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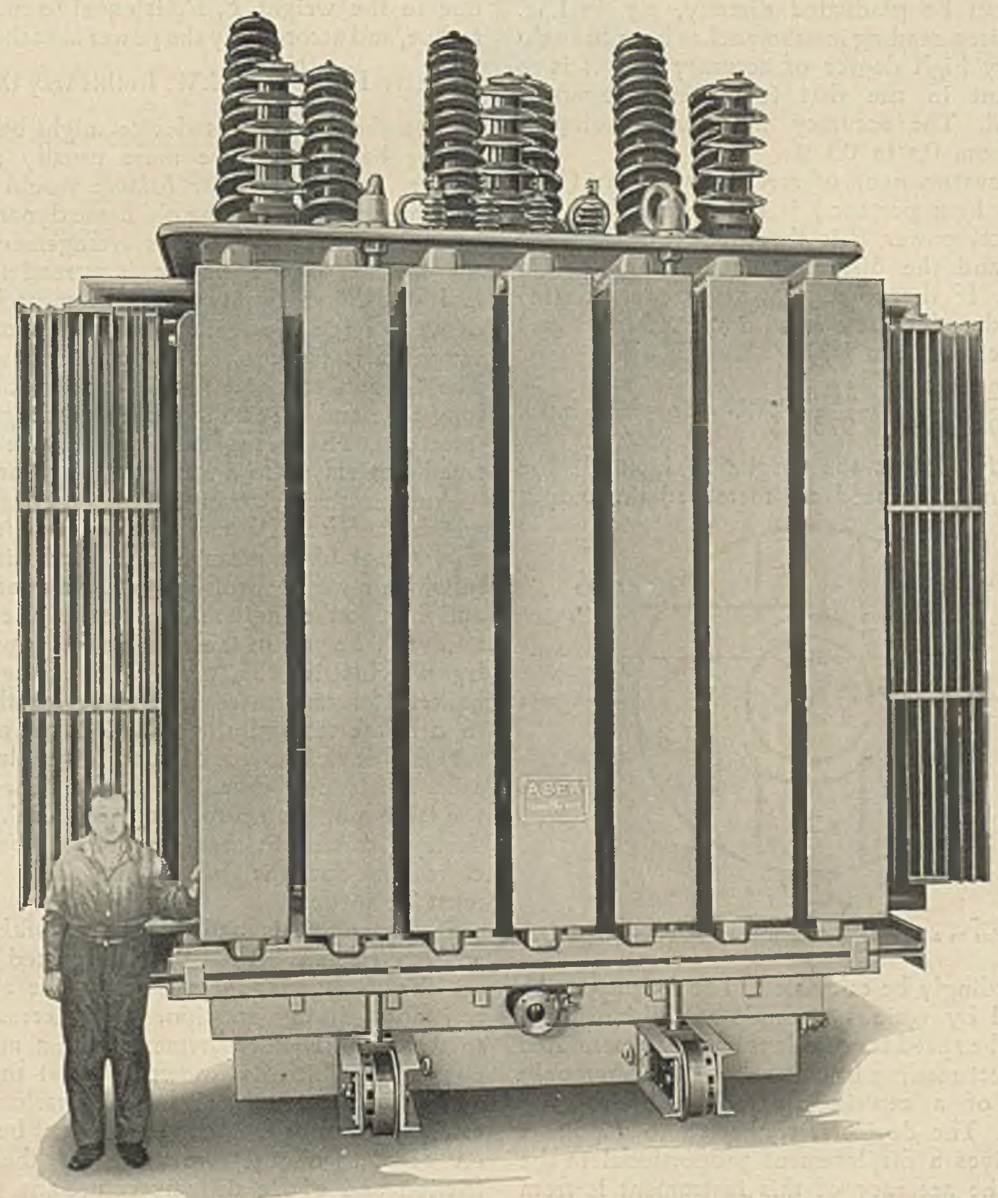

12,000 kVA self-cooled transformer $\frac{56,500}{46,500}$/5,600 volts, 50 periods.

DYNAMOMETERS.

The measurement of *electric power* (*e.g.* kW) is, of course, fairly simple. It is done by the help of a direct reading instrument, which consists in principal of two coils, one fixed and the other moving, and furnished with a pointer. The currents in both coils are very small and proportional respectively to current and voltage, in that part of the circuit in which the power is to be measured. The displacement of the moving coil is practically proportional to the currents in the coils, *i.e.* to the product of voltage and current in the circuit, or the power, and the scale over which the pointer moves can be graduated directly, *e.g.* in kW.

This direct reading instrument has been brought to a very high degree of accuracy and it is so convenient in use that it is very commonly employed. The accuracy with full reading is within from 0.2 to 0.5 %.

The measurement of *mechanical power* (kW, h.p., or kgm per sec.) is not so simple. The mechanical power P is the product of the force F (kg) and the distance per unit of time (m per sec). If the force acts at a radius R (m) on a body which rotates with a speed n (r.p.m.) the power is given by

$$P = \frac{F\ 2\ \pi\ R\ n}{60 \cdot 101.9} = \frac{M\ n}{973}\ \text{kW}, \quad \left(\text{or} = \frac{M\ n}{716}\ \text{h.p.}\right),$$

where $M = FR$ is the torque in kgm. If the torque and the speed are measured the output

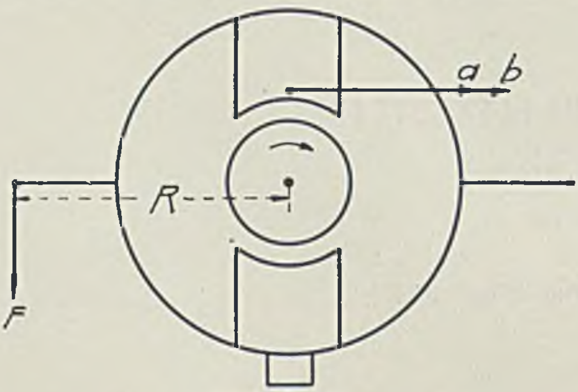

Fig. 1. Generator.
Torque due to a = rotor current, b = losses, FR = weights.

can accordingly be calculated. The torque can be measured by various methods as will be shown below. The speed is nowadays usually determined by a direct reading instrument, which commonly consists of a centrifugal device opposed by a spring. The device is connected to a pointer which gives a displacement proportional to the speed. The accuracy of this instrument is from 0.3 to 0.5 %.

When it is desired to measure the shaft h.p which a steam engine or internal combustion engine gives out, the engine is suitably loaded by a machine which is specially designed for power measurements. Such an arrangement is the *friction brake*, which consists of two brake blocks which are clamped on a pulley fixed to the shaft, and which, on account of the friction at the face of the pulley tends also to rotate. The whole of the power is transformed into heat by friction. If one side of the brake is loaded with a weight F_1 kg, at a radius R_1 m so that the brake is in equilibrium at a certain speed n, the torque due to the weight $F_1\ R_1$ is equal to the friction torque, and accordingly the power absorbed by the brake is $P = \frac{F_1\ R_1\ n}{973}$ kW. In this way the torque is "weighed" and this device might be called a torque balance; as we more usually speak of power, the name *power balance* would perhaps be more suitable than the old name dynamometer. The disadvantage with this arrangement is that the whole of the power is turned into heat and on this account the brake must be made of very large dimensions, or else cooled with water, if it is required for continuous service. The friction cannot be kept constant for a very long time and the readings are accordingly rather uncertain. The arrangement can only be used for small powers up to a maximum of 30 or 40 kW.

Another similar arrangement is the *water brake* which consists of a container of cast iron with an internal blade arrangement, filled with water, in which a wheel furnished with vanes or buckets and fixed to the engine shaft rotates. The housing tends to take part in the rotation but is prevented by weights in the same way as the friction brake. If arrangements are made for the water to circulate through the brake it is not necessary for the device to be of such large dimensions as the friction brake. Water brakes are made for large powers up to about 3,000 kW. If the shaft is carried in separate pedestal bearings a correction for the friction in these bearings must be made.

If the engine is loaded by an *air brake*, which consists of fan blades or plates fixed to arms on the shaft and against which the air exerts resistance during rotation, it is necessary first to make special measurements with a motor the power of which is known, so that the power necessary to drive the air brake at various speeds can be determined. A correction must be applied on account of the variations of the bearing friction and of the air temperature and pressure. This arrangement is not properly speaking a "power balance" unless the driving engine or motor is itself supported in a manner allowing it to turn so that, due to reaction, it can be subjected to a displacement in the opposite direction to the direction of rotation and the torque measured directly by the application of weights. Such an arrangement is sometimes used for testing aeroplane engines which are then loaded by means of the propeller belonging to the machine.

Probably the most common method of measuring the power given by an engine or motor is to couple it to an *electric generator* the losses of which are known, and for which the power given out can be determined by electrical measuring instruments. The various stray load losses in the generator cannot be fixed with any great accuracy and in order to calculate the resistance losses the temperature of the windings must be known. An error of 5° in the temperature measurement amounts to approximately 2 % on the resistance losses and possibly 1 % on the total losses of the machine. A greater accuracy than from 1 to 2 % cannot accordingly be obtained by this method, but there is the great advantage that the energy can be recovered, returned to the supply and employed on useful work.

If it is required to measure the power taken by a pump, fan, machine tool, *etc.*, there must be a motor of some kind or other to drive it. The most usual choice — for reasons which will be easily understood — is an *electric motor*, the power supplied being measured and the losses calculated from measurements made at no-load. This does not permit of any greater degree of accuracy than as stated above.

In the two last mentioned cases the electric machine is not used as a "power balance". *If, however, the stator is flexibly supported* the torque can be measured by using weights, the advantage is gained that the method is practically independent of any losses occurring, and the accuracy is consequently increased. In constructing such an *electric dynamometer*, it is, however, necessary to take into account a number of conditions in order that the result may be the best possible, and this will be dealt with in the following.

When the rotor in a D.C. generator for example is rotated and loaded, it reacts upon the stator, so that this also attempts to take part in the rotation. If this is prevented by the stator being provided with feet which stand upon a bedplate, this reaction appears as an increased pressure between one foot and the bedplate. If the feet are removed and the stator hung in a suitable manner in trunnions so that it can turn about the centre line of the shaft of the machine, the pressure or torque can be measured by means of weights hung upon the stator, the effect of which is to oppose the above reaction and maintain the stator in equilibrium in the same position as before. In an electric motor the stator tends to turn in a direction contrary to that of rotation and the weights must accordingly be placed on the opposite side of the stator to that necessary in the case of a generator.

The torque obtained by this method, is however not exactly equal to that produced or absorbed by the electrical machine because a part of the losses in the machine cause no reaction upon the stator. Considering a D.C. generator, the torques which act upon the stator and tending to rotate it, are the following, fig. 1.

1) When $n_a \cdot \frac{p}{c}$ effective conductors in the rotor at a speed n r.p.m. cut the field under the main poles, the flux being Φ per pole, the e.m.f. which is induced is $E_i = \Phi \frac{n}{60} n_a \frac{p}{c} \cdot 10^{-8}$ volts. p is the number of poles for the machine, n_a is the number of conductors, and c the number of circuits in the armature winding. If a current of I_1 amps. flows in each conductor the total current is accordingly $I = c\, I_1$ amps., the output of the machine in kW

$$0.001\ E_i\ I = 0.001 \cdot c\ I_1\ \Phi\ \frac{n}{60}\ n_a\ \frac{p}{c} \cdot 10^{-8}$$

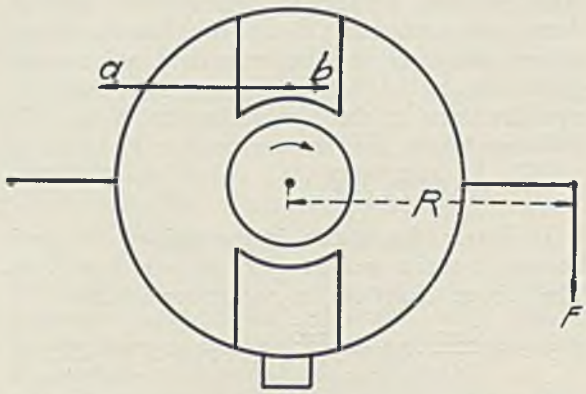

Fig. 2. Motor.
Torque due to a = rotor current, b = losses, FR = weights.

and the corresponding torque in kgm

$$M = 0.973\ \frac{E_i\ I}{n} = I_1 \cdot p\ \Phi \cdot n_a \cdot \frac{0.973}{60} \cdot 10^{-8}.$$

It will be noticed that if $\Phi = \frac{\pi\ D}{p}\ \alpha \cdot L\ B$, where D is diameter of the rotor, L its length, α that part of the pole pitch which is embraced by the pole arc, and B the induction under the pole, then

$$M = I_1 \cdot n_a L \cdot B \cdot \pi D \alpha \frac{0.973}{60} \cdot 10^{-8},$$

which is the torque, produced by the current I_1 in a conductor of length $n_a L$ and induction B. This torque acts upon the stator in the direction of rotation, fig. 1 a.

2) Iron and friction losses (P_{Fe} and P_{fr} kW) exert a reaction on the stator in the same direction as the direction of rotation.

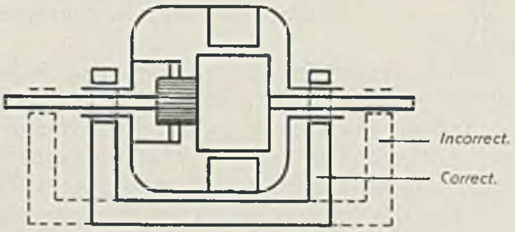

Fig. 3. Method of supporting stator.

The iron losses are partly eddy-current losses and partly hysteresis losses. The former are due to currents induced in the iron parts and accordingly have the same action as the currents in a generator winding. The hysteresis losses depend on magnetic friction in the iron and they endeavour to rotate the stator in the same manner as the friction between the rotor and the brushes and bearings, which are fastened to the stator. When the rotor rotates the surrounding air is disturbed and some of it takes part in the rotation, and is being blown against the stator, in the same direction as the direction of rotation. Another part of the air which is in motion does not encounter the stator but is blown against the walls of the room and accordingly gives rise to no torque on the stator. If the two divisions of this air friction are P_{l_1} and P_{l_2} kW the torque on the stator due to this loss $= \frac{973}{n} (P_{fe} + P_{fr} + P_{l_1})$.

3) Lastly the stator is maintained in equilibrium by the weight F kg at a radius R m. The torque equation on the stator is then

$$I_1 p \Phi n_a \frac{0.973}{60} \cdot 10^{-8} + \frac{973}{n}(P_{Fe}+P_{fr}+P_{l_1}) - FR = 0.$$

If this is compared with the equation which states that the power supplied is equal to the output + the losses, transformed in torque, where M_1 is the torque supplied

$$M_1 - 0.973 \frac{E_i I}{n} - \frac{973}{n} (P_{Fe} + P_{fr} + P_{l_1} + P_{l_2}) = 0$$

we obtain

$$M_1 = FR + \frac{973}{n} P_{l_2}.$$

If the machine runs as a *motor* in the same direction, the load current torque on the stator acts in a direction opposite to the direction of rotation, fig. 2. The torque due to the losses continues to act in the direction of rotation. The torque due to the weights applied acts in the direction of rotation and as it is now the torque produced, M_2, which is to be measured, we obtain

$$M_2 = FR - \frac{973}{n} P_{l_2}.$$

To arrive at the exact torque produced or supplied we must accordingly add a correction to the torque given by the applied weights to compensate that part of the windage which does not react upon the stator. As the windage is greater at higher speeds the magnitude of the correction depends on the speed. If the machine has a fan mounted on the shaft the correction is greater, but if it is totally enclosed the correction becomes zero since in that case the air in motion must always strike some part of the stator. The correction can easily be determined by running the machine alone as a motor at no-load, one side being weighted with F_l kg to maintain equilibrium. The torque due to the weights acts in the direction of rotation and is clearly equal to the windage torque which does not act upon the stator, since the rotor current alone corresponds to all the losses, and accordingly $F_l \cdot R = \frac{973}{n} P_{l_2}$. Measurements are made at different speeds and it is convenient to draw a curve showing F_l in relation to the speed, fig. 4. The magnitude of the windage also depends on the temperature and pressure of the air, but the effect of this on the correction is so small that it may be neglected.

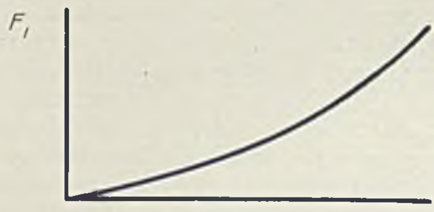

Fig. 4. Correction curve.

Thus the torque to be measured is given by

$$M_{\frac{1}{2}} = (F \pm F_l) \cdot R,$$

where M_1 and + refer to a generator and M_2 and − to a motor. At a given speed the correction is constant and accordingly of greater influence at small loads.

It is not necessary to know the magnitude of the resistance losses, including stray losses. Stray losses arise due to induced voltages in various parts of the machine and are considered and included in the induced voltage E_l. The magnitude of this is of no importance as it does not appear in the final equation. The temperature of the windings does not accordingly affect the reading. The dynamometer is an application of the axiom that action and reaction are equal and opposite and if this is kept in mind the effect is easy to understand.

The dynamometer is connected through a flexible coupling to the machine, the torque or power of which is to be measured, and the stator must accordingly be supported in pedestal bearings so that it can turn about the axis of the machine. This shaft itself must not rest directly in these bearings as in that case bearing friction losses would arise, which would react on the supporting bearings but not on the stator and would accordingly increase the magnitude of the correction F_l. As the bearing losses may vary under different conditions, this would introduce some uncertaincy into the readings, but this can easily be avoided by carrying the stator directly on the supporting bearings which should be ball bearings so that the dynamometer will move easily. The brush rocker for similar reasons should be fixed to the stator, fig. 3.

On the stator are commonly fixed arms with scale pans in which weights can be placed. The supporting points of the scale pans on the arms should lie in a horizontal plane through the shaft as in that case the measured length of the arms gives the radius upon which the weights act when the dynamometer is in equilibrium in its horizontal position and if the dynamometer should be displaced by a small amount from this horizontal plane the error is small and can be neglected. Should the supporting points not lie in the horizontal plane the length of the radius alters with a displacement of the dynamometer and this must be taken into account. Instead of a simple and cheap arrangement with scale pans, a spring balance can be used, or the arm can act on a cylinder containing some fluid, the pressure of which can be read on a pressure gauge. Registering instruments can also easily be applied to the balance. A sufficiently long pointer should be fitted with a scale clearly showing the position of equilibrium for the dynamometer. In addition the rotor should, of course, be well balanced so that unnecessary vibrations are not caused which would make the readings uncertain. Unequal magnetic pull on the rotor only affects the readings if the resultant of the force does not pass through the centre of the shaft. The cables which carry the current to the stator must be flexible.

For the dynamometer to be stable the centre of gravity must fall below the point of suspension, and as the stator is better manufactured quite circular and without feet, an extra weight is generally placed on the under side of the stator. The dynamometer is so adjusted that when the pointer is on the zero and the supporting points of the scale arms lie in the horizontal plane, the centre of gravity lies vertically under the point of suspension. With a displacement from the horizontal position regard

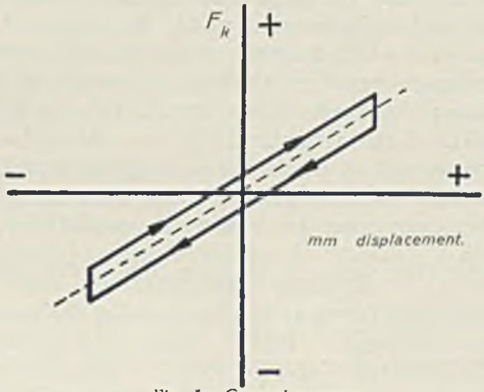

Fig. 5. Correction curves.

must be given to the moment of the centre of gravity about the axis. This moment can be measured by loading first one and then the other scale pan when the dynamometer is stationary and measuring the magnitude of the displacement. The magnitude F_k (in kg) of the weights is best plotted in a curve with relation to the displacement (*e.g.* mm) and the curve has one branch when rising and another when falling, fig. 5. If the stator is supported in ball bearings the distance between the branches, which shows the friction in the bearings, is vanishingly small and we can reckon with an intermediate curve which shows the sensitivity of the dynamometer. The torque is given by

$$M_{\frac{1}{2}} = (F \pm F_l \pm F_k)\, R,$$

where + and − for F_l refer respectively to a generator and a motor and + and − for F_k refer to displacement in the direction of rotation with a generator and motor respectively.

The magnitude of the corrections appear from the following readings taken from dynamometers constructed by Asea consisting of normal open machines without fans, fig. 6.

Type	Indicated kW	r.p.m.	Normal load F kg	F_l kg	F_k with 1° displacement in % of F
DK 7	10	1,200	8.1	0	2.9
		3,000		0.25	
DK 8	12	1,000	16.4	0.06	
		3,000		0.15	
DK 9	8	500	15.6	0	
	32	3,000	10.4	0.29	

The correction for windage is thus so small with these machines that up to 3,000 r.p.m. it can be neglected in practical measurements, at least at full load.

The correction for a displacement from the zero position is not great when we consider that 1° displacement corresponds to 5 mm with a very short pointer which in working can be set to within about 1 mm, and also that the sensitivity can be increased by decreasing the weight which is fixed beneath the stator. The friction in the ball bearings supporting the stator, or the space between the rising branch of the curve and the mean value for F_k is 0.15 % of F. The method can accordingly be considered to be as accurate as an electric measuring instrument.

In order to simplify calculations in practical use the scale arms are commonly made of such a length that $\frac{2\pi R}{60 \cdot 101.9}$ is $\frac{1}{1000}$ or some such even fraction, so that the expression for power is simple, *e.g.* $P = \frac{Fn}{1000}$, where F is the corrected value of the weights in the scale pan and n the r.p.m.

Naturally an A.C. machine can be used as a dynamometer equally as well as a D.C. machine. The advantage of using a D.C. machine is that it can return power to the supply at different speeds whereas the A.C. machine can only act regeneratively at a speed corresponding to the frequency of the supply. In addition, when running as a motor, the speed of the D.C. machine can be regulated within wide limits by simple and cheap arrangements.

The electro dynamic "power balances" have been very widely used in recent years. They are particularly suitable for testing internal combustion engines of all kinds. If the stator is fixed and the dynamometer started as a motor with an ordinary starter, the internal combustion engine can then be started in the most easy manner and, by taking measurements of the power supplied, the no-load losses can be tested and bearings and valves run in before the fuel supply is turned on. When the internal combustion engine is running, the dynamometer is loaded by a resistance, or can return power to the supply, which is of importance if the test is a long one; by releasing the stator the power can be measured easily and quickly at any time.

When testing pumps, fans and machine tools of all kinds, electric motors are now very largely used and if the stator is flexibly supported it is easy to measure the power taken. The efficiency of the dynamometer itself, including all stray losses, can be determined if at the same time the electric power supplied is measured.

E. J. Westman.

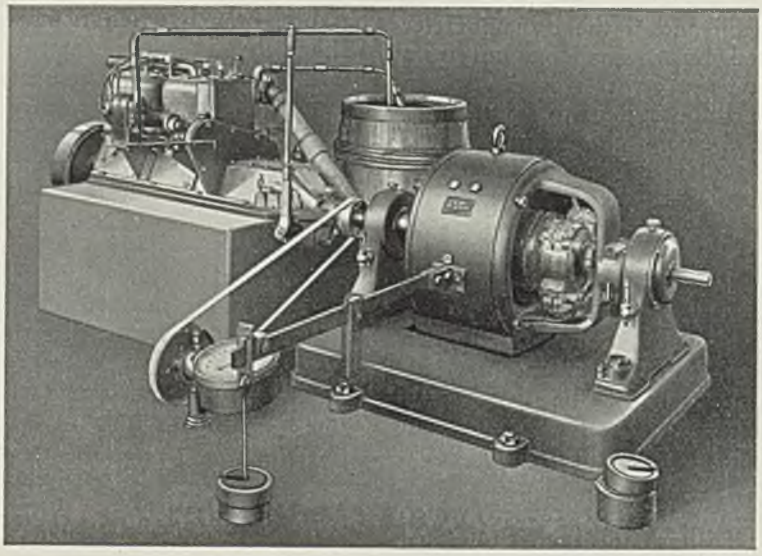

Fig. 6. Dynamometer.

THE NATURE OF BREAKDOWN IN SOLID INSULATING MATERIAL.

Paper read before the third Nordic Electrotechnical Conference in Oslo June 1926.

The nature of breakdown in gases has been fully understood for a long time. The breakdown when it occurs is instantaneous, and in a homogeneous field for any given gas, at a certain temperature and pressure, it takes place at a quite definite field strength and is to be ascribed to impact ionisation of free electrons. (The above rule must be modified to some extent when the field is unhomogeneous or the path of breakdown very small, but there is no need for me to go more closely into this matter).

It was for a long time assumed without any further consideration that breakdown in solid insulating material was of a similar nature to that taking place in gases, and also occured as soon as the field strength overstepped a certain critical value. Curiously enough, it appears that this primitive conception of an exeedingly important question, both from the practical and theoretical point of view, seems to have been exclusively believed on the continent, in England, and in America until quite recently.*)

The question rested at this point, when K. W. Wagner in a most notable paper read before the A.I.E.E., in 1922, subjected the matter to investigation. Wagner put forward the view that breakdown in solid insulating material was a purely thermal phenomenon. Wagner's paper awakened the greatest attention and was quickly followed by a number of publications dealing with theoretical and experimental investigations by various well-known scientists, chiefly in Germany and America. Among these must be mentioned Hayden and Steinmetz, Clark, Rogowski, Günther-Schulze, Kármán, Schumann and others. (See bibliography at end).

In the following I wish to give a short account of the historical development of knowledge as regards the nature of breakdown, and point out what at the present time must be regarded as probably most correct.

First of all, however, it is necessary for me to point out that among other opinions held by Wagner his statement that the nature of breakdown was completely unknown up to 1922 is incorrect. In Asea this question long ago received the most careful attention, and ten years since, we had come to a conclusion which is as nearly as possible in agreement with the newest accepted theories when these are subjected to careful examination. I even expressed the conclusions which I had then reached in two articles which appeared in Teknisk Tidskrift, 1916 (see Bibliography). These articles, as far as I can judge have not become known outside Scandinavia and on this account the theories published later by Wagner and others must be considered to have been independently developed.

The investigations which, more than ten years ago, assisted me to bring to life the question of breakdown, consisted of tests on condenser leading-through bushings. It would be difficult to find anything more suitable for investigations of such a nature than paper-insulated bushings for high voltage. The thickness of the material is great, approximately 50 mm, and the specimen acts as a consequence as if it were quite homogeneous, provided one does not confine oneself to very small elements. (Material of this character has been called quasi-homogeneous.) The fault which occurs with most investigations of breakdown lies in the fact that they are conducted on a laboratory scale using very thin test specimens. The lack of homogeneity which is bound to exist in the material then exercises a very large influence and affects the results, making them puzzling and contradictory. When we wish to arrive at the innermost nature of breakdown, it is clearly of importance that all chance causes should be eliminated.

It was impossible to fail to observe at a quite early date, that breakdown in solid bodies was unlike breakdown in gases in that respect that it did not occur instantaneously, but in general required a certain time, this time being longer the lower the voltage existing. In Asea, it has for long been usual to express the breakdown voltage by a so-called time curve, having the time for breakdown as abscissa and breakdown voltage as ordinate. The curve has a falling characteristic and approaches asymptotically to a definite minimum value of the breakdown voltage, which thus corresponds to the pressure which the specimen can withstand continually. Generally it seems as if the reason for this was sought in the unhomogeneous structure of the solid body where parts of different qualities of resistance to breakdown are mixed up together, thus requiring a certain time for breakdown to be fully established, and before which the pressure can eat through the stronger sections.

*) In K. W. Wagner's treatise of 1922, referred to later, the following occurs:
»The nature of the breakdown in solid and liquid insulating materials has up till now remained in complete obscurity.«
and
»According to the prevailing opinion the rupture takes place at the moment when the density of the electrical field exceeds a certain limit at any point of the insulator. This is called the electrical strength of the material and . . .«

When testing thicker specimens, it does however appear incontestably that the whole proceeding is a purely thermal phenomenon. I cannot do better than make one or two quotations from my article of 1916. — »If these (*i.e.* condensor bushings) are subjected to continuous load at a high temperature and with little power behind them, they are heated up further, due to their own losses and on this account the losses themselves increase *etc.*, until the material can be considered to be completely conducting and the voltage of the testing transformer sinks to zero . . . No breakdown or damage to the material can, however, be detected and after the bushing has cooled down it can again withstand considerable voltages.» (In general, however, some alteration occurs as the temperature often becomes so high that the material is to some extent carbonised). If the voltage is altered slowly, giving time for a steady temperature condition to be reached for every voltage, the connection between the pressure and losses or current respectively can be represented by a curve in accordance with fig. 1. The large thermal capacity makes it relatively easy to establish even the unstable falling part of the curve. With thin test specimens, as used by most experimenters including Wagner, it is however very difficult and requires special skill. Quoting further: — »The greatest disadvantage with condenser type leading-through bushings, as with all paper leading-through bushings for high voltages, is the low heat resisting quality of the varnished paper. With temperatures from 50° to 100°, *i.e.* the normal working temperature for transformers, the dielectric losses increase enormously, while at the same time the breakdown voltage sinks to a small fraction of the normal. Leading-through bushings are rendered particularly risky by the fact that the losses within the temperature limits in question, are of such a magnitude that they give rise to considerable heating on their own account. In this way the losses are further increased and the temperature rise is still higher, *etc.* An unstable equilibrium is thus reached with a given temperature and even the smallest temperature rise makes any equilibrium impossible on which account breakdown, after some hours must infallibly occur. If we know and can express the losses as a function of the temperature, and know also the heat conducting qualities of the bushing it is then easy to calculate the critical point mathematically.»

At this time I carried out an elementary calculation of this caracter and I am giving this below in somewhat modified form as it will serve to show the character of the phenomenon in a simple manner. The assumption is that the specimen is of such thickness that the temperature variations in it are relatively small, the chief temperature drop occurring between the specimen and the surroundings. We can thus experimentally obtain the total losses as a function of the mean temperature of the specimen

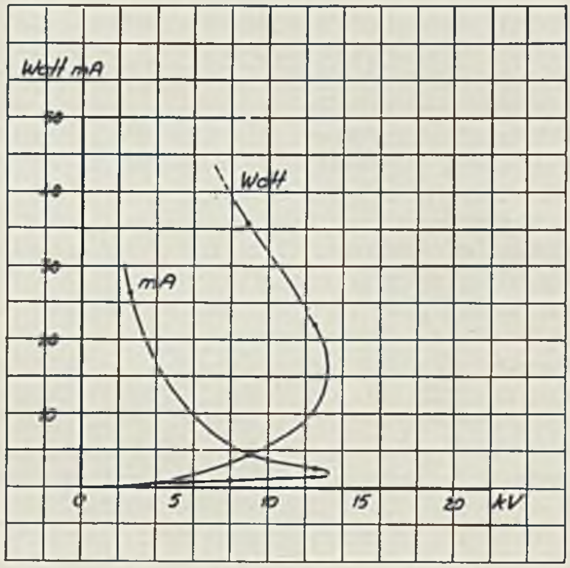

Fig. 1.

reckoned above the surroundings. For field strengths occurring in practice the losses in general are proportional to E^2 where E is the voltage. We can thus put the losses

$$P = \frac{E^2}{R} \qquad (1)$$

where R is the "effective resistance" of the specimen to a current of the frequency in use. R_0 is the magnitude of the resistance at the temperature of the surroundings. In fig. 2 $\frac{R}{R_0} = f(\vartheta)$ is given as a function of the temperature ϑ. Thus the critical point can be calculated.

If the heat conducted away is to be equal to $\mu\vartheta$ we have clearly

$$\frac{E^2}{R} - \mu\vartheta = 0 \qquad (2)$$

and differentiating

$$-\frac{E^2}{R^2} \cdot \frac{dR}{d\vartheta} - \mu = 0 \qquad (3)$$

from which

$$\frac{R}{R_0} = -\vartheta \cdot \frac{d\frac{R}{R_0}}{d\vartheta} \qquad (4)$$

or if the resistance at the critical point is called R_k and the temperature ϑ_k

$$\frac{R_k}{R_0} = -\vartheta_k \cdot f'(\vartheta_k) \ldots\ldots\ldots\ldots (5)$$

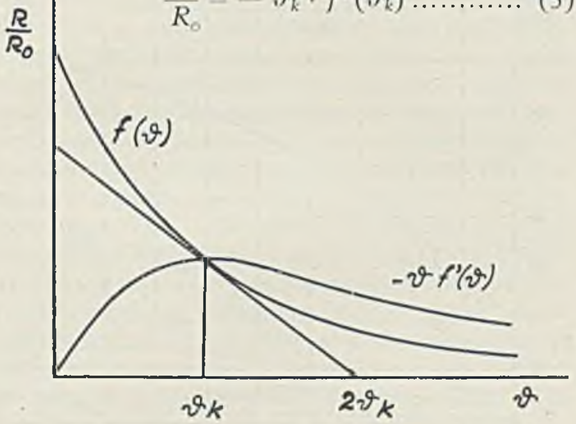

Fig. 2.

If we construct the curve $y = -\vartheta \cdot f'(\vartheta)$ it is clear that this cuts the curve $\frac{R}{R_0} = f'(\vartheta)$ for $\vartheta = \vartheta_k$. The highest field strength corresponding herewith is in accordance with equation (2).

$$E_k = \sqrt{\mu \vartheta_k R_k} \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

From the figure it can further be seen that if $f(\vartheta)$ should actually, over the whole distance, coincide with the tangent at ϑ_k, then R_k would become equal to $\frac{1}{2} R_0$ and in consequence $P_k = 2 P_0$. In practice R_k is somewhat less, or between $\frac{1}{2} R_0$ and $\frac{1}{3} R_0$ so that it follows that $P_k = 2$ to $3 \cdot P_0$. If the losses are so great that they warm up the bushing to such an extent that the losses are multiplied by from 2 to 3, it is obvious that breakdown is certain to occur.

The realisation that breakdown in paper and similar materials was a purely thermal phenomenon lead me immediately to an idea for improving paper leading-through bushings by introducing layers of mica and this is more fully described in the articles already mentioned, and was patented at the same time (mica has a very small temperature coefficient). This has in fact made it possible to use condensor type leading through bushings in transformers where they are subjected to warm oil and high voltages. Another alteration was that the thickness of material in, for example, 80 kV leading-through bushings could be reduced by about 30 % without decreasing the resistance to breakdown. In accordance with equation (8) the critical voltage certainly increases as the square root of R_k and thus with the square root of the thickness, but taking into account the heat drop in the bushing, it will be understood that the critical voltage cannot be raised to any considerable extent by increasing the thickness of the material after a certain limit has been reached. Fig. 3 shows curves made at the beginning of 1916 giving the dielectric losses for 80 kV leading through bushings of bakelite paper with and without mica layers as a funtion of the temperature. Figs. 4 and 5 show curves measured later for condenser type leading through bushings of bakelite paper at different temperatures and for various frequencies. It is important to note that the heat capacity in large paper bushings and insulating material of corresponding dimensions is so great that the bushing will often easily withstand, on a one minute test, more than four times the breakdown voltage for a continous test, a point which all the standard rules for testing have neglected. If a long duration test is required this should be continued for at least 24 hours in the case of large bushings. On the other hand this test can be dispensed with if instead we measure the dielectric losses after having once determined how great these may be to be succesfully withstood by a bushing of any given type.

After this basic rule obtained by experience had been established, a large number of very complete experimental investigations were carried out in Asea's head laboratory regarding the loss characteristics of different insulation materials at various temperatures, and based upon

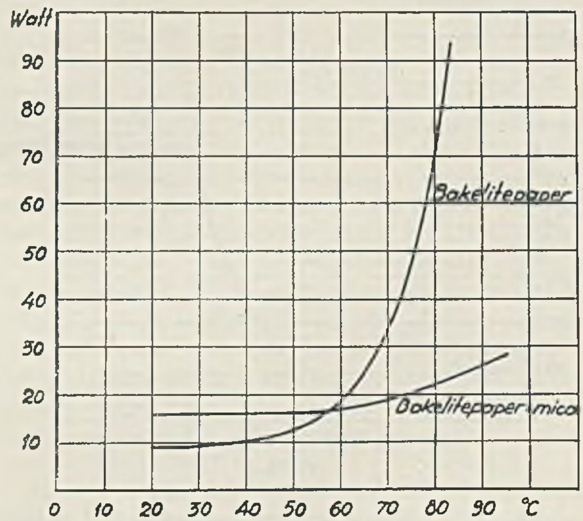

Fig. 3.

these Dr. Dreyfus developed a matematical theory of breakdown, which was first issued as an internal technical report in 1920, and afterwards published in a more fully developed form in the Teknisk Tidskrift and in the Bulletin des Schweizerischen El. Verein, 1921. These articles covered all parts of the earlier work referred to above.

In making this calculation it is assumed partly, that the temperature of the electrodes is kept constant and equal to that of the surroundings, so that the whole of the heat drop occurs in the test specimen, and partly that a heat drop exists also between the electrodes and the surroundings.

In the former case we obtain:

$$E = k \cdot \varDelta^{\frac{n-2}{n}} \cdot \lambda^{\frac{1}{n}}$$

In the above E is the maximum voltage which the specimen can withstand continuously. $\varDelta$ is the thickness of the specimen in cm, λ is the conductivity in cm $\frac{\text{Watt}}{\text{cm} \frac{C^{\circ}}{\text{cm}}}$, watts a constant applying to certain material with a given proportion between specific losses and temperature, n is the power of E by which the losses are increased. With thick specimens which are only subjected to small field strength $n = 2$, and it will be seen that E is independent of the thickness so that among other things it will be noted that an increase in the thickness above a certain limit does not increase the breakdown pressure for the specimens on a test of long duration. As I have already pointed out this agrees well with the results obtained on *e.g.* bakelite paper bushings. With high field strength

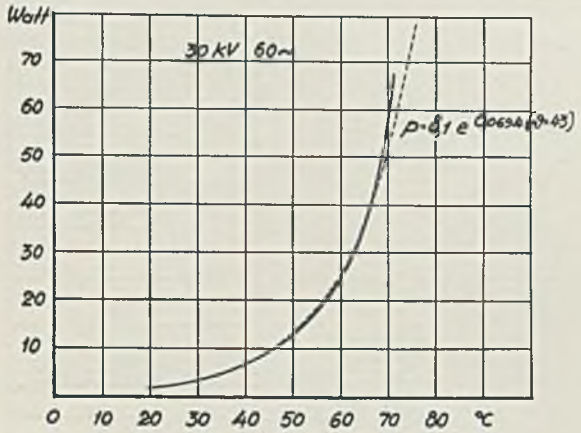

Fig. 4.

which thin plates can withstand $n > 2$. Here accordingly, with a constant external temperature, the breakdown voltage increases with the thickness of the test specimen.

If we only consider the fall in temperature between the electrodes and the surroundings *i.e.* if $\lambda = \infty$, the exact theory for relatively thick specimens, where $n = 2$, gives the same result as my elementary treatment; that is the breakdown

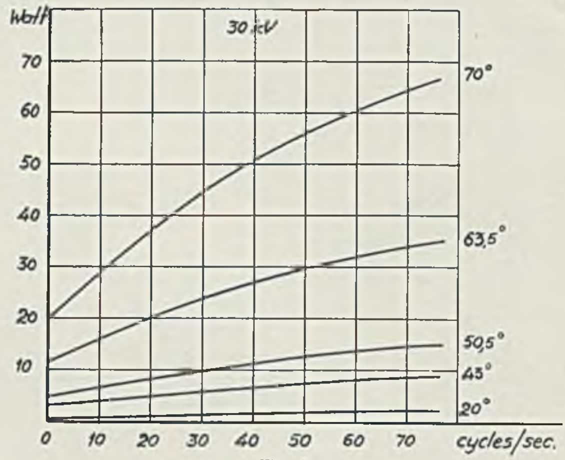

Fig. 5.

voltage increases as the square root of the plate thickness.

If we consider both the temperature drop in the specimen and also between the electrodes and the surroundings we also obtain an expression for the maximum breakdown voltage. This increases, as we should expect, for relatively thick plates with $n = 2$ much more slowly than as the square root of the thickness. I do not, however, propose to occupy time here by giving the mathematical expression for this.

It is sufficient to state that the theoretical conclusions agree very well with the experimental results.

As I pointed out before, the losses with high field strengths increase more quickly than as the square of the voltage. The reason for this is apparently that ionisation takes place in bubbles of gas imprisoned in the material. The modification of the law for brekdown with thin sheets of material is however not only due to this reason. It is clear that, when using thin plates of material, if the specimen is at all unhomogeneous this must greatly affect the result. Although when subjecting a condenser bushing to a test of long duration with large series resistance, no local breakdown can be observed, but the whole bushing or a greater part of it is warmed up, and if the temperature becomes sufficiently high, swollen up or carbonised, it is known that with thin test specimens local breakdown can occur, the material being otherwise unchanged. Clearly if a weak spot exists the losses will be concentrated at this point which is accordingly warmed up by a relatively large amount. Here also, a heat breakdown is possible, although the conditions are very unlike those existing in the case of breakdown in quasi-homogeneous material.

Wagner investigated, in the article previously referred to, just such breakdown which he conceived as a pure thermal proceeding analogous to the representation I gave earlier for quasi-homogeneous material. He considers a duct or canal in the specimen where the losses are concentrated, and investigates the requirements for thermal equilibrium. Here he considered the heat as only being conducted radially from the cylindrical canal, and obtained in this way the breakdown voltage proportional to the thickness of the layer. The general applicability of this result, however, differs so entirely from all experience that it must be abandoned. Wagner himself has certainly conducted a large number of tests, but on very thin specimens, and thus found his theory corroborated. The fact that the rule for certain material and for very thin specimens where the losses increase in proportion to a high power of the field strength, may be correct within certain limits is also demonstrated by the theory for quasi-homogeneous material explained above. It cannot, however, be even approximately general, and it is probable that Wagner's results, as suggested by Kármán and others, have their origin in the unhomogeneous wooden electrodes which were used by him for certain reasons in his investigations. The results obtained in this way thus do not depend on the characteristics of the actual material under test.

Dreyfus, Rogowski and others have later critised Wagner's exposition much more severely. Dreyfus has developed a very complete theory for "canal breakdown" for thin test pieces and has shown in this way that if attention is paid to heat conduction in both the axial and radial directions of the "canal" the result is that the breakdown voltage increases more slowly than the layer thickness which is in accordance with experience. To arrive by purely theoretical methods at any more definite results, causes us however, with "canal breakdown", to encounter difficulties as we depend on the "canal" dimensions which we cannot obtain exact knowledge of by any theoretical investigation since they depend on the unhomogeneous state of the material. Rogowski, who regards the new idea of breakdown, as a thermal phenomenon, as the most interesting advance in this direction since Townsend solved the problem of breakdown in gases, considers the action as a combination of thermal and electric phenomena.

For my part I have never gone as far as to state that in the case of solid bodies breakdown must under all conditions be regarded as a purely thermal phenomenon. A test specimen is unable to withstand easily high voltages even if the outgoing temperature is so low and the stress of such short duration that there is no time to reach a dangerous temperature. The atoms are held together by electrical stresses and sooner or later this power of retention must be lost, due to the action of the exterior field. It is certainly true that the retaining electrical forces between the atoms are apparently so great that they cannot be directly neutralised by any exterior field which it is possible to obtain in practice. But in most solid insulating material there exist spaces and pores which are filled with gas, whether air or vapours from the impregnating varnish, *etc.* Here impact ionisation can occur in the same manner as in gases and due to the imprisoned free electrons, the solid material can be broken up and a progressive breakdown commenced. Experiments carried out in the Asea laboratory on bakelite paper insulating material of some millimetres in thickness show that breakdown even with such high field strengths as 500 kV/cm requires a time approximately corresponding to the calculated time for thermal breakdown with quasi-homogeneous material so that it can be asumed with a large measure of probability that the breakdown is of a purely thermal nature up to and including field strengths of this order of magnitude.

To a great degree it may be said that with fibrous organic insulating material commonly used for high voltages, such as impregnating paper, cotton, *etc.* a pure heat breakdown occurs in so far as affects working at voltages ordinarily in use. A purely electrical breakdown can only be imagined in the case of normal voltages with such thin sheets of insulation as never occur in practice. Strains of short duration due to atmospheric discharges *etc.* may however act even in a purely electrical manner. In certain inorganic material such as mica, porcelain, glass *etc.* dielectric losses, even at temperatures between 50 and 100° are often so exceedingly small, that a breakdown entirely due to a thermal effect is only to be expected with very thick layers of insulation, or in the case of constructions which are well heat insulated. Here accordingly purely electrical or thermo-electric breakdown is relatively common.

I have discovered support for this idea in an article by Schumann in the Zeitschrift for Technische Physik, No. 9, 1925. In his article among other things measurements are given for glass lenses, the temperature immediately before breakdown having been measured by the alteration in the optical characteristics and it was thereby established that no appreciable temperature increase existed.

In conclusion I must just touch on the fringe of a question which is closely connected with the nature of breakdown, the character of dielectric losses. If we wish to explain fully the purely physical nature of breakdown it is impossible to escape the solution of the problem of dielectric losses also. I shall here confine myself to referring to my above mentioned article in Teknisk Tidskrift in 1916. I endeavoured to show there that the dielectric losses are entirely conduction losses in an unhomogeneous dielectric. Possibly this is going too far. On the other hand it is indisputable that any fibrous material such as varnished paper preparations *etc.* and with temperatures where heat breakdown occurs, the dielectric losses, to an altogether overwhelming extent, are made up of just such ohmic losses. We obtain here the most perfect agreement between theory and experiment. Especially in the case of the material which is imperfectly dried we often obtain a maximum loss with about 30°. The losses begin once more to increase at about 50°. The maxima and minima in question are transferred at higher frequencies in the direction of higher temperature. The calculated curves show similar curious properties.

R. Liljeblad.

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SOME IMPORTANT ELECTRICAL CONCEPTIONS POPULARLY TREATED.

The electrical characteristics which are considered most suitable for discussion in the present article have regard to electric motors, and are: losses and efficiency, heating and methods of cooling, and reactive power and cos φ.

The losses in electric machines (motors) are of two chief kinds: (1) mechanical, (2) electromagnetic.

The mechanical losses consist of friction in bearings, commutators and sliprings, and windage due to rotation with which must be included losses due to any arrangements for cooling. Their magnitude is dependent on the speed of the machine, and in such a way that their connection is in general somewhere between direct and quadratic proportionality to the speed. Only in cases where the windage losses are very large can the proportionality be greater than the square. They are constant with constant speed and, practically speaking, independent of the load. The magnitude of the mechanical losses is usually from 1 to 2 % of the full output in the case of motors of small and medium size.

The electro-magnetic losses consist partly of *iron losses* and partly of *copper losses*. The former have their origin in the sheet from which the iron core (the armature of a D.C. machine and the stator of a three-phase motor) is made up. One variety of iron loss is called *hysteresis* loss and depends on the quality of the sheet used (alloy) being due to a certain sluggishness of the iron in changing its magnetisation, while another variety, *eddy-current loss*, depends partly on the quality of the sheet (the electrical conductivity) partly on the thickness. The lower the electrical conductivity and the thinner the sheet, the smaller is the loss. Iron losses change with the speed but at a constant speed are independent of the load. In their outward effect they accordingly resemble the mechanical losses and are usually included with these under the general designation *no load losses*, denoted by p_0 (watts or kilowatts). Copper and resistance losses manifest themselves in a wholly different way and depend on the resistance of the conductors and windings being always proportional to the square of the current flowing. As the current in that type of machine which we are chiefly considering, namely the three-phase induction motor, is approximately proportional to the load, it follows that the copper losses are proportional to the square of the load. They are usually denoted by p_{Cu} (W or kW). In fig. 1 the two chief varieties of losses, p_0 and p_{Cu} for a common induction motor (the speed of which is of course practically constant) are drawn in curves as a function of the load, and likewise the *derived efficiency curve*.

If we draw a tangent from the origin to the curve of total losses, the point of contact of the tangent denotes the load for which the efficiency is a maximum. And the tangent of its angle of inclination (tan α) is also the magnitude of the corresponding percentage loss. In this case the maximum efficiency occurs at about 5.5 kW and the percentage loss is accordingly $\frac{0.67}{5.5} \cdot 100 = 12.2$ % and thus the maximum efficiency $\eta = 87.8$ %.

Electric motors, as is well known, become warm when running — sometimes more and sometimes less — and it is not without reason that we connect the degree to which heating takes place with the quality of the motor. A high temperature of course adversely affects the reliability and the length of life of the motor — and in particular as regards the insulating material used such as cotton, paper etc. The heating is of course caused by the losses which have just been referred to, and if the motor becomes hot (or too hot) this indicates that the losses are too high. This is actually the case but it may not always follow that on this account

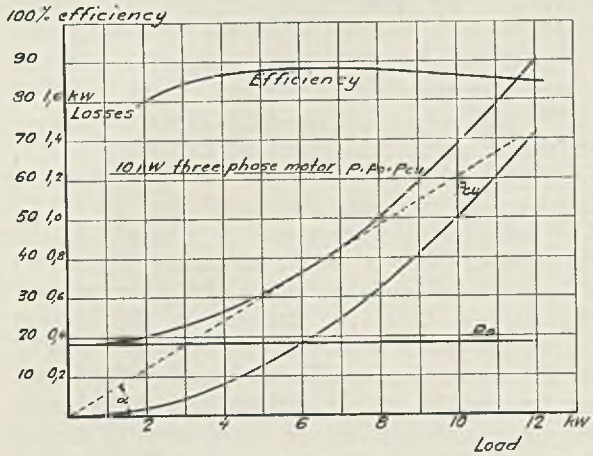
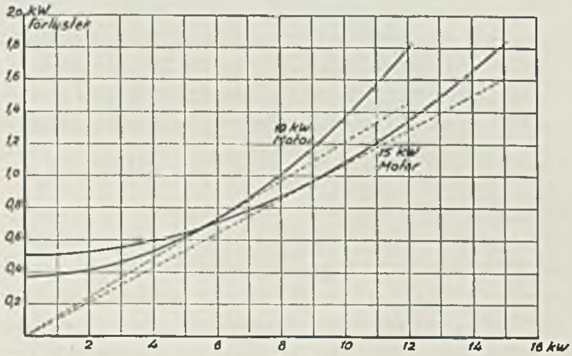


Fig. 1.

the motor is a bad one. Excessive heating can for example be due to the fact that the motor is overloaded or that the conditions as regards cooling are inadequate. It cannot be too strongly emphasized that insufficient ventilation always leads to overheating. But it should be noted that there is a limit to ventilation; it costs money in the same way as losses, and one should not go further than to ensure that the motor with adequate ventilation and full (normal) load will not attain a temperature which would endanger reliability.

There is however another limit to cooling which does not depend on the necessary power expenditure. In certain industrial applications it is necessary to ensure that the inner parts of the motor are not exposed too much to the air which surrounds the machine; this both from the point of view of keeping the motor clean and



förluster = losses

Fig. 2.

also with regard to fire risks. If the air surrounding the motor is laden with dust the motor should be ventilated by means of air brought from outside the factory, or the machine must be totally enclosed and no ventilation allowed for. In the former case the motor is of approximately normal size and costs only slightly more, although the necessary fans and duct work take up space, increase the capital charges, and absorb power. In the latter case the motor is much larger and more expensive and the losses may possibly be higher.

We will now more closely examine this rather indefinite statement regarding increased losses. In fig. 2 the loss curves are drawn as a function of the load for a 10 and for a 15 kW motor and from these it is seen that the small motor has a better efficiency up to 5.5 kW while above that point the efficiency of the larger motor is higher. If the output which the motor is required to develop is 10 kW it will be seen accordingly that the larger motor has the lower loss and the higher efficiency. As in general motors are designed with copper losses which are twice as great at full load as the no-load losses the highest efficiency occurs at about 70 % of full load and as on the other hand the maximum efficiency is higher for large motors than for small ones it will easily be understood that the larger motor has better efficiency in the neighbourhood of the full load capacity of the smaller machine.

To return now to the question of cooling, it can accordingly be said that the large totally enclosed motor without cooling pipes has lower losses than the smaller totally enclosed motor with pipe ventilation for which in addition the larger losses are increased by the losses occurring in the fan. The larger machine certainly costs more than the smaller one, but the question to be considered is whether the increased price is greater than the increased cost entailed by the fan and cooling pipes, and it should also be borne in mind that the larger motor entails lower amortisation due to its greater reliability, longer time of amortisation, and higher value at the conclusion of the amortisation period.

We shall return to this question later on in conjunction with

The reactive power and cos φ.

In recent years a great deal has been said on the subject of cos φ, perhaps more than is really helpful. The reactive power which is the cause of low cos φ is certainly an evil, but evil must exist — otherwise it would be impossible to appreciate anything good — and the only thing to do is to keep the evil within reasonable limits, or even to turn it to good account.

The reactive power which an ordinary induction motor takes of necessity from the supply, is required partly for magnetising the iron core, and partly for the so-called magnetic leakage field. The former part of the reactive power appears even when the motor is running at no-load, the latter part arising as the load is applied. The former can, like no-load losses, (the active no-load power) be regarded as constant (with constant speed and voltage) over the whole load range while the latter are similar

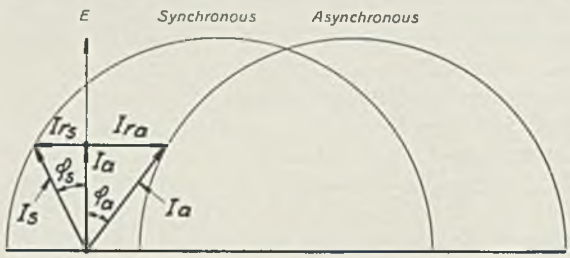


Fig. 3.

to the copper losses and thus increase as the square of the load. Since the reactive power (like the active) is represented by the product of voltage and current, and the voltage is seen to be constant, it follows that the reactive current, which the motor requires and uses, varies with different loads in the same way as the reactive power, and accordingly approximately as in fig. 1, if p_0 and p_{Cu} represent the constant and variable parts respectively of the reactive power or current, naturally with the difference, that the relation between the two parts is in general otherwise, the variable part being relatively smaller.

From the simple Heyland diagram for a three-phase induction motor a number of important working characteristics can be obtained, such as cos φ at various loads, overload characteristics, etc.

Here we shall not deal further with the Heyland diagram, except, returning to the large totally enclosed motor without pipe ventilation, as a substitute for the smaller enclosed motor with pipe ventilation, previously mentioned, to establish the fact that by the choice of the larger motor we obtain a lower power factor (cos φ) than with the smaller motor.

We can however get round this disadvantage by ordering the larger motor for a higher voltage than that which will actually be used, by which means we certainly adjust the losses and efficiencies a little in accordance with fig. 2, but obtain a cos φ so altered that the larger motor is practically as good as the smaller in this respect.

In connection with this we would, however, say that the customer by careful selection of the voltage when placing his order, or the supplier by skilful design and construction can ensure that the larger, totally enclosed motor without pipe ventilation, will be better as regards efficiency and not worse as regards power factor than the enclosed pipe ventilated motor.

Lastly by the help of a diagram we shall show, how a synchronous or autosynchronous motor can improve the power factor or reduce the amount of reactive current and power when this is too great.

In fig. 3 diagrams for both classes of motor, synchronous and asynchronous, are drawn together. From these it will be seen that the reactive current of the former motor is negative as also is the phase displacement. It follows that the positive reactive current of the asynchronous motor is compensated to a greater or less extent by the synchronous motor and herein lies the value of the practice lately developed, and continually gaining ground, of displacing asynchronous motors on large installations by synchronous or autosynchronous motors in cases where working conditions allow the use of a motor running at synchronous speed.

It should be unnecessary to go further here into the question of the disadvantages arising from reactive current. We may, however, point out that the reactive energy is not an actual power, corresponding to a definite expenditure of water or steam, but that the reactive current is added to the active, giving an increased total current value which in turn increases the losses in generators, transformers and feeders, and so lowers the efficiency of the whole installation.

This addition is not, luckily, an arithmetic addition but a geometrical addition in the same way as two forces at right angles. This introduces the condition that a small phase displacement *i.e.* cos φ in the neighbourhood of 1 does not exercise any great effect. It is when we reach the point where $\varphi = 30$ to $40°$, *i.e.* when cos φ reaches 0.8 or is lower than this figure, that the disadvantages become of a serious nature.

A. Lindstrom.

THE FRONT PAGE.

The photograph on the front page shows one of two self-cooled transformers manufactured by Asea for the Sydsvenska Kraft A.-B. of Malmo, Sweden, each of 12,000 kVA, $\frac{56{,}500}{46{,}500}$/5,600 volts, 50 periods, provided with extra terminals for voltage regulation on load and designed for outdoor installation.

At the present time Asea also has under construction for the same firm 2 very similar transformers, one designed for 18,000 kVA, 47,000/52,000 volts and the other for 6,000 kVA, 56,500/5,600 volts and this order as a whole may be regarded as a good example of the capabilities of Asea as regards transformer construction.

The largest sizes in self-cooled transformers previously delivered by Asea were as follows:

1910	1,000 kVA
1915	1,500 kVA
1920	3,600 ,,
1925	12,000 ,,
1926	18,000 ,,

Sizes which in 1910 were looked upon as technically impossible do not now cause Asea any difficulty whatever. The main reason why such transformers can now be constructed of the self-cooled type is that use is made of powerful radiators which are joined to the transformer tanks and by which means sufficient cooling surface and effective cooling is obtained. As the radiators can easily be removed they are easy to maintain clean and free from oil sludge while at the same time transport does not give rise to any difficulty in spite of the fact that the transformers, as will be seen from the photograph, are of very large dimensions on account of their high output.

ELECTRIC SECTIONAL DRIVE OF PAPER MACHINES.

The problem of sectional drive for paper machines has been discussed in a number of publications during the last few years. The question has lately been of special interest to our engineers, as the first equipment for electric sectional drive has recently been set to work in Sweden. During the present year, Asea has installed the electrical equipment for a large paper machine for Holmens Bruk, Hallstavik. The excellent results obtained with this plant have led to the placing of orders with Asea for sectional drives in connection with further two machines for the same customer (one for a large new machine, and the other for the conversion of an existing machine), while interest in the system has also been evidenced in other places.*)

The running of a paper machine, it will be borne in mind, is characterised by the special requirement that the speed for which the machine is set, both as regards the absolute speed and the relative speeds between the various parts of the machine, must be kept constant within very close limits, while at the same time it must be possible to adjust this speed over a very wide range. When cleaning etc., it is also necessary to be able to inch the machine an exceedingly small distance at a time without difficulty.

Formerly, paper machines were, in general, driven by variable speed steam engines. The different parts of the paper machine were connected together by belt drives with conical pulleys and friction clutches so that correct variations in speed between the different sections could be arranged. During the last ten or twenty years, however, there has been a tendency to change over to electric drives, the paper machine simply being run by an electric motor instead of a steam engine and the same arrangements retained for transmission between the various sections. In the older plants, where a D.C. supply on the three-wire system was often available, use was made in a number of cases of ordinary D.C. motors with shunt regulation, or motors provided with two armature windings either in series or in parallel in combination with shunt regulation to obtain very wide speed range.

Since the three-phase supply has become general for all the larger industrial undertakings in most cases use has been made of the Ward-Leonard system. By a three-phase to D.C. motor-generator set, continuous current is generated, the voltage of which is varied by shunt regulation in the field of the D.C. generator. In this way a continuous speed range is obtained from the lowest possible speed up to full speed, for the main motor of the paper machine. This system has, from the point of view of regulation, considerable advantages over the older method with a D.C. motor operating from a D.C. supply at constant voltage.

Several advantages are gained by using electric drive instead of direct drive from a steam engine. The possibilities of maintaining the speed constant are greater than for the direct coupled engine, operation is improved and less attention is required. At the same time, naturally, the electric transmission involves certain losses. On this account it was urged in many quarters that a change to electric drive with a main motor was not justified. The supporters of the direct coupled steam engine have emphasised, among other things, the advantage of being able to use the exhaust steam direct for heating drying cylinders. This, however, really only applies to machines which work in general at the same speed. For machines which under different conditions operate at widely different speeds it should be noted that the amount of exhaust steam available only corresponds to the demand at a certain speed. Generally, perhaps, it may be said that as long as electrification was confined to driving by a main motor, retaining the old transmission gear, the value of electrification was, at any rate in some cases, very doubtful.

The question is on an entirely different plane if the electrification of a paper machine is effected by the use of electrical sectional drive. Here the full advantages of electric drive can be obtained.

First of all it should be noted that a saving of about 20 % in the power supply is obtained due to the elimination of the mechanical transmission.**)

The best of the systems now in use for speed regulation make possible, in addition, a much more definite adjustment of the relative speeds between the different parts of the machine. This means that the number of breakages occurring in the paper web are greatly reduced and production thereby much increased.

Production is also increased, and to a much greater extent, by the fact that the speed can be considerably raised. The belts in general make the speeds of necessity very low in the case of transmission drive. Seldom is it possible to obtain a higher speed than 250 m/minute. With sectional drive speeds up to about 350 m/minute can be obtained.

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*) Since this article was written a further order for a similar equipment has been obtained.

**) For machines with a speed between 150 and 250 met./min.

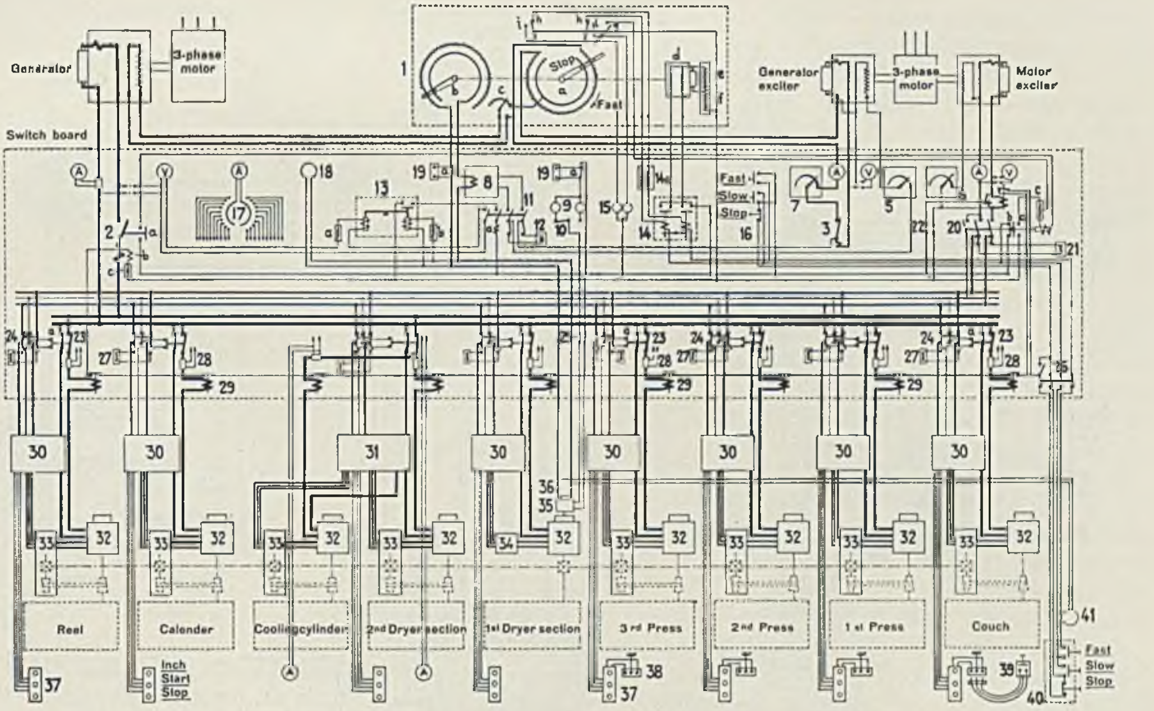

Fig. 1. Simplified diagram of electric equipment for paper machine with 9 motors.

1. Motor operated regulating apparatus.
   1 a. Generator field resistance.
   1 b. Adjustable resistance for pressure coil of regulator (8).
   1 c. Adjusting resistance.
   1 d. Operating motor.
   1 e. Parallel resistance.
   1 f. Series resistance.
   1 g. Contact for closing (20). Only closes when the contact arm moves from the stop position in the direction "increase".
   1 h. Limit switch.
   1 i. Signalling contact.
2. Circuit breaker for generator.
   2 a. Auxiliary contact for closing (20).
   2 b. No-volt relay.
   2 c. Series resistance for same.
3. Circuit breaker for generator exciter.
4. Overload relay, hand resetting, for motor exciter.
5. Field resistance, for generator exciter.
6. ,, ,, for motor exciter.
7. Adjusting resistance.
8. Speed regulator. (Voltage regulator).
9. Iron wire resistance.
10. Changeover switch for same.
11. Changeover switch for disconnecting (8).
    11 a. Releasing relay.
12. Substitution resistance.
13. Differential relay. Releases 11 if tachometer dynamo voltage fails.
    13 a. Series resistance for (13).
    13 b. ,, ,, ,, (13).
14. Operating relay for (1 d).
    14 a. Series resistance for (14).
15. Signalling lamps.
16. Push buttons.
17. Ammeter changeover switch.
18. Speed indicator. (Voltmeter).
19. Plug contact for portable ammeter.
    19 a. Short circuiting switch for (19).
20. Contactor with breaking contacts for the field excitation of the motors and for the starter operating current.
    20 a. Retaining contact.
    20 b. Operating contact. (After opening of (20), (1) returns to stop position).
    20 c. Series resistance for (20).
21. Discharge resistance.
22. Fuse for operating circuit.
23. Disconnecting switches for the separate motors.
    23 a. Auxiliary contact for breaking the operating current for the starters.
24. Disconnecting switches for motor fields and starting operating circuits.
25. Disconnecting switch for field winding of tachometer dynamo.
26. Switch for operating circuits.
27. Discharge resistances.
28. Ammeter shunts.
29. Overload relays with delayed action.
30. Starters.
31. Starter common to 2 motors.
32. Motors.
33. Shrinkage regulators.
34. Field resistance for master motor.
35. Tachometer dynamo.
36. Fuses for same
37. Push button boxes for the separate motors.
38. Plug contacts.
39. Portable push button for "inching".
40. Push button box for common speed regulation.
41. Speed indicator.

The windage set up by the large belt transmission also causes the paper to be unevenly dried, thus lowering the general quality, and often making it necessary to scrap a large part of the output. With sectional drive it has been found much more easy to obtain even drying of the paper.

Convenience in operation is also greatly increased. Starting and stopping of the different sections as well as alteration in the overall machine speed can be effected from push buttons mounted on the front of the paper machine. During examination of the machine, and especially during the frequent cleaning of the wire, control can be easily effected by means of a portable push button attached to a flexible lead and accessible from any suitable point. The machine in this way can be inched forward in suitably small amounts by the man carrying out the cleaning.

Lastly considerable space is saved due to the elimination of the transmission arrangements especially in the basement so that the building costs are much reduced.

If the costs incurred by electric sectional drive are compared with those when the drive is made with a main motor and transmission they are more likely to be lower in the case of sectional drive. The primary driving unit in the Leonard set is smaller in the case of sectional

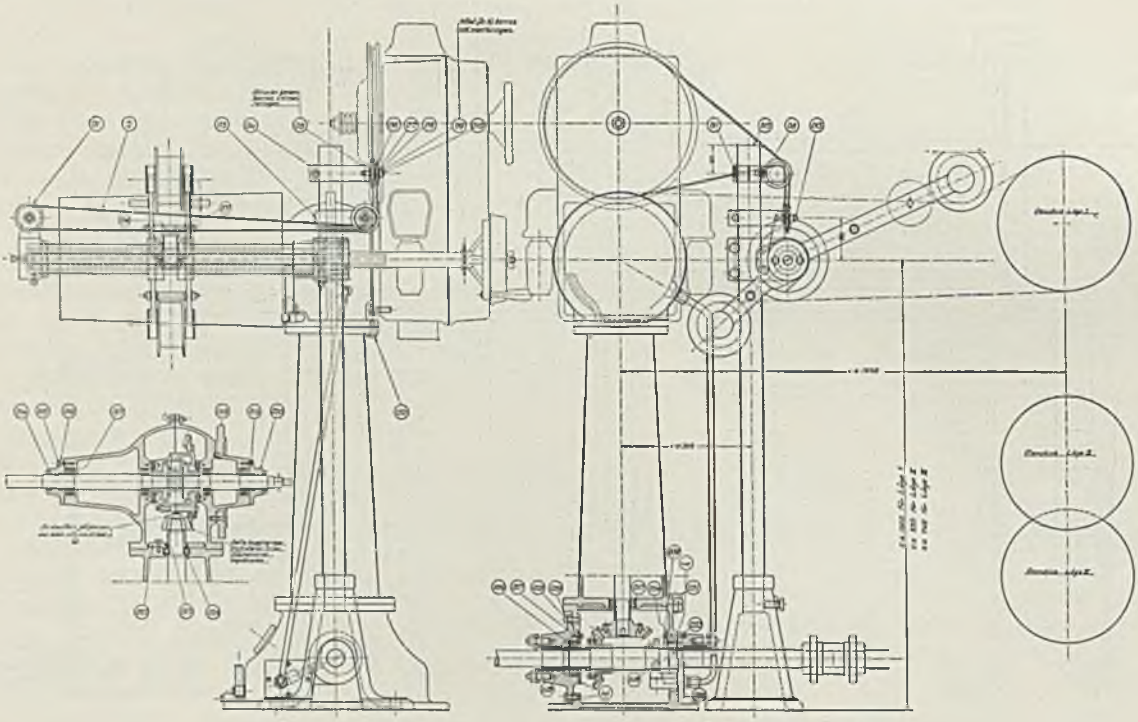

Fig. 2. Shrinkage regulator.

drive due to the saving in power by eliminating the transmission. The switchgear for this system is largely unaltered. Instead of the main motor with starting resistance etc., and transmission for the paper machine, separate motors are used with starters and speed regulating arrangements. Yet the increase in the price of the electrical equipment should not, in general, be greater than the saving effected on the transmission.

Under such conditions the equipment of any new large or medium sized paper machine with anything but electric sectional drive is hardly worth consideration. The advantages with sectional drive are in themselves so great that, in many cases, it pays to convert older transmission driven machines, and a number of such changes have already been carried out or are under consideration in various parts of the country.

When designing the drive of a paper machine on the sectional system we can reckon with a saving of about 20 % in the power required (in comparison with a machine with Leonard drive and a main motor). It is practically impossible to give any simple rule of general applicability, as even machines of approximately the same size give widely varying results.

The best course to pursue is undoubtedly to make use of experience already gathered from similar machines with transmission drive taking into account the saving mentioned above, due to elimination of the transmission. The speed for sectional driven machines, it is true, can be pushed higher than formerly, but we can approximately assume that the torque necessary increases with the fourth root of the speed and the power required accordingly somewhat more rapidly than the speed within the speed interval between that normally used with transmission driven machines and the highest obtainable with sectional drive.

Regarding the division of the power between the different parts of the paper machines there is, unfortunately, less experience available from transmission driven machines as in general no simple means were available for determining this power distribution. As a rough approximation we can say that the wire requires about 20 %, the wet presses about 25 %, the drying rolls about 35 % and the calender and reeling apparatus about 20 % of the total power. Large variations are, however, found in different machines. It should also be remembered that large differences occur in the power required for driving different arrangements of wet end, depending on the location and type of the suction boxes.*)

Finally, two systems for electric sectional drive are conceivable. The first and most important

*) For calculating power requirements see further W. Stiel, "Electrische Papiermaschinen Antriebe".

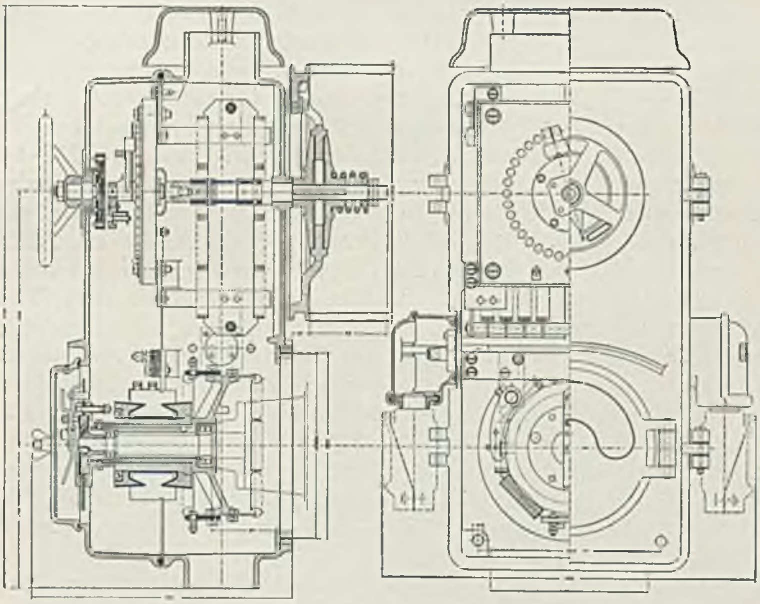

Fig. 3. Rheostat box of shrinkage regulator.

The first experiments in Germany and America which were carried out about 1909 were failures because this exact requirement regarding relative speed was not appreciated. An attempt was simply made to supply machines running at speeds as constant as possible, and to this end provided with an exceedingly large number of studs on their shunt resistances so that speed could be adjusted by hand very closely. It was, however, found in practice to be quite hopeless to regulate the different motors to a certain constant speed. The unavoidable departures from this speed were cumulative and at last a higher strain occurred than the paper was able to withstand without breaking. What we have to obtain is thus a regulation on the same relative angle between a certain radius in the different rollers, so that, for example, a departure from the correct speed during a given instant will be compensated in the next instant, not only by the regulator restoring the speed, but also first giving a small overalteration of the speed in the opposite direction.

is the Leonard system, *i.e.* the same system as used for driving with a main motor but employing separate D.C. machines coupled to the different parts of the paper machine. The other is the direct A.C. drive, using commutator motors with speed regulation by brush shifting. In what follows we shall chiefly deal with the first mentioned system.

In maintaining the speed constant on a section motor no great difficulties are experienced (see fig. 1). It is done in the same way as with the Leonard system, using a main motor. The section motor is furnished with a tachometer dynamo, the current from which traverses the coil of an automatic regulator, the contacts of which regulate the amount of resistance in the field of the exciter of the generator. Equilibrium obtains only when the voltage of the tachometer dynamo, and thus the speed of the driving motor, is equal to that for which the machine is adjusted. To enable the regulator to operate for different speeds it will be seen from the diagram that its coil is connected in series with a rheostat which is operated at the same time as the field resistance of the generator. Thus the regulator always has the same voltage applied to its coil at all speeds.

Although it is easy to obtain a constant speed for the first motor or for one motor it has been a very much more difficult problem to get correct relative speeds between the different parts of the paper machine. The necessary exactness is here of a very high order and departures from the predetermined speeds must not be more than a small fraction of 1 %.

This problem would naturally be easy to solve if it were not for the shrinkage in the paper web. It would be a simple matter to synchronise the different machines, for example by furnishing them with sliprings as on a rotary converter, and paralleling the motors on the A.C. side. The shrinkage in the web of paper, from the wire to the end of the drying rolls, reaches however several per cent and also varies for different classes of paper. It is, therefore, necessary to be able to adjust the different motors for certain speed differences. A conceivable solution would naturally be to make use of the above mentioned synchronisation but to allow each motor to drive the respective part of the paper machine through an adjustable belt running on conical pulleys. In this way, however, many of the advantages occuring from sectional drive disappear, and losses again occur in the transmission.

The General Electric Company, however, as late as 1919 introduced a system closely resembling the above in principle. For each D.C. motor there is a small synchronous motor having an output of about 20 % of the output of the D.C. machine and which is connected to the shaft of the D.C. motor with a belt drive on conical pulleys. All the synchronous motors are connected in parallel. If now one part of the paper machine strives to alter speed, this is made impossible since all the synchronous motors run in parallel. It follows that the synchronous motor for the part in question takes over a proportion of the driving power which was before supplied by the D.C. motor connected to it. (The assumption is naturally made that the alteration in power is not so great that the synchronous motor will be so overloaded as to drop out of step.) In this way we have at any rate secured an arrangement by which the belt drive does not transmit more than a part of the power. By hand regulation in the shunt field of the D.C. motor it is clear also that the synchronous motor and belt drive can afterwards be unloaded, the D.C. motor being made to take over the whole output.

It need hardly be pointed out that even this system is by no means perfect. Belt drives for considerable powers still remain while the synchronous motors increase the total cost of the installation materially. In addition, hand regulation must still be used to a great extent if the synchronous motors and belt drives are not to be overloaded under certain conditions.

It is clear that a solution correct in principle must ensure that the D.C. motors have their correct speeds maintained directly. Such an idea was put forward for the first time in 1912 by G. Stjernberg, M.I.E.E., now head of the Sales Department in Asea, and at that time manager of the English branch of the AEG. The AEG had delivered an equipment for sectional drive of a paper machine to an English firm, The Wall Paper Manufacturing Co., although the machines were not furnished with any direct regulating arrangements but only finely divided field rheostats and partially compounded motors. The proposal of Stjernberg led, however, to the provision of regulating arrangements for the most sensitive parts of the machine. (A patent for this arrangement was later applied for and granted in 1913 by the AEG but was not kept in force probably due to the outbreak of the War, when most of the staff who had been concerned with the regulating arrangement in question left the firm.) The installation of the

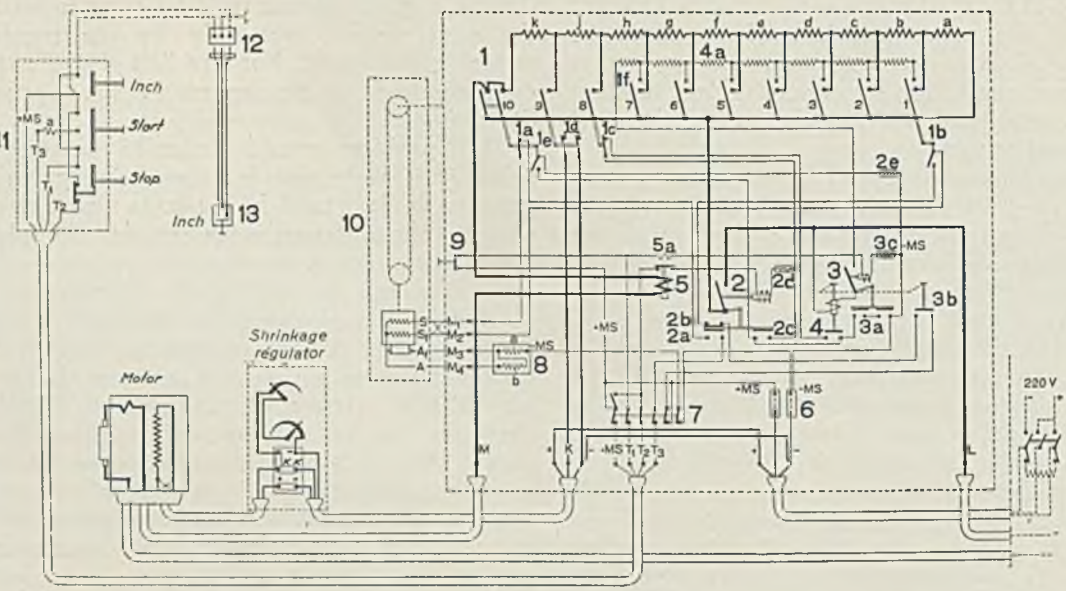

Fig. 4. Diagram for motor operated starter of sectional driving motor.

1. Starter.
   1 a and 1 b. Limit switches for operating motor.
   1 c. Interlocking contact.
   1 d. Contact for short circuiting shrinkage regulator during starting.
   1 e. Retaining contact. Short circuits the closing contact of the auxiliary relay when the starter is all out.
   1 f. Voltage contacts.
2. Main contactor.
   2 a and 2 b. Auxiliary contacts for operating the motor 10.
   2 c. Holding in contact.
   2 d. Series resistance.
   2 e. Auxiliary contact.
3. Intermediate relay.
   3 a. Closing contact for (2).
   3 b. Auxiliary contact with delayed action for running the operating motor in the direction "off".
   3 c. Series resistance.
4. Voltage relay. To enable the relay to close the contact, (3) must be closed and the current in the coil be less than a predetermined value.
   4 a. Voltage resistance (= series resistance for 4).
5. Instantaneous overload relay.
   5 a. Locking magnet for same.
6. Fuse for operating circuit.
7. Disconnecting switch for operating circuits. The control leads can, if necessary, be disconnected during running for examination without interrupting the working.
8. 8 a. Series resistance for operating motor.
   8 b. Parallel resistance for operating motor.
9. Push button. Used only when operating by hand.
10. Starter operating mechanism.
11. Push button box. The stop button remains depressed and must be drawn out again before a new start can be made.
    11 a. Signalling device. Shows red when the operating motor is running in the direction "on", otherwise white.
12. Plug contact.
13. Portable push button.

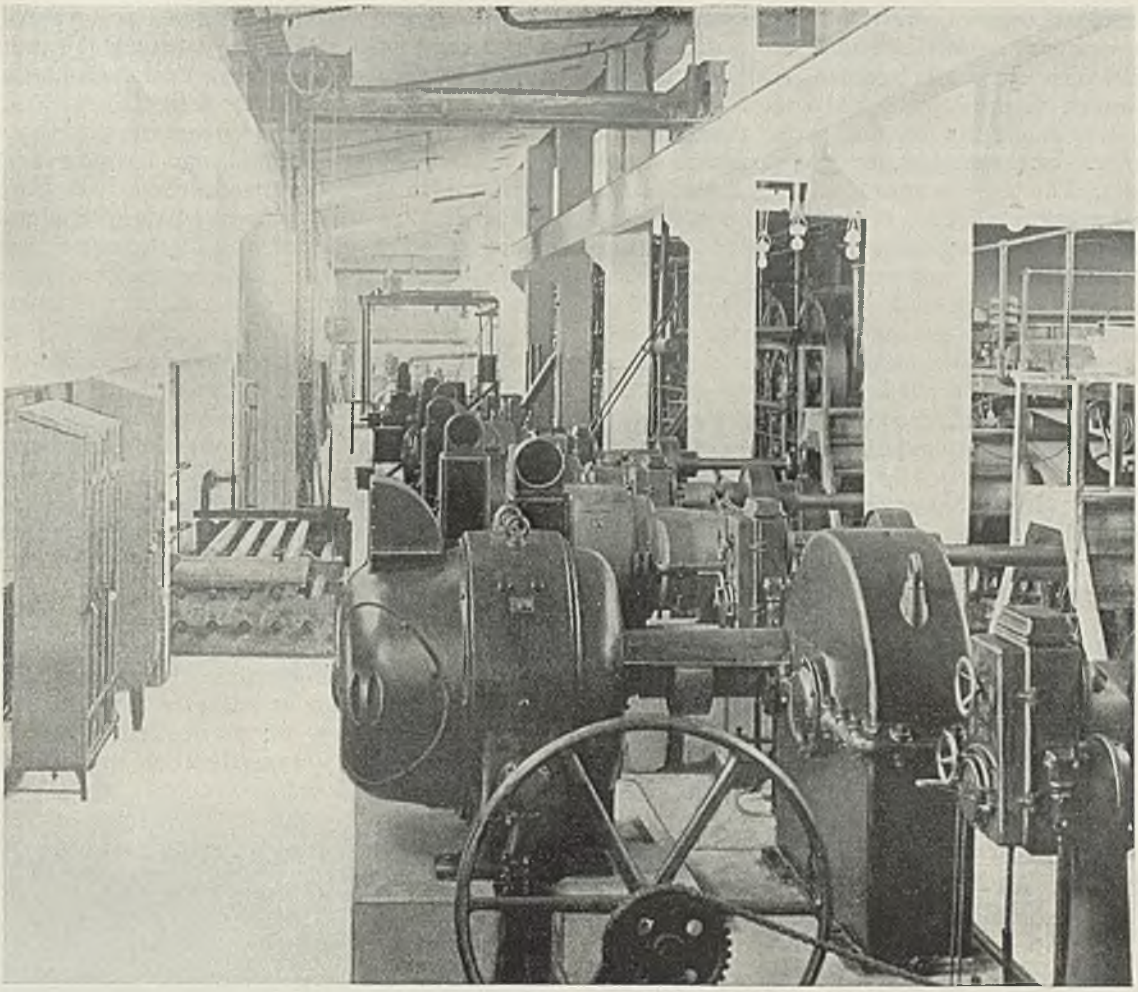

Fig. 5. Electric sectional drive of paper machine at Holmens Bruks Fabriks A.-B., Hallstavik, Sweden.

Wall Paper Manufacturing Co. was demonstrated in England to a number of interested engineers and paper manufacturers and aroused considerable attention. In 1914 the Harland Engineering Co. applied for a patent for the same arrangement and, thanks to the situation in England at the time and the imperfect circulation of information, they succeeded in their application.

Not until after the War were equipments for paper machines with electric sectional drive taken up seriously in America and England, while in Europe generally interest has only just been awakened.

The arrangement with the system referred to is in principle that of placing between the leading motor, *i.e.* the driving motor to which the tachometer dynamo for maintaining the absolute speed is attached, and the remaining motors, differential gears comprising three elements. The first element, the housing, is driven from the regulating shaft driven from the leading motor, the second element is driven by a belt running on conical pulleys from the respective motor shafts (or gear shafts), and the third element is connected to the shunt rheostat of the respective motors. If the speeds of the three elements at the same time are called n_1, n_2 and n_3 we get the equation

$$n_2 - n_3 = 2\ n_1.$$

The operating spindle for the shunt resistance can, evidently, not possibly spin round. Even a small movement amounting to a fraction of a turn alters the motor speed considerably and immediately. We thus obtain

$$n_3 = 0, \text{ and } n_2 = 2\ n_1.$$

The two first elements of the differential gear must accordingly work synchronously. Even after any length of time it would be impossible for them to become more than a fraction of a turn out of phase, as thereby the speed of the motor would be considerably altered. (As the formula shows, one turn of the second element corresponds uniformly with two turns of the first.) The conical belt drive makes it possible, however, to vary the speed somewhat between the various parts of the paper machine in a manner corresponding to the shrinkage in the paper. The motor speed adjusts itself so that the equation $n_2 = 2\ n_1$ is true for the differential gear. It should, however, be noted that this belt drive does not transmit any considerable amount of power. It has only to deal with the friction losses in the differential gear.

The design of regulating apparatus produced by Asea, the so-called shrinkage regulator, is shown in figs 2, 3 and 6. From the leading driving motor a regulating shaft runs the whole length of the machine, passing through the bases of all the shrinkage regulators. From the regulating shaft the rotation is transmitted through bevel gears to vertical shafts in the bases of the regulators connected to the housings of the respective differential gears. The conical pulley will be seen in the illustration. The losses in the differential gear only amount to from 5 to 10 watts, so that the power to be transmitted through the belt is exceedingly small. Theoretically, there is always a certain amount of slip in a belt drive when any power at all is transmitted. The tight side of the belt runs on to the pulley somewhat thinner than the slack side and this difference is partly maintained as the belt passes over the pulleys. As, however, the same weight of belting must pass each point of the drive in a unit time it is clear that the speed of the pulley faces must be somewhat different and this difference changes with the load. The diameter of the belt pulleys has, however, been selected so large that the peripheral stress is sufficiently small to enable us entirely to neglect the slip due to the belt stretch for the small power variations of 5 to 10 watts, which occur depending upon whether the losses in the differential gear are supplied from the regulating shaft or from the motor shaft. With a common belt drive, transmitting a real amount of power, it is in general not possible to prevent the occurrence of an additional true sliding of the belt over the entire pulley in certain cases. With the belts in question such slip would not occur unless the greatest power variations actually occurring were to be exceeded 10 to 20 times. The factor of safety against the slip being too great is accordingly fully adequate.

It should, perhaps, be noted that it is the large slip which gives rise to the difficulties as regards speed regulation in the transmission drives which have so far been used.

In order to obtain as small steps as possible for the shunt rheostats of the motors, which has been found desirable to prevent hunting, *etc.* Asea has divided the resistance into two parts. This will be seen from figs. 3 and 4. The main portion of the resistance, or approximately 75 %, can be set by hand, and is automatically regulated at the same time as the belt is shifted. The belt is shifted whenever an alteration in motor speed is desired and at the same time a rough setting of the resistance can be obtained. The actual automatic part of the resistance is the smaller remaining section of about 25 %*). The shaft from the differential gear is connected to a small commutator between the segments of which the last resistance is coupled. The brushes are fixed. The differential gear thus functions in such a way that the commutator with the resistance appertaining to it turns through a small angle when a speed alteration occurs and thus corrects the incorrectness in speed. Normally the commutator makes small and hardly perceptible movements, the brushes being in turn upon one or both of two adjacent segments. As $n_2 - n_3 = 2\ n_1 =$ constant, it follows that if $n_3 = 0$, *i.e.* if the commutator is stationary, n_2 is absolutely constant. If the collector makes a movement through a small angle φ_3 the corresponding cylinder in the paper machine is displaced by a corresponding angle φ_2 in relation to the leading driving motor (on the assumption that there is no gearing between the regulator and the corresponding cylinder in the paper machine). It is thus of importance

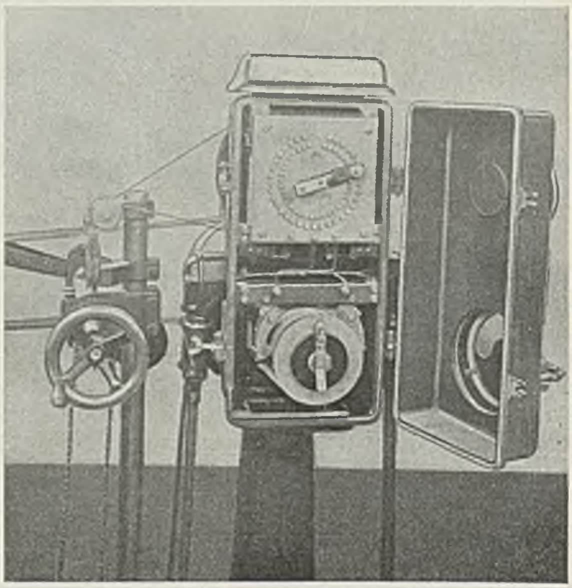

Fig. 6. Shrinkage regulator.

*) Arrangement patented by Asea.

to make the construction such that the motor reacts to the least possible displacement of the commutator in the shrinkage regulator. The commutator is connected with the differential gear through a friction clutch which can slip for a long time without excessive heating. When the machine is started, which is most suitably done section by section, or when any section of the machine is stopped, the shaft from the differential gear to the rheostat rotates, and as the movement of the commutator is limited and amounts only to something less than half a turn the apparatus would be smashed without this friction coupling.

It is desirable that the motors should be compounded to give as far as possible constant speed between no-load and full load. When starting the machine a web of paper is first passed through the whole machine and this web is increased in width gradually until the full width of the machine is reached. When the suction boxes at the wet end become fully covered there is a sudden increase in the power absorbed. If this increase, apart from the regulating arrangement, gives rise to an inconsiderable speed variation the work of the regulating apparatus is simplified, the momentary speed changes are less, and the chances of breaking the paper are reduced.

It is clear that the motors can suitably be supplied as geared motors of the modern type or coupled to the paper machine through up-to-date precision gears.

Regarding the arrangements of the system further particulars can be gathered from figs. 1 and 4. The last figure shows the arrangement for starting. Starting is most suitable effected by push buttons from the front of the machine. In this case, a motor operated starter is used.

When designing the resistance it must be remembered that approximately $2^1/_2$ times normal current may be required for starting. This occurs in general at a relatively low voltage corresponding to about half normal machine speed. It is, however, necessary that the resistance should be designed so that starting can also be effected at full voltage. If, for example, the paper web should break in the drying section it must be possible to disconnect this section to enable the broken part to be removed and a new start made without having to alter the quantity of stuff supplied to the wire. The wet end must, accordingly be kept running. This condition makes it necessary for a large amount of care to be taken in designing the resistance. With a normal start with relatively low voltage a large part of the resistance must be short circuited before the paper machine gets away. If, however, the machine is started with full voltage with the resistance short circuited, a risk is run of the motor's either flashing over or burning out. Under such conditions we may obtain more than 5 times normal current. As the diagram in fig. 4 shows a safeguard against such incorrect operation is obtained by a type of interlock which makes it impossible to close the main circuit breaker if a suitable proportion of the resistance corresponding to the voltage is not in circuit*).

There are also other arrangements for electrical sectional drive with speed regulation by means of differential gears. The Westinghouse Co. have brought out such an electrical system where the differential gear is composed of a small three-phase motor. If the rotor of this machine and also the stator is supplied with current of the same frequency the rotor naturally remains stationary. If there is a discrepancy between the frequencies the rotor rotates at a speed corresponding to the difference between the speeds of the rotating fields in the rotor and stator. The Westinghouse Co. have since modified their system. Other firms have also used systems for electrical speed regulation. All these electrical systems are, however, more complicated than the system employing simple mechanical differential gears. They are all likely to have originated as attempts to get round the patents on the mechanical arrangement, in such quarters that have been ill informed as to the historical developments of the mechanical system and the consequent weakness of the Harland patent regarding novelty.

As we stated at the commencement, the only possible rival to the sectional drive system with D.C. motors is the A.C. drive with variable speed commutator motors by which the primary unit of the Leonard system can be dispensed with. Such installations have already been designed. The only motor which can be considered suitable for this arrangement is the Schrage motor constructed by Asea. This machine has shunt characteristics and the speed can be regulated in the ratio of 1 to 3 by brush displacement. By using a series resistance the speed can be further reduced but the machine naturally assumes a series characteristic if this is done.

The arrangement is otherwise similar in character to the D.C. system. Instead of the shrinkage regulator operating on the shunt resistance of the respective D.C. motors it works the brush shifting devices of the three-phase motors.

Occasionally one hears it objected that the direct use of a three-phase supply introduces the disadvantage that the absolute speed varies with the frequency of the supply. This, how-

*) Patent applied for by Asea.

ever, is not the case any more than it is with the D.C. system. The absolute speed of the leading driving motor can easily be kept by means of a regulator. For example, a mechanical centrifugal governor can be used for this purpose. It is also possible to use a tachometer generator, electrical regulator and operating motor for adjusting the brush rockers of the leading motor. Other means of similar character might also be used. There is, accordingly, no doubt that the system employing commutator motors is technically quite satisfactory. The question whether or not it will be of economic value must be investigated in each case, as the saving due to the elimination of the primary unit may be outweighed by the more expensive motors.

Figs. 5 and 6 are illustrations of the plant delivered by Asea to Hallstavik, Sweden. The paper machine in question has a width of 5.15 metres and working is arranged for a maximum speed of 325 metres per minute. The number of motors is 9.

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