of the armature is due principally to the

copper loss, which varies as the square of the current, a much greater capacity is required to deliver a certain amount of power than would be necessary if the load were constant. The load on the induction motor does not vary greatly, and consequently it is designed to carry only the average load.

To protect the generator and driving motor against excessive overloads, due to "stickers" or cold slabs, overload trips for the circuit breakers are provided in each armature circuit, which are arranged to open the circuit at a load corresponding to approximately 8000 h.p. The primary circuit of the induction motor

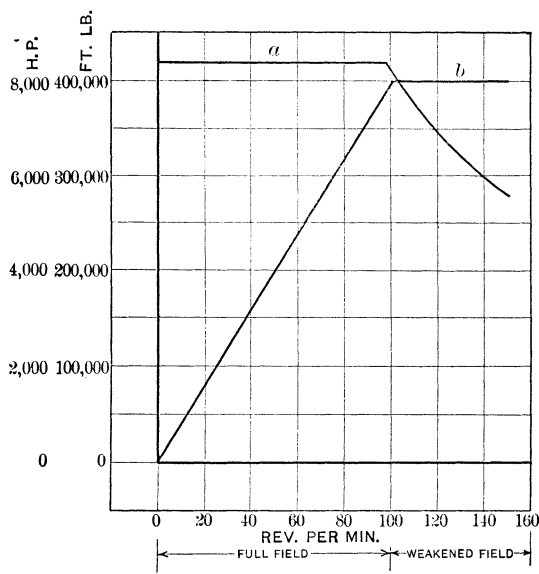


FIG. 4—COMBINED RATING OF ROLL MOTORS UNDER MAXIMUM OPERATING CONDITIONS.

a.—Torque. b.—Horse power.

is provided with the usual instruments and overload protection. Speed meters showing the speed of the rolls, and double reading ammeters are provided on the operating pulpit, for the guidance of the operator. It has been found, however, that the electrical equipment is capable of performing heavier work than the mill, so that the operators are controlled during rolling more by the limitations of the mill than those of the electrical equipment.

DRIVING MOTORS

The driving motors have a nominal rating of 2000 h.p. each, making a total of 4000 h.p. for the set. The maximum combined

rating of the motors is shown in Fig. 4, which shows a maximum torque of 420,000 ft-lb. (58,086 kg-m.) at a speed up to 100 rev. per min., which is obtained with full voltage on the armatures. At speeds above this the horse power remains constant, the torque decreasing correspondingly, the higher speeds being obtained by weakening the field of the motors.

The motor was divided into two units, with the object of reducing the armature diameter, and consequently the inertia, and at the same time to facilitate handling the heavy current, which at 8000 h.p. is about 11,000 amperes. They are designed for a normal armature voltage of 575, and 220 volts excitation.

When the plant was designed, it was proposed to increase the speed from 100 rev. per min. to 150 rev. per min. for the longer passes, and, so as to insure that the flux in the motor fields would follow the quick changes of the exciting current, the

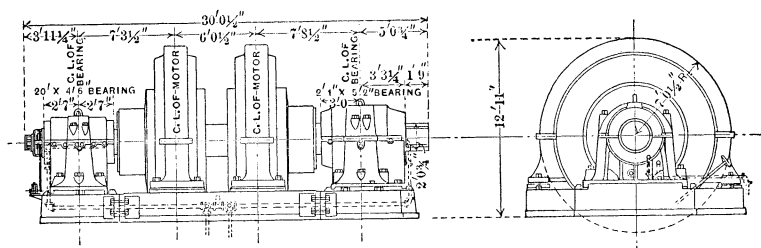


FIG. 5—OUTLINE OF MOTORS FOR DRIVING MILL.

magnetic circuit was laminated. Experience gained from the operation of the plant has shown that this refinement was unnecessary, although required in order to meet the original guarantees for acceleration and reversal asked for.

The general dimensions of the machines are shown in Fig. 5, from which it will be seen that the two armatures are mounted on one shaft, supported by two bearings, the field frames being mounted side by side on the bedplate. The laminations are supported by a cast iron frame which is split horizontally to facilitate repairs. The machines are of the commutating pole, compensated type, the compensating windings being imbedded in the face of the main poles. The armatures, which are 7 ft. 6 in. (2.28 m.) in diameter, were especially constructed to stand the severe shocks anticipated with this class of work and to be capable of withstanding the severe stresses due to the rapid reversing and acceleration. On this account, very great attention was paid to the methods of supporting and holding the armature

windings, a special steel ring being provided to support and fasten the end connections rigidly where they connect to the commutator lugs. With the ordinary construction, a certain amount of movement is always possible, and a very slight bending of the end connectors if repeated often enough will lead to crystallization and breaking, which has been demonstrated repeatedly where machines have been subjected to severe service. That the great care in supporting the end connections was justified, has been demonstrated by the fact that in some of the earlier European installations there was considerable trouble due to the breakage of the armature connections, whereas in the case of this plant there has never been the slightest difficulty from this cause.

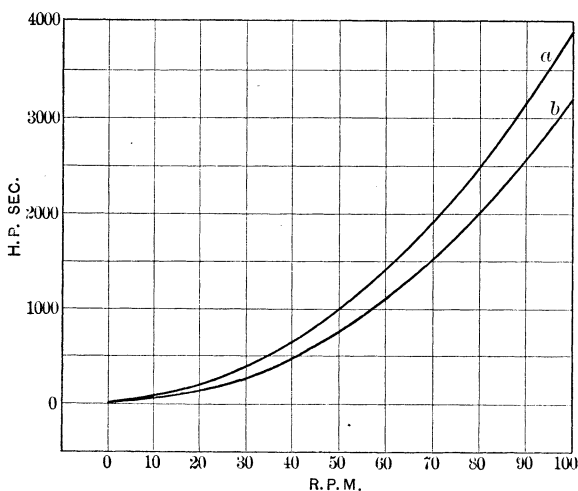


FIG. 6—CURVE SHOWING ENERGY STORED IN ROTATING PARTS OF ROLL MOTOR AND MILL.

a.—European installation. *b.*—Illinois Steel Company's installation.

The importance of reducing the armature diameter and weight will be appreciated on referring to Fig. 6, which shows the energy stored in the rotating parts of these motors at various speeds, the energy varying as the square of the speed. The inertia curve of a European installation is also shown, the rating of the two plants being almost identical. From these curves it will be seen that in the American installation the inertia has been kept somewhat lower than in the European plant, although the latter was installed about two years later.

Although very high efficiency in the motors of such an installation is not of very great importance, considering the other

losses, yet it is desirable, inasmuch as it affects the heating of the machines, and a well designed machine will naturally have high efficiency. In Fig. 7 is shown the efficiency curve of these motors, from which it will be seen that the losses are extremely small. Of particular importance are the copper losses, which con-

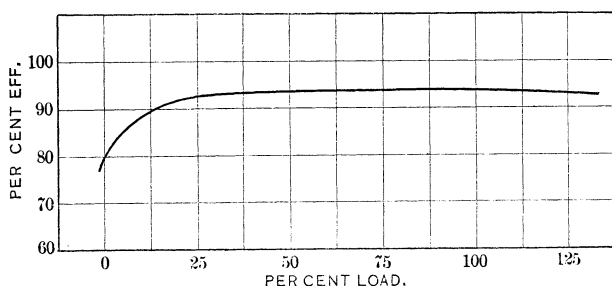


FIG. 7—EFFICIENCY CURVE OF ROLL MOTORS.

Two 2000-h.p. shunt motors—575 volts, 2800 amperes, 12-pole, 0-150 rev. per min.
Efficiency at 100 rev. per min., including excitation.

trol to some extent the energy returned from the motors during braking, as the current is usually high and the period short. It will be noted that the bearing at the coupling end is unusually large, and at the maximum load the stress in the shaft is less than 3000 lb. (1360 kg.) per sq. in. (6.45 cm.).

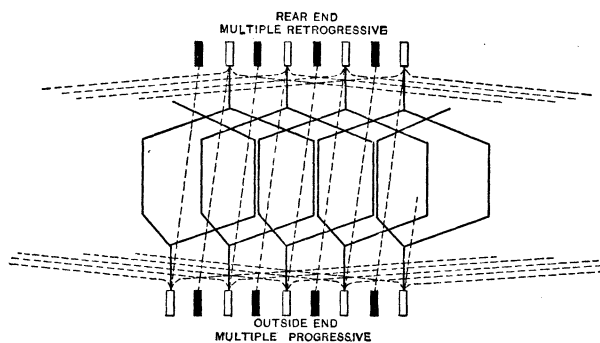


FIG. 8—ARMATURE CONNECTIONS OF DOUBLE-COMMUTATOR GENERATOR SUPPLYING POWER TO ROLL MOTORS.

The weight of the complete motor (two machines) is 356,000 lb. (161,488 kg.), made up as follows:

Rotating part.....	124,000 lb.	(56,245 kg.).
Fields.....	107,000 "	(48,534 ").
Base and bearings.....	125,000 "	(56,699 ").

MOTOR-GENERATOR SET

The generator of this set is of the double-commutator type, and embodies some design features of special interest.

It was decided to use a double-commutator type machine, so as to reduce the current to be collected from a single commutator, thereby allowing a single comparatively high-speed machine to be used. The field is of the laminated type, so built that it will answer changes of field current very rapidly, this being necessary to obtain quick reversing and speed changes.

The machine is of the commutating-pole compensated type, similar to the roll motors, the diameter of the armature being the same. The normal full speed of the generator is about 375 rev. per min. and the minimum speed about 300 rev. per min. At 375 rev. per min., the voltage of the generator with full field is approximately 600.

The armature winding is of especial interest, as there are

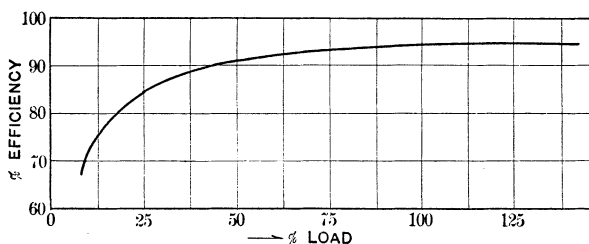


FIG. 9—EFFICIENCY CURVE OF GENERATOR SUPPLYING POWER TO ROLL MOTORS.

Shunt generator, 3000-kw. Efficiency at 300 rev. per min., including excitation.

twice as many commutator bars as there are coils, the equivalent of a half-turn coil being obtained by the connections, as illustrated in Fig. 8.

The generator is designed for a normal capacity of approximately 3000 kw. and a maximum capacity of about 6400 kw. Special attention was given to the design of the generator, to insure good commutation under the severe conditions of operation. The commutating pole and compensating windings are not shunted, care being taken to render this unnecessary, so as to avoid any trouble due to difference in the self-induction of the windings and shunt affecting the division of the current with rapid changes of load. The necessity of commutating the maximum current with a weak field, requires that the closest attention be given to commutating characteristics of the generator.

The efficiency of the machine is shown in Fig. 9, this curve being based on tests made after the plant was installed.

The motor for driving the generator and flywheel has a normal rating of 1300 h.p., and is designed for three-phase, 25 cycles, 6600 volts, eight poles. It is of the wound rotor type, the rotor circuit being controlled by an automatic slip regulator, previously referred to, and is of the usual standard construction.

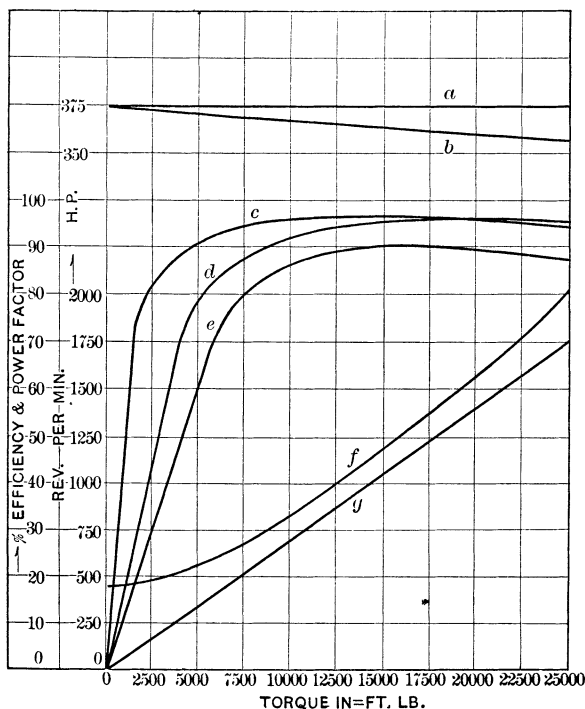


FIG. 10—PERFORMANCE CURVES OF THREE-PHASE MOTOR DRIVING FLYWHEEL MOTOR-GENERATOR SET.

(1300 h.p., 2200 volts, 25 cycles, 8 poles, 375 rev. per min. synchronous speed.)

a—Synchronous speed. *b*—Motor speed. *c*—Real efficiency. *d*—Power factor. *e*—Apparent efficiency. *f*—Apparent h.p. *g*—Real h.p.

The performance of this motor is shown in Fig. 10, and the speed-torque characteristics for the various steps of the regulator are shown in Fig. 11.

The flywheel of this set presents some interesting features, as, owing to difficulties in transportation and in obtaining reliable steel castings, the wheel was built of comparatively thin punched laminations on a steel spider, the sheets being bolted between

cast steel end rings. The peripheral speed of the wheel at 375 rev. per min. is 15,500 ft. (4724 m.) per minute. In order to facilitate handling, the wheel was built in two parts, each weighing 100,000 lb. (45,359 kg.), the total weight, therefore, being 100 tons. The flywheel effect of this wheel is 5,500,000 ft.-lb., and under normal conditions of operation the speed of the set seldom falls below 320 rev. per min., and the input does not as a rule exceed about 900 kw. The energy stored in the wheel at full speed is 250,000 h.p.-sec., and the amount given up when the wheel slows down to 300 rev. per min. is 90,000 h.p.-sec.

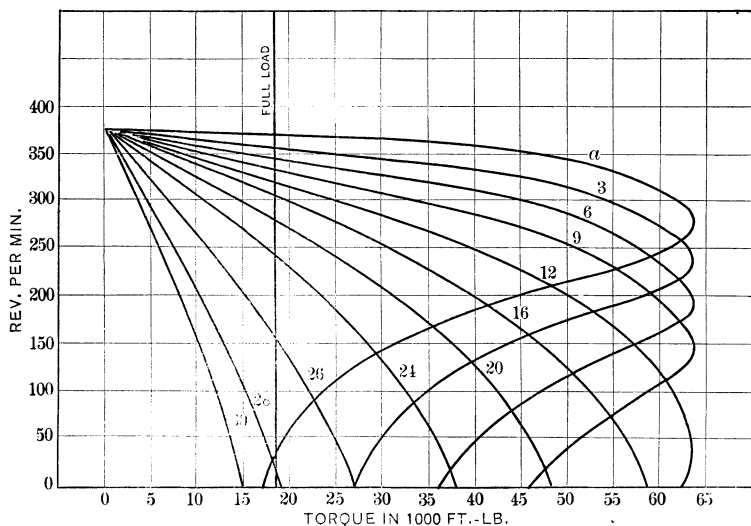


FIG. 11—SPEED-TORQUE CURVES OF THREE-PHASE MOTOR FOR DIFFERENT STEPS OF SLIP REGULATOR.

(1300 h.p., 2200 volts, 25 cycles, 8 poles, 375 rev. per min. synchronous speed.)

Curve *a*—Rotor ring short-circuited. Curves *a*–3–24—Running. Curves 24–30—Starting.

The general assembly of this set is shown in Fig. 12, which gives the principal dimensions, and a view of the complete machine is shown in Fig. 13. The rotating parts are supported by four bearings, the flywheel having a bearing on either side and a separate shaft. The shafts for the motor and generator are supported at one end by a bearing, and at the other are bolted to the flywheel shaft. The maximum bearing pressure has been limited to approximately 80 lb. (36 kg.) per square in. (6.45 sq. cm.). Both machines and the flywheel are mounted upon a single base plate, which is securely fastened to the foun-

dation by numerous bolts. All bearings are water-cooled and oiled from a central gravity oil system, so as to insure a continuous supply of oil to all wearing parts. In order to facilitate starting the set, a pneumatic barring gear is provided, controlled by a hand-operated triple valve.

CONTROL APPARATUS

For controlling the excitation of the generator, a special controller, operated on the principle of a Wheatstone bridge, was designed, the connections of this controller being shown in Fig. 3. The current handled by this controller is, approximately, 50 amperes, with maximum excitation, which can be readily handled by a controller of the face plate type. The slip regulator for automatically varying the rotor resistance, so as to limit the input, consists of a number of pneumatically operated switches,

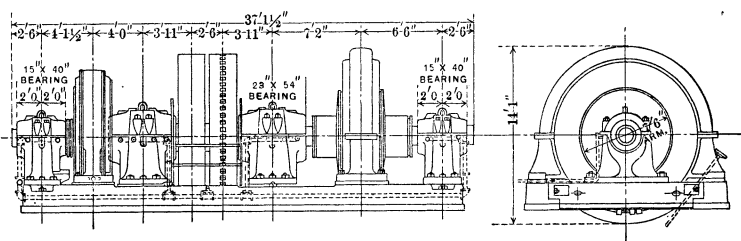


FIG. 12—OUTLINE OF FLYWHEEL MOTOR-GENERATOR SET SUPPLYING POWER TO ROLL MOTORS.

arranged in groups, their operation being controlled by two relays. One of these relays causes the switches to drop out when the current in the primary of the motor reaches a certain value, and so long as this relay is open the switches will continue to drop out successively. When the current reaches a normal value, the relay closes and no further switches are opened. When the current falls below the normal, the second relay drops, and causes the switches to close automatically in the proper order, and in this way the input to the motor, under normal operating conditions, is maintained approximately constant.

The connections of this regulator are shown in Fig. 14, and in Fig. 15 is shown a group of the pneumatic switches, which are of the same type as used for the control of large electric cars and locomotives. In all, thirty switches were provided for starting and regulating the speed of the motor, and, consequently,

the resistance is varied in very small steps. The capacity of these switches to withstand very severe service has enabled them to be operated successfully since the plant was installed, although each switch may be closed or opened eight or ten times a minute.

TEST RESULTS

After five years' operation of the plant, it was decided that it would be advisable to make a complete set of tests, to determine, not only its operating characteristics, but also

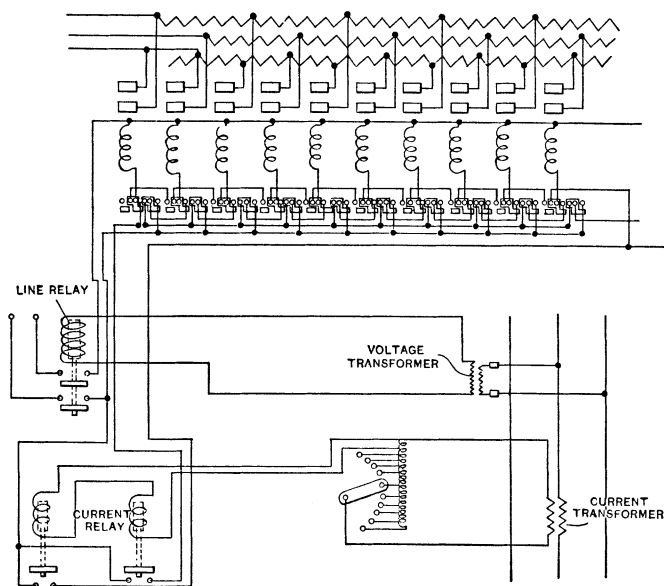


FIG. 14—DIAGRAM OF CONNECTIONS OF AUTOMATIC SLIP REGULATOR CONTROLLING INPUT TO FLYWHEEL MOTOR-GENERATOR SET.

whether such an installation could be improved upon and how closely the designed capacity approximated to the actual operating conditions. Owing to the difficulty in obtaining suitable apparatus to make such tests, most of the instruments were specially designed and built for this test. The current in the motors varies, under normal conditions, so rapidly that ordinary indicating or recording instruments were not suitable and it was therefore decided to use an oscillograph for recording the direct-current voltage and current. The speed of the roll motors was recorded by means of a special graphic recording

meter, controlled by a suitable magneto, driven from the motor shaft. The recording instrument was especially designed so as to be capable of following rapid changes in speed, and to avoid errors usual with graphic instruments. It was decided to avoid the use of a pen for recording and the position of the pointer was recorded by causing a spark to pass from the end of the pointer through the paper to an insulated plate. In designing these instruments, provision was made to avoid introducing errors in the readings due to the static effect of the high-tension current for the spark. The speed-recording instrument for the roll motors had a center zero so as to record both directions of rotation.

The speed of the motor-generator set was also recorded, to determine the amount of energy given up or absorbed by the flywheel, during the period of test. The instrument used was similar to that adopted for the recording of the motor speed, except that provision was not made for recording the speed in both directions. In order to obtain a large reading for a comparatively small change of speed, a battery was connected to oppose the magneto, and the meter recorded the difference in the potential of the magneto and the battery. All the instruments, including the oscillograph and the speed meters, were provided with a time-recording device, all of these attachments being controlled by a single contact-making clock.

The input of the motor-generator set was determined by means of a wattmeter of the same type as the speed meters.

In addition to the above apparatus, provision was made for recording signals from the mill. In the mill, records were obtained as to the size and weight of material rolled and the reduction per pass, and at the same time readings were taken to determine the temperature of the metal.

These tests gave, simultaneously, readings of the input to the roll motors and the input to the motor-generator set at the speed of the set and motors.

With this information, together with the known characteristics of the apparatus, and the data obtained as to the work done by the mill, it was possible to obtain a complete analysis of the power requirements and operating characteristics.

While it is not possible within the scope of this paper to go into detail as to these tests, a few characteristic curves are given which may be of interest.

Fig. 16 shows the power required for rolling a slab, $3\frac{1}{2}$ by

11½ by 95 in. (8.9 by 29.2 by 241 cm.), weighing 1080 lb. (489 kg.), to a plate $\frac{5}{16}$ in. (7.9 mm.) thick by 12 in. (30.5 cm.) wide, and 1060 in. (26.9 m.) long. From these curves it will be seen that the maximum current was approximately 4100 amperes, and the maximum braking current about 2350 amperes. The maximum speed of the rolls during this test was 86 rev. per min. during the sixth pass, whereas in the first pass the maximum speed was 50 rev. per min. The total time required from beginning to end of the test was 58 seconds, showing a maximum capacity when rolling this size material of

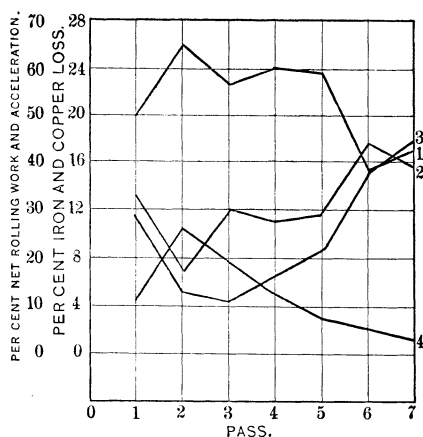


FIG. 17—ANALYSIS OF POWER INPUT TO ROLL MOTORS WHEN ROLLING PLATE (SEE FIG. 16).

1. Percentage of net rolling work to total input.
2. " " acceleration " " " "
3. " " friction & iron loss " " " "
4. " " copper losses " " " "

Original slab 3½ by 11½ by 94.9 in. Finished plate $\frac{5}{16}$ by 12 by 1016 in.—Temperature of metal 1860 to 1810 deg. fahr.—Composition: Carbon 0.10 %, Phosphor 0.033 %, Manganese 0.51 %, Sulfur 0.044 %.—Ultimate tensile strength 53,000 lb. per sq. in.

approximately 30 tons per hour. The temperature of the metal varied during the test from 1920 deg. fahr. to 1800 deg. fahr.

In Fig. 17 is shown an analysis of this test, which gives the relation between the total input to the roll motors and the various items. It will be seen that the percentage of net rolling work averages about 55 per cent. The input required for acceleration is about an average of 30 per cent. The loss due to friction of the mill and iron loss in the motors is approximately 10 per cent. The average copper loss is about 5 per cent.

The reason for the very large drop in the percentage of net roll work in the last two passes, is the fact that the draft was comparatively light on these two passes.

The comparatively large proportion of the input required for acceleration shows the importance of keeping the inertia as low as possible, and the great advantage of the voltage control system is that it enables a considerable proportion of this energy to be recovered. In this particular test, the total energy required to accelerate the motors for the seven passes was 11,800 h.p.-sec. and there was returned by the motors to the generator 8317 h.p.-

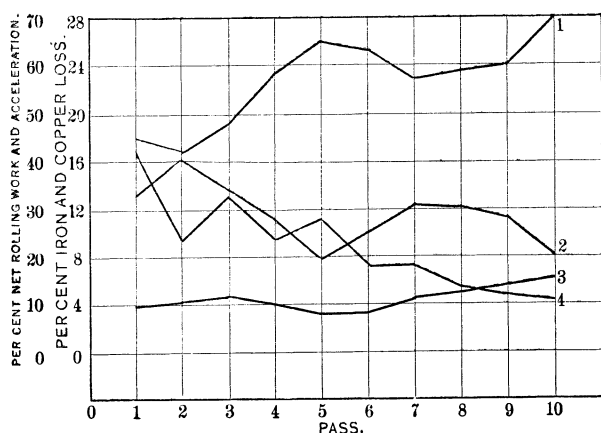


FIG. 19—ANALYSIS OF POWER INPUT TO ROLL MOTORS WHEN ROLLING PLATE, (SEE FIG. 18).

1. Percentage of net rolling work to total input.
2. " " acceleration " " " "
3. " " friction & iron loss " " "
4. " " copper losses " " "

Original slab 3 by 30½ by 75.9 in. Finished plate ¾ by 30 by 612 in. Temperature of metal 2030 to 1200 deg. Fahr.—Composition: Carbon 0.18 %, Phosphor 0.025 %, Manganese 0.48 %, Sulfur 0.038 %.—Ultimate tensile strength 62,900 lb. per sq. in.

sec. or somewhat more than seventy per cent. It should be noted that with this system the energy taken from the generator is only half what it would be if rheostatic control were used and that with the latter system none of the energy would be recovered. In this test, if rheostatic control had been used, the total energy required for acceleration would have been 23,600 h.p.-sec., which would have increased the total net input to the motor about 50 per cent.

In Fig. 18 are shown the curves when rolling a slab 3 by 30 by 76 in. (7.6 by 76 by 193 cm.) weighing 1960 lb. (889 kg.), to a plate

$\frac{3}{8}$ in. (9.5 mm.) thick by 30 in. (76 cm.) wide. The total time of the test was 100 seconds, indicating a maximum capacity of the mill when rolling these slabs of approximately 36 tons per hour.

It will be seen from these curves that the maximum loads are considerably higher than shown in Fig. 16. In this case, the maximum current input is slightly in excess of 6000 amperes, and the braking current reaches a maximum of, approximately, 3150 amperes. The maximum speed of the mill did not exceed 75 rev. per min. during any pass. The temperature of the metal during this test varied from approximately 2040 deg. fahr. to 1300 deg. fahr.

In Fig. 19 is shown an analysis of this test, from which it will be seen that the percentage of net rolling work to the total input gradually increased, and the percentage of power required for acceleration decreased. The copper losses decrease on account of the maximum current being smaller, and naturally the friction loss increases as the mill is running the greater percentage of the time.

The percentage of energy returned by the roll motors was about 62 per cent of the input for acceleration. An examination of a number of other tests taken at random gives the following figures:

	Input for acceleration	Energy returned during braking	Percentage
1.....	21,610	14,197	66
2.....	21,700	14,215	65.5
3.....	18,855	10,657	56.5
4.....	18,208	12,512	68.7
5.....	17,035	9,105	53.5
6.....	20,320	12,449	61.5
7.....	23,800	15,546	65.5
8.....	18,620	12,111	65
9.....	29,195	24,058	82.2
Total.....	189,343	124,850	66

The power required to displace the metal varies considerably, depending upon the operating conditions. The absolute figures depend upon the temperature of the metal, its composition, and the type of mill, etc.

Fig. 20 shows a characteristic curve, when rolling plates on this mill, from which it will be seen that the power required increases very rapidly with the reduction in thickness, this being due to the greater density of the metal, the lower temperature, and the lower rate of displacement.

The total power required for rolling varies considerably, and no definite rule or formula can be produced that will cover all the conditions. The relation of the amount of metal displaced during the earlier passes, to the total, and such items as the temperature, amount of draft, number of passes, etc., make it impossible to give general figures. The net rolling work which is independent of the losses in the equipment also varies widely, and a thorough knowledge of the conditions is necessary to predict

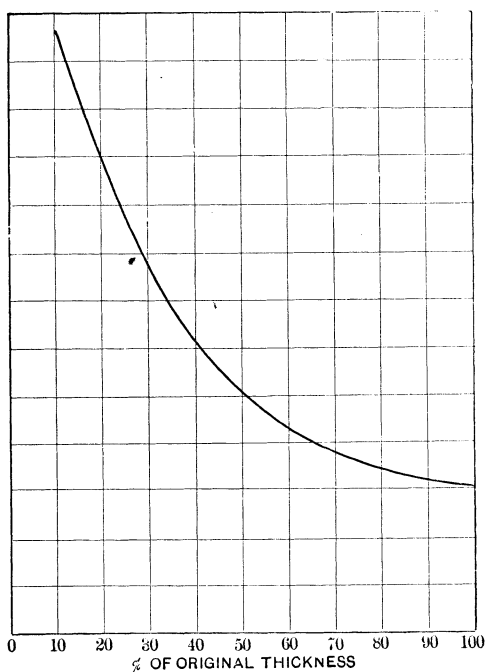


FIG. 20—CURVE SHOWING INCREASE IN POWER REQUIRED FOR DISPLACING METAL WITH REDUCTION IN AREA.

the power requirement of an installation. In Fig. 21 are shown some curves of the net rolling work per ton plotted against elongation and it will be seen that the variation is considerable. The difference in the total power required may show a much greater variation than given, but these curves will indicate in a general way how the net rolling work varies with the displacement of the metal. In a test made when rolling a certain slab, in seven and in fifteen passes, the net rolling work showed a difference of about 10 per cent, but the total input varied about

50 per cent, due to the reduced capacity of the mill when rolling at the lower rate. Such points as these show the importance of a very close examination of operating conditions when designing a mill of this kind, and to insure success an electrically driven reversing rolling mill requires very careful engineering, as the problem is not so much to get a mill that will work, as to get one that will work economically.

At times great stress has been laid upon the advantage and necessity of very rapid acceleration and reversal. The author has pointed out previously that this feature is of little importance, as, with a well designed plant, the roll motors can be handled

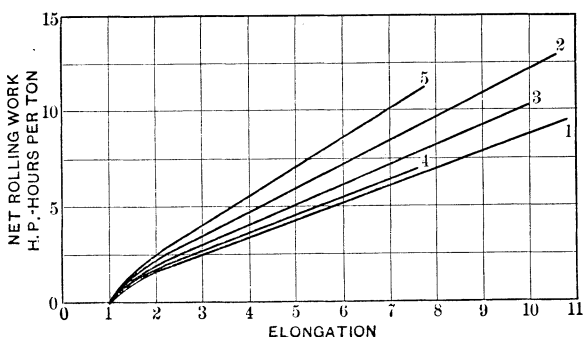


FIG. 21—TYPICAL TESTS SHOWING POWER REQUIRED TO ROLL PLATES FROM SLABS.

Slab	Plate	Temperature, deg. fahr.
1.—4 by 21.5 by 95 in. to $\frac{3}{8}$ by 21 $\frac{1}{4}$ in.;		2160 to 1536
2.—4 " 21.5 " 60 " " $\frac{3}{8}$ " 21 $\frac{1}{4}$ "		2172 " 1578
3.—4 " 8 " 100 " " $\frac{3}{8}$ " 8 $\frac{3}{4}$ "		2208 " 1944
4.—6 " 9 $\frac{1}{2}$ " 90 " " $\frac{3}{4}$ " 10 "		2076 " 1800
5.—6 " 7 $\frac{1}{2}$ " 82 " " $\frac{3}{4}$ " 8 "		2016 " 1692

more quickly than the material to be rolled. In this mill it is the general practise during the earlier passes to have the feed rolls running at full speed in the opposite direction to main rolls, so that when the slab leaves the mill, it is returned in the shortest possible time. In spite of this, the main motors are easily capable of reversing in ample time. An examination of a large number of tests on this and other mills shows that the average rate of acceleration used does not exceed about 20 rev. per min. of the rolls per second, the maximum being about 30 rev. per min. per second. The rate of retardation is, however, very much greater and generally varies between 40 and 50 rev. per min. per second.

The over-all efficiency of the plant depends in the first place

upon the relation of the size of equipment to the material to be rolled. As already pointed out, a mill of this kind cannot be compared to one rolling only a single product, in which case the operating characteristics can be very accurately predicted. As this mill will be often underloaded, the efficiency naturally suffers, which is true, independent of the system of driving. In Fig. 22 are shown some over-all efficiencies when rolling slabs of various sizes, and it shows how the results improve with an increasing load. In addition to the losses in the electrical equipment, these curves also allow for the friction of the mill. To show the difference that the underloading, when rolling the smaller slabs, makes upon the efficiency, compared to what can be obtained when the mill is designed for one class of product only, there are presented in Fig. 23 the over-all efficiency curves of a blooming mill taken from a previous paper by the author.²

The results obtained from this mill indicate that although the equipment was built six years ago, it compares very favorably with some of the latest designs and is quite capable of meeting the most severe service it may be called upon to perform. In new designs, certain features would be improved upon, with the object of somewhat simplifying the equipment from a manufacturing standpoint, but it is not believed that any great improvement could be made from an operating standpoint, as since it has been in regular service the electrical equipment has given no trouble. The experience gained has shown that the engineers of the Illinois Steel Co. were thoroughly justified in undertaking this pioneer installation without having any precedent whatever to work upon.

2. *Electrically Driven Reversing Rolling Mills*, TRANSACTIONS A.I.E.E., 1911, XXX, II, page 1599.