CHAPTER XXXII.

THE SUPPLY OF POWER—(*Continued*).

(4) Electric Driving.

Water Power.—In some few instances power may be obtained from water, but in the nature of things such power can only be had, in any quantity, in mountainous districts, which is where steel works usually cannot be placed. To produce cheaply the works must be in proximity to ore, fuel, limestone, and refractory materials, none of which will bear the cost of transport over long distances, nor over railways whose construction is rendered unduly costly by tunneling and climbing mountain ranges. Though ore may often be found in a mountainous region, it will rarely suffice by itself, and other ores must be mixed with it to render it fusible, or to supply Manganese, which in many cases is deficient. However cheaply the steel may be manufactured, it cannot compete in the markets of the world if it cannot be transported cheaply from the works to the consumer; hence a steel works, which is to do more than supply a very limited local demand, must be situated at least on a good railway system, and is better placed on a navigable river, or close to the seaboard. Doubtless many small works making a high-grade product, the cost of carrying which forms a small percentage of the total selling price, are situated in very inaccessible regions, and where charcoal is used extensively in the manufacture, are necessarily so placed, but such cases are exceptional.

At Terni, in Italy, water power, in addition to driving directly a small rail mill, is employed to compress air, which is used for working a large hammer.

Occasionally water power can profitably be generated on the spot, or in the adjacent mountains, where it may be converted into high tension electric current, which can be conveyed to works in the plain—but these cases are very few.

Nor is water power so cheap as is frequently imagined. The capital charges on the heavy first cost of the hydraulic works required to get the water to the turbines may be nearly as much as the cost of coal to produce an equal amount of power in the neighbourhood of collieries. The Carville Station on the Tyne supplies current for electrolitic purposes at a price lower than is charged by the great water power stations at Niagara. Moreover, all water power may be interrupted in dry seasons, or during severe frosts. Hence, for steel works of any magnitude, the employment of water power has very rarely to be considered seriously.

Transmission of Power Generally.—Where power has to be transmitted for more than 200 or 300 feet, the problem of its transmission mechanically is not an easy one to solve.

A revolving shaft cannot be carried far without introducing considerable difficulties, besides the heavy loss in the friction of the bearings. A wire rope running over a pair of pulleys is more efficient than a shaft. At Schaffhausen, Bellegarde, and elsewhere, very considerable powers have been conveyed over long distances in this manner, with remarkably little loss in friction, the distance between pulleys in each span being as much as 300 or 400 feet. But the machinery to be driven in this way must run in one direction, and at one fixed speed, while the starting and stopping of any machine which absorbs much of the power causes much vibration in the ropes. The space taken up is also considerable. Transmission by fluid pressure is more convenient. Its action is readily controlled at will by valves which can start, stop, and vary the speed or direction of rotation of the parts driven. Of the fluids in use, water is convenient where heavy pressures are to be exerted through short distances, as in the case of hydraulic forging presses, but it is quite unsuitable for driving parts moving at high speeds. Compressed air would be entirely satisfactory but for the fact that, by the act of compressing it, so large a portion of the power is converted into sensible heat, which is entirely wasted, that only one-third of the power exerted by the compressing engine is usually returned by the engine driven by the compressed air. Thus, when power has to be conveyed through any appreciable distance, electricity is the only satisfactory means of conveying it. But there is no gain whatever in using electricity, when the engine can be coupled to the mill directly, or by ropes or gearing.

Electric Transmission of Power.—Electricity is frequently spoken of as if in itself it were a source of power capable of replacing, not only the prime mover, but even the fuel consumed by it, instead of being, what it really is, merely a convenient means for conveying power from a prime mover to the machinery driven by it.

The electric cable performs precisely the same function as the driving ropes which convey the power from the flywheel of the engine to the machinery it drives. The wire transmits an electric current, which can be made to give a mechanical pull; the ropes transmit the pull direct. There is frictional loss in forcing the current along the wire, as there is in bending the ropes round the pulleys and dragging them through the air. But as a current does not transmit a pull directly, it necessitates the interposition of two additional pieces of mechanism between the prime mover and the machinery to be driven by it, both of which absorb power in friction and in internal resistance. These are the dynamo, which converts the mechanical energy of the engine into electrical energy, and the motor which converts it back again into mechanical energy. In this, just as in every other case where one form of energy is converted into another, there is a loss every time the conversion takes place, and from a purely theoretical point of view electrical transmission of power is indirect and far from ideal. Were not dynamos and motors such exceptionally efficient pieces of mechanism, the round-about nature of the operation would make itself manifest by the waste of power which would ensue.

No one would attempt electric transmission of power, where a shaft or a pair of pulleys could do the work, but an electric cable can be carried anywhere, up or down hill, and into corners or spaces where transmission by belts, gearing, or shafting would be cumbersome or impracticable. Energy, in the form of an electric current, can be picked up by a shoe moving along a bare insulated wire, and so conveyed to cranes or other pieces of travelling machinery with much greater ease than any other form of energy is capable of being conveyed; and, finally, the loss by friction in a stationary wire is less than in any moving belt, rope, or shaft.

Efficiency of Electric Transmission.—Motors and dynamos of fair size can generally be relied upon to give an efficiency of 92 per cent. at full load, 90 per cent. at half-load, and 86 per cent. at quarter-load, so that of the power transmitted it is usually practicable to get out, at the end of the system 80 per cent. at full load, 77 per cent. at half-load, and 70 per cent. at quarter-load. The balance is wasted in the resistance of the cable, and in the friction and internal resistance of dynamos and motors.

Kind of Currents Employed.—The current employed may be a direct or an alternating one, the former flowing continuously in one direction, while the latter flows alternately in opposite directions, the change occurring many times in a second.

The sectional area of a cable to convey a given amount of power is inversely proportional to the pressure; hence, when a current has to be carried some miles, unless the voltage is fairly high, the cost of copper required to convey it becomes prohibitive. Therefore, for long distance transmission the alternating current is most suitable because the pressure employed may be so much greater than with a direct current.

The most convenient form of alternating current, and the one requiring the least copper in the lines, is the three-phase system, which is now usually employed; and by common consent a period of 50 alternations per second is becoming the recognised frequency. To secure economy of steam, turbines must be run at speeds too high to admit of the use of commutators, and with turbo-generators an alternating current becomes a practical necessity, while the high speed of rotation reduces the cost of the whole of the generating plant.

The chief objection to an alternating current is that when a motor driven by it is run at a reduced speed by inserting a resistance in the rotor circuit, which is the simplest means of obtaining this reduced speed, a loss of power takes place which is practically proportional to the reduction in speed, and that portion of the power which is not beneficially utilised is wasted in heating up these resistances. On the other hand, the speed of the continuous current motor may be reduced by varying the resistance in the circuit which is used to excite the field without interfering with the main current circuit.

As the current in this field circuit is of the order of 1 per cent. of the main current, the losses occurring in the field circuit never exceed more than about ½ per cent. of the total power, and are, therefore, negligible.

It is generally advisable, when currents of high voltage are brought from a distance, to transform them down to a lower pressure at once, before commencing to distribute or use them, although three-phase motors of 50 H.P can be run safely off a 3,000 volt circuit, 120 H.P. off a 5,000 volt circuit. If the alternating current is to be transformed down to an alternating current of lower voltage, this can be done with a static converter, in which there are no moving parts whatever, with a loss of only 1 or 2 per cent., but when the alternating current is to be transformed into a continuous one, a motor transformer must be employed, which consists of an alternating motor coupled to a direct-current generator. As this involves the use of running parts, the amount of output is only 88 per cent. of the input.

Power Obtainable from the Current.—The difference in potential of the current flowing in an electric supply cable, measured in volts, corresponds to the pressure of steam in a steam main measured in lbs. per square inch; the quantity of current taken from the cable measured in amperes (usually shortened to amps.) corresponds to the cubic feet of steam taken from the steam main Just as the power obtainable from the steam main

is the product of the pressure by the volume of steam, so the power taken from the electric main is the product of the amps. by the volts. One volt by 1 ampere is equal to 1 watt, and 746 watts per hour are equal to 1 H.P.-hour; 1,000 watts are 1 kilowatt, or Board of Trade unit, which is, therefore, equivalent to 1·34 H.P.

By multiplying together the volts recorded on the voltmeter, and the amps. on the ammeter, the power supplied to the motor is known.

Power Factor.—The above applies strictly to a continuous current, but in any system of alternating current supply the amps. vary rapidly from a maximum positive to a maximum negative value, and if the actual value of the voltage is plotted vertically, and the time horizontally, a wave-like curve is obtained—generally a sine curve—which crosses the horizontal zero line continually. If the alterations are 50 per second, there will be 50 positive maxima and 50 negative maxima, the curve crossing the zero line 100 times in one second.

The amps. corresponding to this voltage also vary, forming a very similar curve having the same number of maxima and minima, but not necessarily occurring at the same time. In fact, usually, for many electrical reasons, the maximum amps. occur slightly later than the maximum volts. The real power obtained is the momentary voltage by the momentary amps., and is expressed by finding the mean of the fresh curve thus obtained.

If the maximum volts and maximum amps. occurred simultaneously, the maximum possible power, which may be called unity, would be obtained. The actual power is always less than this, and the proportion which it bears to unity is called the power factor.

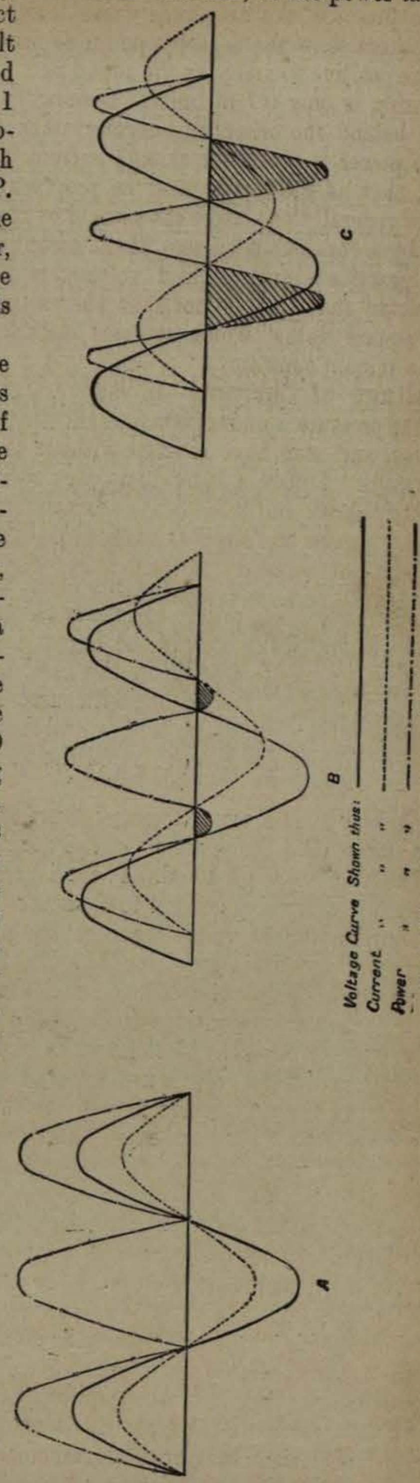

Fig. 447.—Diagram to explain Power Factor.

In fig. 447, A shows unity power factor, which would be given out did maximum voltage and maximum amperage occur simultaneously. B shows how, in practice, the amperage curve lags behind the voltage curve; the shaded areas show the negative power so produced, which must be deducted from the positive to arrive at the actual nett power exerted, which in the case in question is only 0·7 of unity. C shows how, if the one curve lags sufficiently behind the other, the negative areas become equal to the positive, and no power is given out though current is passing. The consequence of this is, that as the mains must be proportional to the amps. carried, they have, in general, to be larger than would be required for transmitting the same power by a continuous current of the same pressure.

In practice ammeters and voltmeters for alternating currents are so constructed that they do not show the variations, but the square root of the mean square value, which remains constant, provided the maxima and minima remain constant.

Voltage of Current.—In case of accidental contact with a live wire, when the pressure is under 200 volts, the shock received may be comparatively harmless, and men have escaped without serious injury even with currents of 500 volts. Different individuals vary greatly in their ability to withstand an electric shock, but it is always advisable to take every practicable precaution, and expose one's self as little as possible to the risk of sustaining one. If it should be necessary to touch a live wire, do not touch it with the inside of the fingers, because the muscles of the hand are contracted by the current, and it may be impossible to release the hold upon the wire; whereas, if it is touched with the back of the fingers, the contraction of the muscles of the hand and arm at once throw the hand away from the wire. The greatest care is necessary when dealing with currents of very high pressure, as a serious shock is fatal; for pressures of several thousand volts the switches are usually worked from a distance, to avoid the necessity of the men approaching the switch board.

Where it is necessary to convey current for many miles very high pressures are employed. There are several plants working in America at 110,000 volts, even 200,000 is proposed. The Niagara Company, working with 60,000 volts, are delivering current to Syracuse, 150 miles away. On the Continent of Europe 10,000 volts is a common pressure, but in Great Britain it is necessary to obtain special permission from the Board of Trade to use pressures of 3,000 volts or over, and the authority requires very elaborate and particular precautions to be observed wherever the current is taken. Accordingly, when the blast furnaces are some distance from the steel works, a pressure of 2,750 volts is usually employed in this country.

Any of these pressures necessitate the use of an alternating current, as there are difficulties with sparking at the commutator, when direct currents are used at pressures exceeding 500 volts.

When the current is generated and used within one works, a common pressure is either 500 or 440 volts, which is found to be a very convenient one for driving auxiliary machinery, and for working arc lamps in series.

Small Reversing Motors.—The small motors used for driving auxiliary machinery, such as live rollers, cranes, &c., are usually required to run at various speeds and in either direction. For such purposes, if a direct current is used, the controller, with resistance for regulating the speed, is placed in the armature circuit, and if an alternating current in the rotor circuit. In both these cases there is a loss of power and waste of current due to the heating up of the resistances proportionate to the fall in speed, so that, generally speaking, so far as efficiency and facility of control are concerned, both systems are on a level for this purpose.

Where a direct-current series motor is used the turning moment which the motor can give is roughly proportional to the square of the current taken, because increased current in the armature increases the magnetisation of the field, and the turning moment is proportional to the product of the current in the armature multiplied by the field magnetisation. But where a three-phase current induction motor is used, the turning moment is directly proportional to the current, because an increase in the current does not alter the field magnetisation. On starting up, therefore, under a load, a direct-current motor can speed up more quickly than a three-phase motor of the same size.

If the same work is required from a three-phase as from a direct-current motor, a larger three-phase motor must be chosen, and, as such a machine has a larger and heavier armature, an appreciable amount of the work done goes in accelerating the armature. Generally speaking, therefore, if a comparison be made between a direct-current and three-phase motor of the same size for such purposes as driving live roller gear, where rapid reversal is required, the three-phase motor will be the slower. If the motors are required to have an equal starting torque, and work equally rapidly, the three-phase motor is larger and more expensive than the direct current. Further, if the voltage from the supply system varies, the turning moment given by a direct current series-wound motor for a definite current does not change, although the speed will fall, but with a three-phase motor the turning moment for a definite current will be considerably diminished, because the value of the magnetic field will be reduced.

The number of three-phase and direct-current motors actually used for driving live roller gears is about equal, so that the inherent advantages of the direct-current machine do not seem to outweigh the disadvantages of having to transform the current where the supply is an alternating one.

Motors for Steadily Loaded Mills.—It is a simple matter to drive electrically such mills as rod or wire mills, which run at one regular speed, under constant load, with material passing simultaneously through all the stands all the time. Even when starting the load comes on with regular increments, as each stand comes into operation and falls off with regular decrements, as the stands in turn run empty. Either alternating or direct current may be used, but the alternating motor is the cheaper and simpler, as it requires no commutator, that part which gives most trouble and wears out most rapidly. The question is generally settled by the class of current which chances to be available. The motor should be capable of withstanding a momentary overload of 50 per cent.

It is usual to provide a flexible elastic coupling between the motor and flywheel, to serve as a cushion, and provide for the possible contingency of a settlement in the foundations.

Driving Irregularly Loaded Mills.—When the piece rolled is short, the periods during which it is being rolled are considerably less than those during which it is being handled between the passes; short periods, in which much energy is demanded, alternate with longer ones, in which energy is required sufficient only to overcome the friction of the mill when running empty.

The difficulty was met by the mill manager who, two generations ago, had to work with a slow-running engine, capable of giving out only a fraction of the maximum power needed. He used then to gear to his mill a large heavy flywheel, running several times faster than his engine, in which was stored as much energy as the engine gave out in from one-quarter to one-half minute, and thus tided over the momentary excess in demand. A flywheel is like a reservoir into which water flows. The height of the water is the measure of the potential power stored in the tank, and the speed of the flywheel that of the energy stored in it. If water is pumped into the tank at a steady uniform rate, it may be withdrawn intermittently, for short periods, at a much greater rate than that at which it is supplied; but the level of water must fall whenever the rate of expenditure exceeds the rate of supply. Similarly, if energy is expended at a uniform rate upon turning a flywheel, its speed increases, and the power thus stored in it may be extracted from it again, for short intervals, at a much greater rate than that at which it was supplied to it; but the speed of the wheel must fall during these periods when the expenditure of power by it exceeds the income received by it from the engine, its fall in speed returning just as much energy as had been expended in speeding it up. A flywheel which is running at constant speed is giving out no power whatever.

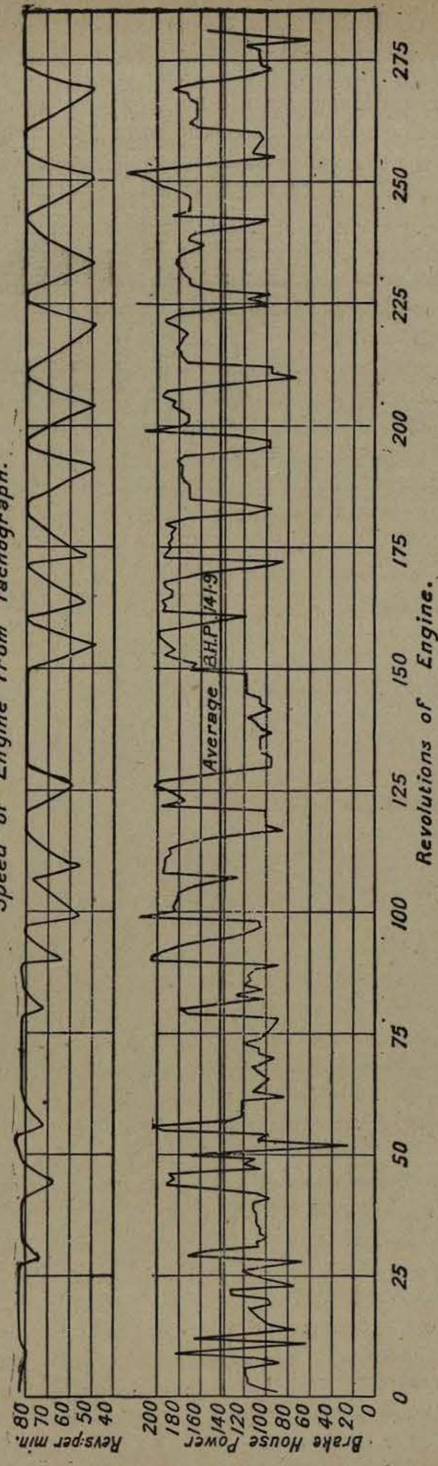

Fig. 448.—Speed of Mill and Power absorbed in Rolling a Sheet.

Mills used to exist at which, when a leading spindle broke, the roller boasted that he had time to cross the road and "have a couple of pints," and yet find the flywheel still running when he returned. Usually the speed of the flywheel varied from 5 or 6 per cent. below, to 5 or 6 per cent. above, its nominal speed. So dependent was the mill upon the flywheel, that when Mr. Ramsbottom proposed a reversing mill, he was told by all the mill managers that without a flywheel no plate could be rolled. Had he not used reversing engines capable of exerting momentarily an effort five or six times as large as the flywheel engines commonly employed, the statement would have been correct.

Fig. 448 shows the power absorbed by and the variation in speed of a sheet mill occupied in rolling down in eighteen passes, nine in the soft rolls and nine in the hard rolls, a sheet 56 inches wide by No. 8 gauge thick from a slab 3½ inches thick, weighing 6 cwts. It will be seen that the engine is too small for the work, and the flywheel much too light, so that the speed, which was taken by a tachograph, varied widely at every pass, beginning at 83 revolutions per minute, and ending up at 48 revolutions when the sheet was in the last pass.

The difficulty of dealing with loads varying between any reasonable limits no longer exists in the case of steam engines, because modern quick-running steam engines with high-speed governors controlling automatic cut-off valves respond promptly to any demand for power, and prevent variations of more than 2½ per cent. above or below the nominal speed. The steam consumption per horse-power between half and double the nominal power need not vary more than 6 per cent. in the case of compound condensing, or 5 per cent. in triple-condensing engines, if the correct size of engine is selected for the work.

Motors for Irregularly Loaded Mills.—Large, sudden, and intermittent rushes of current would so seriously interfere with the generating station, particularly if driven by gas engines which run badly under rapidly varying loads, that the source of supply must be protected by some method for smoothing out the rate at which current is demanded. These precautions are particularly necessary when the current is taken from public supply mains, which serve other customers also, and usually must provide a current steady enough for lighting purposes. Most public electric supply companies, to discourage irregular demands, base their rates for current on a fixed charge per annum proportionate to the maximum quantity taken at any instant during the quarter, plus a reduced rate per unit for every unit used beyond this quantity

Now the speed of the ordinary type of motor falls only about 1 per cent.

or so, as the load increases from no load to full load, and so the power given out by the motor must rise, as the piece is passing through the mill, until this energy and the energy given out by the flywheel as it falls in speed, together equal the resistance to be overcome. As the fall in speed of the flywheel is so trifling, it cannot give out any appreciable portion of the energy stored in it, and the bulk must be furnished by the motor drawing upon the supply system.

Utility of the Flywheel.—Electricians have met this difficulty in the same way as their predecessors, the old mill managers—namely, by supplying a heavy flywheel, and allowing a drop in speed of about 10 per cent. About four-fifths of the power required during the periods of maximum demand is usually provided by the flywheel during its fall in speed, the motor speeding it up again, and so storing fresh energy during those periods when the mill is running empty.

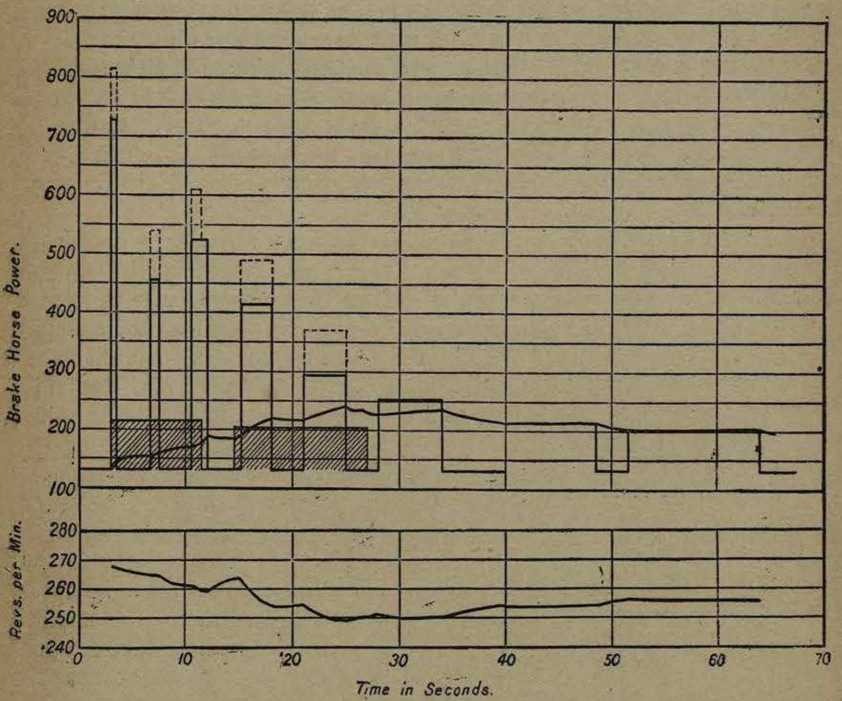

Fig. 449.—Diagram showing Effect of a Normal Size of Flywheel on the Size of Motor, and Regularity in the Speed of the Mill.

This drop in speed is obtained, if the motor is a continuous one, by providing it with a compound winding (the effect of which is to increase the strength of the field as the current taken by the motor increases), and if the motor is a three-phase induction motor, by providing a small resistance in the rotor circuit.

The motor should be capable of withstanding a temporary overload of 100 per cent. without injury. There should be interposed between it and the mill a flywheel of sufficient weight, and as the tensile strength of a steel casting is four or five times that of an iron one, four or five times as much energy may be stored in a given weight of wheel when made in steel, without increasing the risk of its bursting, by running its rim from two to two and a quarter times as fast, both the regulating effect and tendency to burst being proportional to the square of the speed. When several mills are driven from one motor, each rope pulley should be sufficiently heavy to serve as a flywheel for its own mill.

Fig. 449 is a copy of a diagram got out to determine what size of motor was required to drive a mill for rolling down billets into light sections weighing less than ½ lb. per foot. The mill had two stands of rolls, and the piece had to make six passes in the roughing rolls, and two in the finishing rolls, two pieces being in the mill simultaneously to get the output required. The diagram shows very clearly how the energy which could be stored in the flywheel, and the permissible drop in its speed, fixes the size of the motor required to deal with this varying load.

In the upper portion of the diagram the areas bounded by full lines represent the power absorbed in each roughing, and the shaded areas that absorbed in each finishing pass. The vertical dimensions represent the intensity, and the horizontal the duration of each effort exerted. The intensity of these efforts decreases, but their duration increases as the piece lengthens. Before the piece had passed through the last two finishing passes (the efforts required during these passes are shown in the two areas on the extreme right of the diagram) a fresh piece was required to enter the roughing passes, so that allowance had to be made for sufficient power to permit both pieces to be rolled simultaneously. Consequently the two areas representing the power absorbed in these two passes is superposed on the first two passes, as shown in

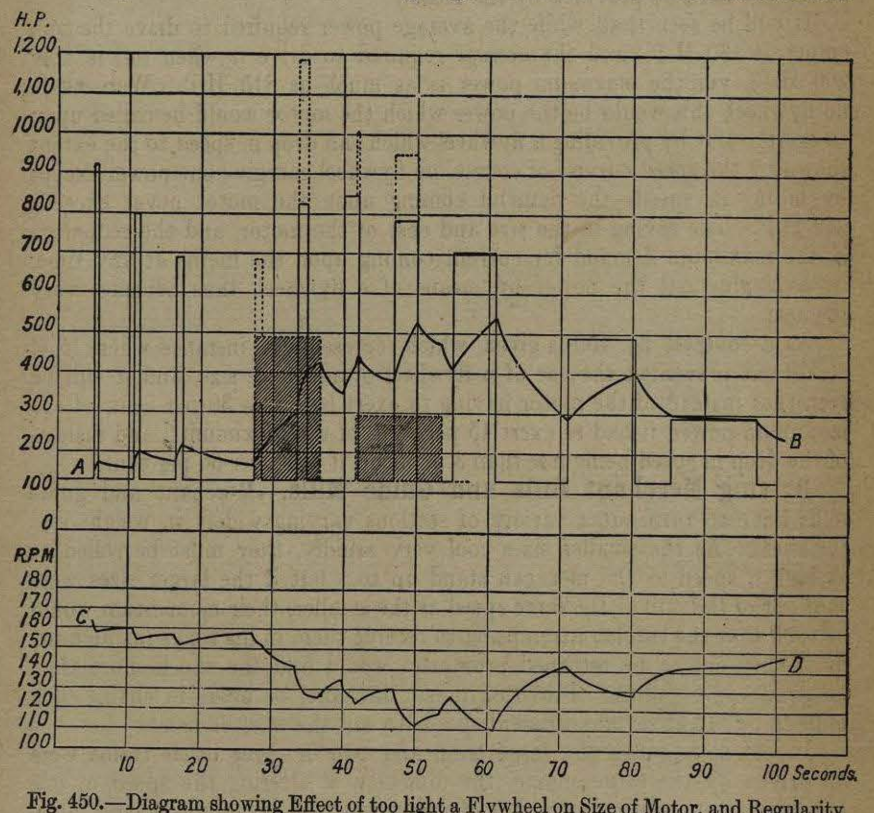

Fig. 450.—Diagram showing Effect of too light a Flywheel on Size of Motor, and Regularity in the Speed of the Mill.

shaded areas on the left, and the increase in power thus demanded during the first two periods is added in dotted lines above the entering passes as shown.

By following the first small piece of straight line at 130 H.P., which represents the power absorbed by the mill when running empty, then following up to the top of the dotted area of the first pass, down to the shaded area of the seventh pass, and up to the dotted area of the second pass, and so on, the total power required at each instant is obtained.

On the portion of the diagram showing the power used is an irregular curved line, and all the power required above this line can be taken from the energy stored in the flywheel, by so proportioning it that it can fall in speed in the manner shown in the lower curved line in the speed portion of the diagram, and then only that portion of the power below the irregular curved power line need be provided by the motor.

It will be seen that, while the average power required to drive the mill empty is 130 H.P., and the *average* required to drive it when full is only 200 H.P., yet the *maximum* power is as much as 815 H.P. Were there no flywheel, this would be the power which the motor would be called upon to exert. But by providing a flywheel which can drop in speed to the extent shown by the speed curve—of course, no flywheel can give out power except by falling in speed—the demand coming upon the motor never exceeds 240 H.P. The saving in the size and cost of the motor, and the reduction in the maximum demand for current coming upon the mains at any time, by averaging out the power by means of a flywheel, thus becomes very obvious.

As a contrast fig. 450 is given, which represents an instance where local conditions prevented the use of a flywheel of adequate size, and it will be seen that instead of the motor having to exert less than 30 per cent. of the maximum power, it had to exert 45 per cent. of the maximum; and instead of the drop in speed being less than 3 per cent. it was over 30 per cent.

Driving Merchant Mills and Guide Mills.—Merchant and guide mills have to turn out a variety of sections varying widely in weight and thickness. As the smaller sizes cool very rapidly, they must be rolled at as high a speed as the men can stand up to; but if the larger sizes were shot out of the mill at the same speed as the smaller, their momentum would be such that the catcher attempting to receive them in his tongs (as he must do if they are to be returned promptly) would find the shock more than his arms could endure. Provision must, therefore, be made to enable such mills to be run at several different speeds to suit the work in hand.

In old days, when the forge train and two or three other trains were all driven by the same engine, the difficulty of altering the speed of one mill without interfering with that of others was met by having several intermediate shafts, provided with wheels of different sizes, which were changed in the same way and at the same time as the rolls, the wheel on the removable driven shaft gearing into one of the fast wheels provided for that purpose on the permanent driving shaft, or by some equivalent device. This had one convenience, inasmuch as the power obtainable was inversely proportional to the speed, a condition which complies with the necessities of the case. Now that each mill is driven by its own engine, the speed of the engine is altered by providing cone pulleys or change wheels to drive the governor, finer regulation being obtained by altering the tension of the spring or adjusting the loading weights on the governor, which can usually be done while the engine is running.

Motors for Merchant and Guide Mills.—The variation in speed of these mills, when driven electrically, can be effected by the changing or sliding of spur gears or rope pulleys, as in the old mills, if desired; but changing the speed of the motors is not quite so easy as changing the speed of a steam engine, but may be effected by one of several different methods.

With direct-current shunt-wound machines the speed may be regulated by resistances inserted in the field winding without very serious loss of current, the speed increasing as the resistance is increased, and variations in speed up to about 25 per cent. may be obtained in this way without trouble, but beyond this sparking occurs. If, however, interpoles and compensating winding are used the speed may be varied as much as sixfold.

In some works the Cascade method of working is in operation, which consists in having two motors coupled together. If, instead of passing the current through both motors in parallel, it is passed through them in series, the speed of revolution is doubled.

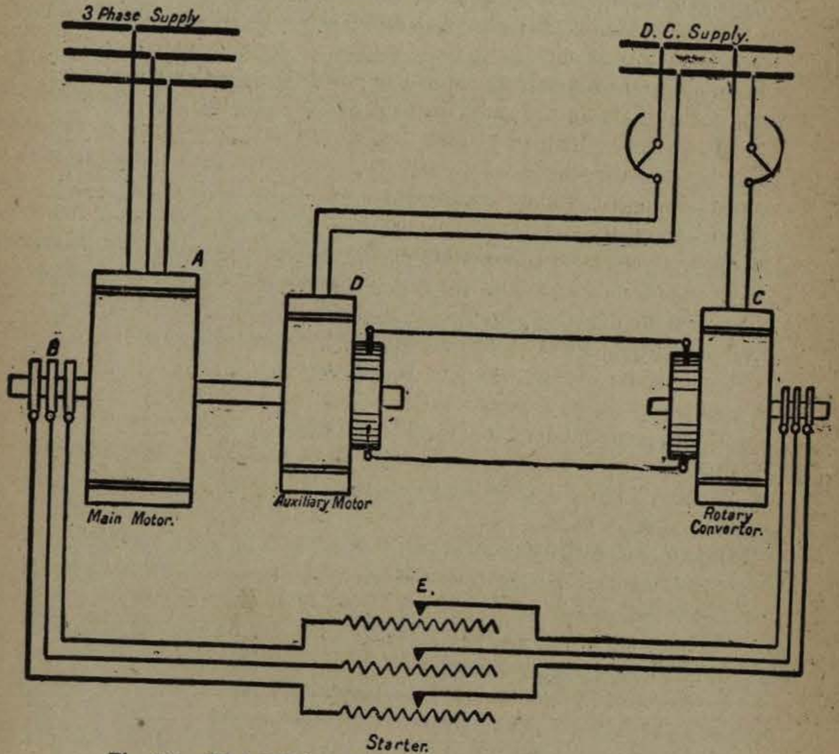

Fig. 451.—High Efficiency Variable Speed Three-Phase Motor Set.

The difficulties are greater in the case of alternating currents, as the three-phase motor is essentially a constant speed machine, tending to run always at an approximately constant rate. The change of speed may, however, be effected in several ways, the simplest being the insertion of resistances in the rotor circuit, when the speed obtained at full load is approximately proportional to the amount of resistance used. This method, however, is very wasteful, for when the motor is reduced to half-speed, half the current is wasted in uselessly heating the resistance coils, and if adjusted for this speed at full load, it tends to run up to full speed as the load decreases. Consequently, when one billet leaves the rolls, the speed may increase too much before the next is ready to enter. This method is really only suitable for mills on which the load is constant, but as an increased turning moment is required for the larger sections rolled at the lower speeds, a larger motor than otherwise would be needed must be installed to provide it.

Another method of altering the speed is to wind the motor so that a suitable switch can cut out one or two out of every three poles in it. This provides speeds in the ratio 3, 2, and 1, at which the motor will work economically, will give approximately the same turning moment at all speeds, and does not tend to increase in speed as the load decreases. But the speed is changed in steps greater than are usually desirable, and to adjust the speed, resistances are inserted in the rotor circuit introducing to a less degree the objection to the first plan. Moreover, the effect on the supply system is bad, making it difficult to maintain a constant voltage in the circuit, and requiring larger cables than otherwise would be requisite.

An ingenious method of getting over these difficulties is employed in some works, including that at the Ormesby Rolling Mill Company, where a three-high merchant mill with four stands of rolls is driven directly by alternating current taken from the Durham Power Supply Company's mains. On the same shaft as the main three-phase mill motor is a direct-current motor of less size. Instead of inserting an ordinary resistance in the rotor circuit, the current, which otherwise would be wasted in reducing the speed, is passed through a rotary transformer, which transforms the three-phase to a direct-current, and this is passed to the direct-current motor on the main shaft, as illustrated diagrammatically in fig. 451. Any requisite speed can then be obtained by merely turning the handle which regulates the current in the shunt field of the direct-current machine, and the turning moment is inversely proportional to the speed at which the mill is run. When set for one particular speed, this will vary between no load and full load by only a sufficient amount to enable the flywheel to properly reduce the variations in the demand for current. This variation in speed is obtained by providing the direct-current machine with a suitable compound winding. The efficiency at full load is 88 to 89 per cent., and unity power factor is obtainable at all speeds.

Driving Reversing Mills.—In the case of ordinary three-high mills, the irregular demand for power; and in the case of the merchant and guide mills, the different speeds, have been the difficulties to be met. But in the case of reversing mills not only is a third factor introduced, but both the previous difficulties increase greatly. The demand for power varies in a second between nothing and several thousand horse-power and back again to nothing continually, the fluctuations occurring several times in a minute, so that the demand rarely lasts, even approximately constant, for many seconds together. Moreover, a modern reversing mill is expected to grip the piece gently, increase the speed of rolling up to the maximum needed during the middle of the run, and slow down again towards the end of it, so as to permit the piece to leave the rolls as quietly as possible.

Mr. Ramsbottom, who invented the reversing mill, discarded the flywheel altogether, and drove with engines capable of exerting high power at will, because it was obvious that a flywheel could not be coupled directly to a reversing mill. Nevertheless, many plate mills, which existed before Ramsbottom produced his invention, were altered afterwards so that the direction of revolution of the rolls could be reversed, although still driven by the old engine still running in one direction only, which, without the aid of the flywheel, would not have been able to do the work. This was accomplished by means of the reversing clutches described on p. 775.

Motors for Reversing Rolling Mills.—A modern reversing rolling mill will need the exertion of a turning moment equivalent to 5,000, or even 10,000 H.P. during one or two seconds, falling off to nothing during the next few, and rising to the same power a few seconds later. Such large and sudden fluctuations in demand could not be tolerated by any public supply company, as they would render impossible the working of everything else supplied from the same circuit, and even from the same generating station. Indeed, they are inadmissible even when the supply is generated by gas engines within the works, for such engines do not work at all well with fluctuating loads; they are far from economical at light loads, and pull up entirely when overloaded. It would, moreover, be excessively costly to have to provide generating plant in the power house large enough to supply, not the mean only, but the full maximum amount of power required at the mill. The generating station, whether public or private, must, therefore, be somehow protected from such sudden and irregular loads. Electric storage batteries can only be used with direct currents, and would be out of the question in any case, because they must be charged and discharged in a regular leisurely manner. Such explosive discharges as that would destroy the plates.

The only possible method, therefore, is to store the power in the form of kinetic energy in a rapidly revolving flywheel, and to draw upon this store as required, the same arrangement in effect as the old clutch-reversing mill, with an electric generator and motor substituted for the reversing clutches.

Though the principle of working is precisely the same, the newer electric reversing device possesses these important advantages over its mechanical predecessor. It does not produce those mechanical shocks, which limited the speed of its prototype; and, still more important, the rolls need not run at one rate only, but their speed may be varied at any instant as desired. In fact, so far as the working of the mill is concerned, it is just as much under control as if it were driven by a reversing engine.

To reverse and control the speed of a large motor capable of giving out 5,000 or 10,000 H.P. by controlling the main current, as is done in the case of the smaller motors for driving live rollers, &c., would necessitate the use of a controller of such enormous size and weight as to be too cumbersome to be handled promptly. Moreover, when rolling ingots or other short pieces, the reversals are so frequent that more power would be wasted in heating the resistances than would be utilised in actual rolling.

The difficulty is got over by what is known as the Ward Leonard system of control, whereby the speed and direction of rotation of a continuous current motor may be controlled by controlling the quantity and direction of flow of the much smaller current flowing through the field winding on the magnets.

Current from a central station is led to a primary motor (fig. 452), to which is coupled a heavy cast-steel flywheel, the rim of which runs at a speed of 14,000 to 18,000 feet per minute, producing a tensile stress of from 3 to nearly 5 tons per square inch in the rim, corresponding to one-seventh to one-fifth of the elastic limit of the material. To the same shaft is directly coupled a direct-current variable-voltage generator, the current given by which is taken to a similar secondary mill-motor, coupled to the roll pinions. In the figure it is shown coupled to the top pinion, which is not an unusual arrangement in Germany. This combination of a primary motor connected directly