THE BROWN BOVERI REVIEW

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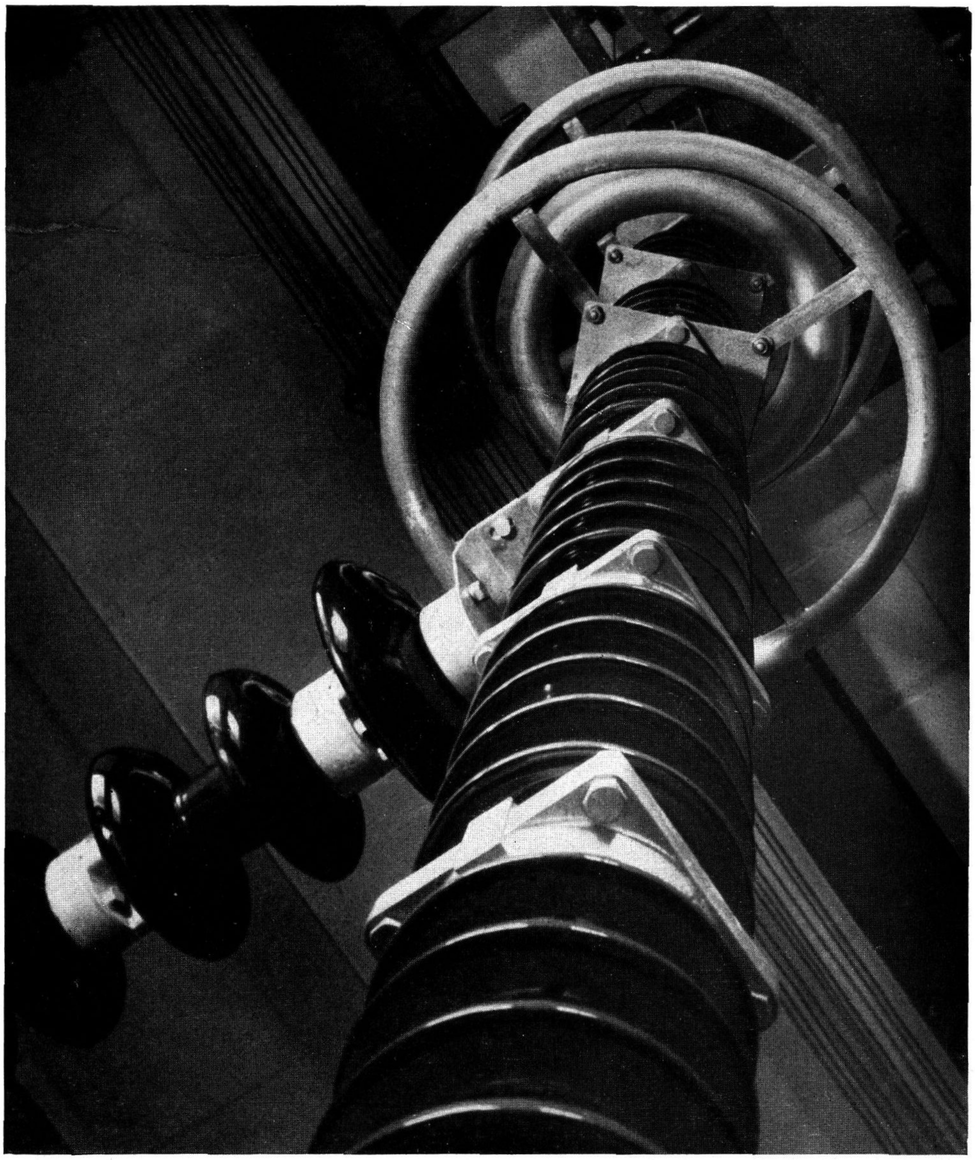
VOL. XXX MAY/JUNE, 1943 Nos. 5/6



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THE BROWN BOVERI REVIEW

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THE HEAT PUMP AS REFRIGERATING AND HEATING MACHINE.

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The article endeavours to describe the working principle of heat pumps in an easily understood manner. Some fundamentals must, however, be accepted without proof. In the second part some of the simplest basic thermo-dynamic relations are briefly recalled.

INTRODUCTION.

THERE is fundamentally no difference between *refrigerating* and *heating machines;* both are *heat pumps.*

Everybody knows the refrigerator: it produces "cold", it supplies ice and keeps food fresh which would otherwise go bad during the hot summer weather. The heating machine is, on the other hand, little known and its value is less apparent. There are so many possibilities of heating without a machine by means of fuel or electricity that it seems at first sight futile to build a special machine for this purpose.

Heating machines do in many cases, however, present important advantages, so that in spite of their high price they may be economical. *A heating machine can, in particular, supply a much greater quantity of heat with the same consumption of energy, as would be available by direct conversion of the same energy into heat.*

This fact often causes much astonishment and is frequently doubted, especially as many popular "inventors" make claims for the application of heat pumps *without either knowing or taking into account the essential facts.*

The additional output of the heating machine is in many cases so large that it enables the higher price of electrical energy compared with that of fuel to be more than compensated. The heating machine is, however, particularly valuable when, as at the present time for instance, coal is difficult to obtain, and on the other hand the electrical energy available as a substitute is insufficient for direct heating. In such cases a heating machine may save the situation and prevent the output of a plant having to be reduced or the plant having to be shut down.

A further advantage of the heating machine results from the fact that there is fundamentally no difference between heating machines and refrigerators. If, therefore, a heating machine is used for warming a building in winter, the same machine can be used in summer for cooling. In the case of large business houses, theatres, and big restaurants, this cooling in summer is so valuable that it may alone provide an economical justification of the heating machine.

In order to be able really to judge the possibilities of a heating machine, a knowledge of certain thermodynamic facts, as well as some experience in this domain are indispensable. The clearest view of the principle of the heat pump is obtained by comparing it with a heat engine; in the following the heat engine is, therefore, first shortly discussed, and the heat pump is thereafter dealt with.

I. HEAT ENGINES.

Heat engines convert heat into mechanical work. Although heat and mechanical energy are equivalent —

when 1 kWh of mechanical or electrical energy disappears as such, there invariably appears a heat quantity of 860 kcal, and every time 1 kWh of mechanical or electrical energy is produced from heat, 860 kcal of heat disappear — the conversion of heat into mechanical energy is subject to certain restrictions. Mechanical or electrical energy may at any time be completely converted into heat. *Experience shows, however, that it is only possible to convert heat into mechanical energy when the heat is available at a temperature higher than that of the surroundings.* Even in this case, it is possible at the best to convert only a fraction of the heat into mechanical energy; the remainder must be given up to the surroundings and is definitely lost as far as further conversion into mechanical energy is concerned.

Heat engines may be subdivided into two main classes: Steam engines and gas engines. In the case of steam engines the working medium passes through various states of aggregation (liquid — steam — liquid); this is not so in the case of gas engines.

The Steam Engine.

The steam engine (Fig. 1) operates as follows:— A feed pump delivers the liquid working medium — generally water — into the boiler, where heat is

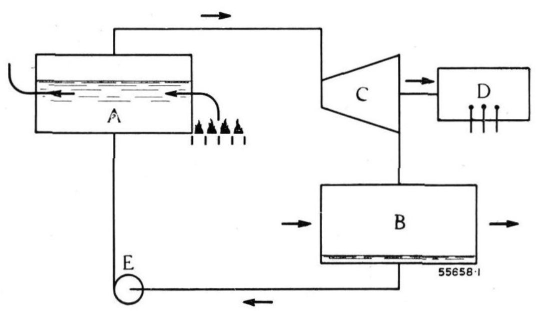


Fig. 1. — Diagram of a steam engine.

A. Heated boiler. D. Generator.
B. Cooled condenser. E. Feed pump.
C. Steam engine.

supplied. The heat supplied causes the working medium to evaporate, whereby its volume considerably increases. The steam, in expanding to a lower pressure in a steam engine — reciprocating engine or turbine — does work, after which the steam is liquefied in a condenser, whereby its latent heat of evaporation is given up to the circulating water. The condensate then returns to the feed pump.

The above-mentioned fundamental principle is here clearly evident: The steam engine can only operate when the boiler pressure is higher than the condenser pressure, that is, when the temperature of the boiler is higher than the temperature of the condenser. Secondly, in order to be able to feed the medium into the boiler, it is essential that the steam shall be condensed and, therefore, that the latent heat of evaporation of the expanded steam shall be given up to the surroundings, so that it can no longer come into consideration for the production of mechanical energy.

The Gas Engine.

In the gas engine the working medium is similarly first compressed, then heated, expands, and is finally again cooled. During the expansion of the hot gas, more energy is produced than is needed for the compression of the cold gas; the difference is the useful output.

The fundamental difference compared with the steam engine consists in the fact that the work of compression is a considerably greater fraction of the work done during expansion. The feed pump absorbs less than 1 % of the output of a steam engine; in the case of the gas engine the work of compression amounts generally to more than 50 % of the expansion work. In order that in practice a useful output will remain available, the efficiencies of both the power machine and of the compressor must be high. This is the reason why the gas engine appeared so very much later, as engineering practice had to attain a relatively high state of development before it was possible for the expansion machine to be able to drive even its own compressor, whereas it is hardly possible to imagine a steam engine which is not able to drive its own feed pump.

II. HEAT PUMPS.

The heat pump is nothing other than a reversed heat engine. It is based on the fact that it is possible — apart from the losses — to reverse the thermo-dynamic process of the heat engine. In place of the rejection of heat at the lower temperature, there is the absorption of heat, the heat engine *develops* power, whereas the heat pump *absorbs* power, and heat is given out by the heat pump at the higher temperature. The heat given out is constituted by the heat equivalent of the energy supplied, whereby 860 kcal appear for each kWh absorbed, and by the heat taken up at the lower temperature. In practice, both the heat absorbed and that given out may be a multiple of the heat equivalent of the energy supplied. Such a machine can, therefore, absorb heat at a lower temperature and give it out again at a higher temperature, whereas only the reverse process is observed to take place in nature. It, therefore, raises the heat to a higher temperature level — hence the name "heat pump".

Refrigerating and Heating Machines.

Heat pumps can be used in two ways: as *refrigerating* or as *heating machines.*

The refrigerator must absorb heat at a low temperature. This heat is abstracted from the substance to be cooled, the temperature of which is thereby reduced. *The useful output of the refrigerator is, therefore, the amount of heat absorbed at the lower temperature.* This heat, increased by the heat equivalent of the energy absorbed, must then be given up in some manner or other to the surroundings. In the case of the refrigerating machine this exhaust heat is useless and generally a nuisance.

The heating machine must, on the other hand, give up heat; the useful output is the *heat given up* at the higher temperature. It is constituted by the heat equivalent of the mechanical energy supplied and the heat quantity taken up at the lower temperature. The lower temperature is either the temperature of the surroundings — the air, a lake, or a river — or the temperature of some available source of exhaust heat. The heat absorbed is usually a multiple of the heat equivalent of the energy supplied. The ratio of the heat given out to the heat equivalent of the energy absorbed is known as the *coefficient of performance* of the heating machine; it therefore indicates how much more heat is furnished by the heating machine than by direct electrical heating with the same consumption of energy.

The heat taken up at the lower temperature is of capital importance. If the heat has to be absorbed at the temperature of the surroundings, coefficients of performance of 3—6 can be attained, for instance, for room heating; if exhaust heat at a more favourable temperature is available — for instance, in concentration or distillation and drying processes — the coefficient of performance may increase to 10—20.

A heat pump can be so built that it may be operated at will as a heating engine or as a refrigerator. The same machine may, therefore, serve for instance in a theatre or in a large restaurant for heating in winter and for cooling in summer.

The Steam Heat Pump.

The steam heat pump (Fig. 2) is a reversed steam engine (Fig. 1). The working medium is evaporated at a low pressure in an *evaporator,* which takes the place of the condenser. The water circulated through the evaporator supplies the necessary latent heat of evaporation. It is no longer heated in the condenser, but cooled; if its temperature then falls below 0°C — as for instance in an ice plant — it is necessary to employ instead of pure water a salt solution (brine) with a sufficiently low freezing point.

The low-pressure steam so produced is continuously absorbed and compressed by the *compressor.* The compressor takes the place of the turbine. The compressor *absorbs* power. Instead of the generator there is the *motor.* The compressed steam is now condensed in the *condenser,* which takes the place of the former boiler. Because of the higher pressure, the steam can now be condensed at a higher temperature than in the evaporator; it can, therefore, give up its latent heat of evaporation at a temperature which is higher than that at which it was absorbed.

The latent heat of evaporation is given up to the cooling water passing through the condenser, which is thereby heated. Whereas in the case of the steam engine the combustion gases are *hotter* than the cooling water, in the case of the heat pump the "heating water" is *colder* than the cooling water.

The condensed working medium must now be returned to the evaporator. Instead of the feed pump there should now be some form of motor which could deliver energy, thereby relieving the motor for driving the

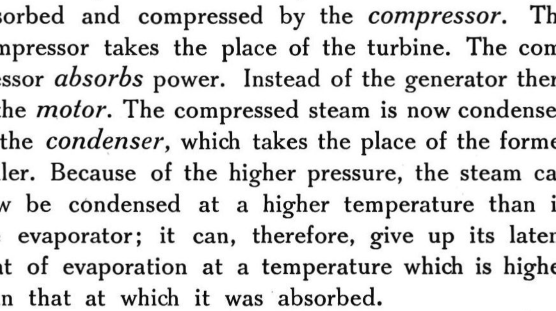


Fig. 2. — Diagram of a heat pump.

A. Cooled condenser. C. Compressor.
B. Evaporator heated with waste heat or heat from the surroundings. D. Motor.
E. Reducing valve.

The steam heat pump is a reversed steam engine.

compressor of part of its output. This energy is, however, so small that it is not worth while to provide a special turbine for this purpose, and therefore the condensed working medium is simply throttled down by means of a float-operated valve or of an orifice plate to the evaporator pressure, and the cycle is completed.

The steam heat pump, hence, requires only a single machine — the compressor. The plant is therefore relatively simple.

The Thermo-compressor.

A very simple form of steam heat pump is obtained when a concentration process is operated by means of a heating machine and the steam produced is itself used as a working medium. The result is the simple plant shown in Fig. 3. The steam generated in the concentrating pan is drawn off by a compressor, by

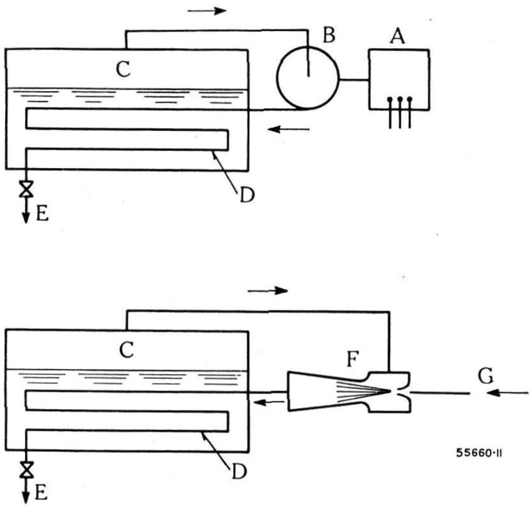


Fig. 3. — Diagram of a thermo-compressor.

A. Motor.
B. Compressor.
C. Cooker.
D. Heating coil.
E. Condensate outlet.
F. Steam heat compressor.
G. Live steam.

The evaporated steam from the cooker is compressed in the compressor to a higher pressure and condensed in the heating coil. The heat of condensation thus given up maintains evaporation in the cooker.

A steam-jet injector may sometimes take the place of the compressor.

The evaporated steam leaves the thermo-compressor in the form of condensate. Its latent heat is, therefore, no longer wasted.

means of which it is raised to a higher pressure and delivered into a heating coil which maintains the evaporation in the pan. Because of the higher pressure the steam may be condensed at a higher temperature; it gives up its latent heat of evaporation again to the contents of the pan. Steam thus produced is again compressed, and so on.

In such a case the heating machine consists only of a compressor, which is then known as a *thermo-compressor*. The concentrating pan is the evaporator and the heating coil serves as condenser. The thermo-compressor makes use of the latent heat of evaporation of the steam which would otherwise be lost. This is most clearly evident from the fact that the steam does not leave the concentrating apparatus as such, but is condensed by means of the *thermo-compressor* and runs off in liquid state—that is without taking with it the latent heat of evaporation. Experience shows that if the evaporator is suitably insulated the mechanical energy supplied suffices to cover the heat losses of the entire concentrating plant.

The Working Medium.

The working medium employed depends on the conditions. At low temperatures carbon dioxyde (CO_2), ammonia (NH_3) and sulphur-dioxyde (SO_2) still have a relatively high vapour pressure and consequently a low specific volume. They are, hence, particularly suitable for reciprocating compressors. In the case of centrifugal compressors such media come into question only for large outputs[1].

Already at an early date hydro-carbon compounds, such as ethyl chloride, ethyl bromide, and later methyl chloride (dichlormethane) were employed. Recently, various other hydro-carbon compounds with chlorine and fluorine have been used with centrifugal compressors; these media have the advantage that they are less poisonous; the fluor compounds (freons) are also practically odourless. The molecular weight of these compounds makes them particularly suitable for centrifugal compressors, because the necessary pressures may be obtained with a small number of stages and moderate speeds.

The Gas Heat Pump.

The gas heat pump is a reversed gas engine. The working medium is compressed adiabatically in the compressor and thereby heated; the heated compressed gas flows through a heat exchanger, where it gives up its heat, after which it is expanded adiabatically in an expansion machine and thereby cooled so far that it may take up heat at a lower temperature in a second heat exchanger.

Just as in the case of the gas engine the work of compression represents a considerable part of the expansion work, so in the case of the gas heat pump the expansion work is a considerable part of the compression work. There can, therefore, be no question of omitting the expansion machine as is usual in the case of a steam heat pump. That this must be so is shown by the following reasoning: When the condensate is throttled, it assumes — when necessary by partial evaporation — immediately the lower boiling temperature. If, however, gas is throttled, its temperature remains practically constant. If, therefore, the gas were to be throttled instead of expanded in an expansion machine, it simply would not assume the lower temperature which alone enables it to absorb heat at the lower temperature.

The gas heat pump without an expansion machine could therefore take up no heat, and hence could only give up as much heat as would correspond to the equivalent of the mechanical energy absorbed, that is, it would be no heat pump.

The gas heat pump must have an expansion machine and is, therefore, more complicated than the steam heat pump. In spite of this, it may present

[1] Thus Brown Boveri already in the year 1925 supplied a centrifugal compressor for ammonia for a cooling output of 8×10^6 kcal/h.

advantages in certain cases. When for instance air is to be heated or cooled, the air may itself be used as working medium. In this way it is possible to avoid one heat exchanger and the temperature drop in the same. Further, it is often an advantage that no special refrigerating medium has to be used. For certain purposes, for instance where low temperatures must be attained — as in the liquefaction of gases or in high altitude test plants for aeroplane engines — gas heat pumps are also of advantage.

THERMO-DYNAMIC FUNDAMENTALS.

I. HEAT ENGINES.

As already mentioned, the heat pump is nothing else but a reversed heat engine. Since, however, the thermo-dynamics of heat engines are usually considerably better known, in the following the thermo-dynamics of heat engines are first discussed, and thereafter the thermo-dynamic fundamentals of heat pumps explained. Certain fundamental ideas must thereby be assumed to be known.

The Steam Engine.

The clearest picture of the working of a steam engine is given without doubt by the so-called *indicator diagram*. This diagram is obtained when the changes of state of the working medium are drawn in a pressure-volume diagram, the ordinates representing the pressure, the abscissæ the volumes. Usually, the specific volume is employed, that is, the diagram is drawn for 1 kg of the working medium. Fig. 4 shows the indicator diagram of a saturated steam engine, the working medium in this example being water.

Point 1 corresponds to water at 100^0 C and a pressure of 1 kg/cm^2 abs. The water is compressed to 16 kg/cm^2 abs. (point 2) and then heat supplied. The temperature rises first to 200^0 C (point 3), the water thereby expanding only unnoticeably. At this temperature the water begins to evaporate under a pressure of 16 kg/cm^2 abs; further heat supply does not raise the temperature, but causes the water to evaporate instead. During this process the volume increases considerably until all water is evaporated (point 4). After all water has been converted into dry-saturated steam, the heat supply is stopped, and the steam expands adiabatically to the initial pressure (point 5). The temperature thereby sinks again to 100^0 C and a small part of the steam liquefies. Heat is now abstracted from the steam at constant pressure; the temperature then remaining constant, the steam condenses, however, and the volume decreases until all the steam is liquefied (point 1). The cycle is then closed and can be repeated as often as desired.

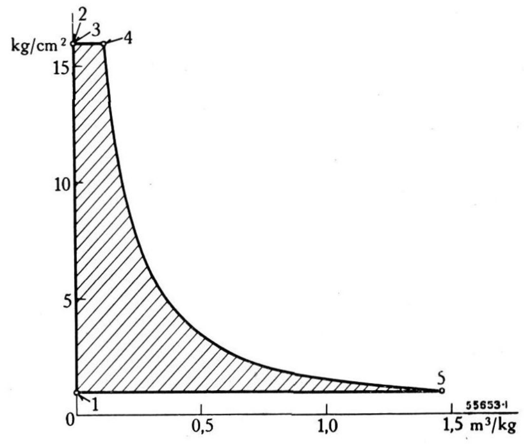


Fig. 4. — p-v diagram of a steam engine.
p. Pressure. v. Specific volume.

As during this whole process no permanent change of any substance occurs, the cycle is purely thermo-dynamic. The mechanical work thereby obtained is represented by the indicator diagram 1, 2, 3, 4, 5, 1.

In this diagram, the net mechanical work is the difference between the expansion work of the steam — surface between 4, 5, and the ordinate axis — and the work of the feed pump — surface between 1, 2 and the ordinate axis. In Fig. 4 this second surface is, however, practically invisible, as the feed pump absorbs only a minute fraction of the work of expansion.

The Gas Engine.

Fig. 5 shows the indicator diagram of a gas engine. Air at atmospheric pressure, that is at a pressure of 1 kg/cm^2 and a temperature of 300^0 abs (point 1), is compressed adiabatically to 3 kg/cm^2 (point 2) and then heated at constant pressure to 800^0 abs (point 3). The air thus heated expands adiabatically to the original pressure (point 4) and is then again cooled at atmospheric pressure to the original

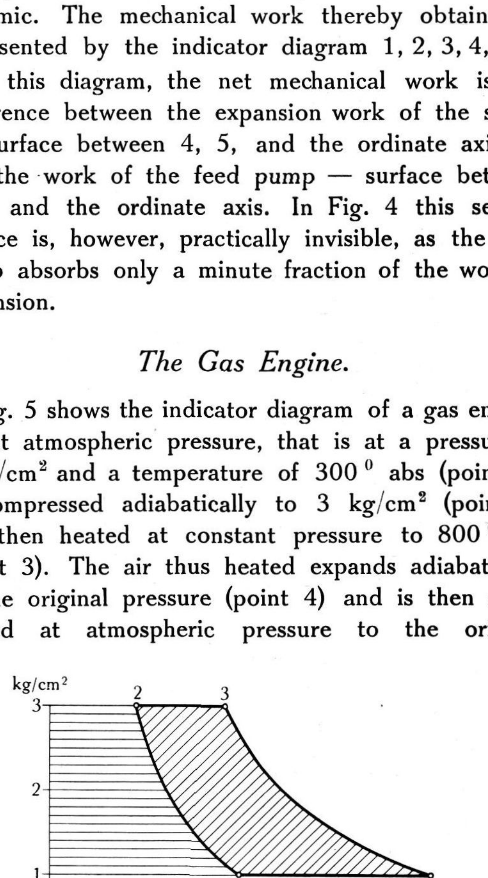


Fig. 5. — p-v diagram of a gas engine.
p. Pressure. v. Specific volume.

temperature (point 1). In practice the expanded air escapes through the chimney, and in its place fresh air is drawn in. The work done is again represented by the surface 1, 2, 3, 4, 1.

Here again the mechanical work is the difference between the expansion work — surface to the left of 3, 4 — and the work of compression — surface to the left of 1, 2. The fundamental difference compared with the steam engine consists in the fact that with a gas engine the work of compression is a substantial amount — in the example illustrated it amounts to 50 % of the work of expansion. If any useful output is to be given at all, the efficiencies of both the turbine and the compressor must clearly be quite high.

from steam tables, such as is the case for the specific volume or the heat content.*

(b) From the definition entropy s

$$ds = dQ/T^{**}$$

where dQ represents the heat quantity supplied at the temperature T, it follows at once that in the temperature-entropy diagram the surface element

$$T \cdot ds = T \cdot dQ/T = dQ$$

represents directly the heat quantity supplied. In this representation, therefore, heat quantities appear as surfaces, isothermal changes of state as horizontal lines, and adiabatic changes of state — since $dQ = 0$ — as vertical lines. Herein lies the great practical value of the entropy diagram. Exactly the same cyclic

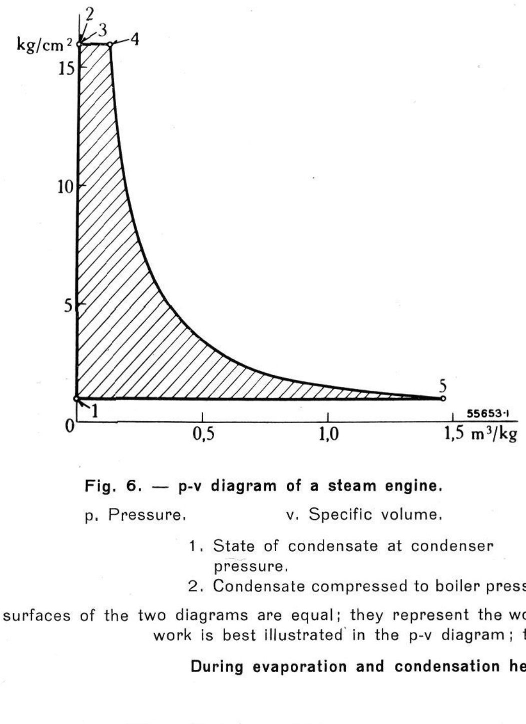


Fig. 6. — p-v diagram of a steam engine.

p. Pressure. v. Specific volume.

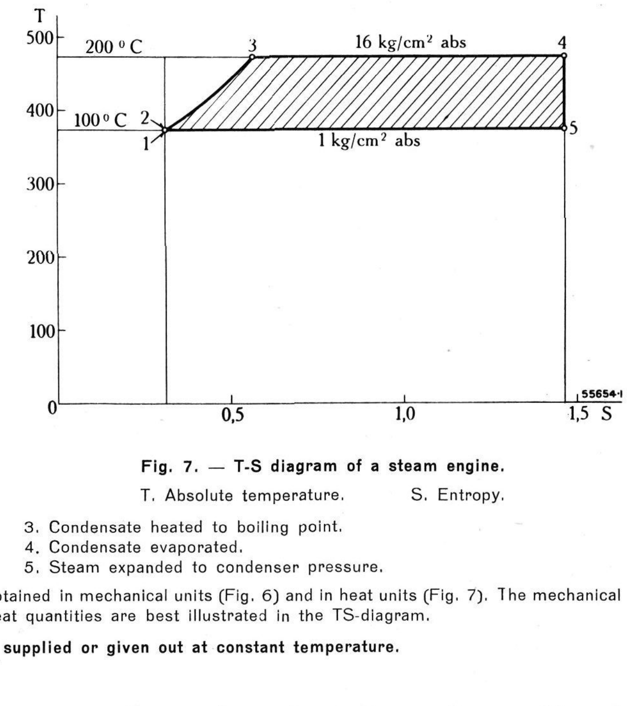


Fig. 7. — T-S diagram of a steam engine.

T. Absolute temperature. S. Entropy.

1. State of condensate at condenser pressure.
2. Condensate compressed to boiler pressure.
3. Condensate heated to boiling point.
4. Condensate evaporated.
5. Steam expanded to condenser pressure.

The surfaces of the two diagrams are equal; they represent the work obtained in mechanical units (Fig. 6) and in heat units (Fig. 7). The mechanical work is best illustrated in the p-v diagram; the heat quantities are best illustrated in the TS-diagram.

During evaporation and condensation heat is supplied or given out at constant temperature.

The Entropy Diagram.

The indicator diagram satisfies all requirements as long as we are interested only in mechanical energy. If, however, heat quantities are to be shown, it is more advantageous to employ a diagram with absolute temperature as ordinates and entropy as abscissæ.

To the average reader the idea of entropy is somewhat abstract. For the present it is, however, sufficient to bear the following in mind:—

(a) The entropy is, just as for instance the specific volume, the internal energy, or the heat content, a pure *function of state*, that is, 1 kg of water or steam has in every state which is given for example by the pressure and the temperature, a certain definite entropy, the value of which may be obtained

process illustrated in the indicator diagram Figs. 4 and 6 can now be represented in the entropy diagram Fig. 7. Point 1 corresponds again to boiling water at 1 kg/cm² abs, the temperature of which is, therefore, 372·1 ° abs, and which has an entropy per kg of 0·3096 kcal/° C. Adiabatic compression of the water causes no noticeable increase of temperature, so that point 2 practically coincides with point 1.

* It would be going too far to prove this statement here. It is a consequence of the second law of thermodynamics. Those wishing to pursue the subject further may follow it up in any text book on thermo-dynamics.

** This definition of entropy applies strictly only to reversible processes. It can, however, by means of an artifice be applied also to irreversible changes of state, such as throttling, by taking into account the heat produced by friction.

During the following heating process the temperature rises first to 473 ⁰ abs, i. e., the boiling temperature corresponding to 16 kg/cm² abs. Simultaneously the entropy also increases (point 3). A further increase of the heat supply causes the water to evaporate, during which process the temperature remains constant, the entropy continuing to increase until all water is evaporated (point 4). Now the steam expands adiabatically to 1 kg/cm², during which the temperature again falls to 373 ⁰ abs (point 5), and when the steam is again condensed by abstraction of heat, its entropy returns to the original value and the cycle is complete.[1]

The total heat absorbed during this process is represented by the surface below the line 1, 2, 3, 4.

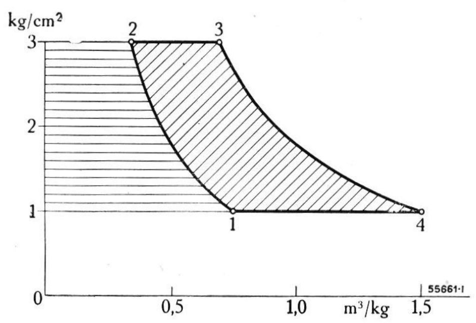


Fig. 8. — p-v diagram of a gas engine.

p. Pressure. v. Specific volume.

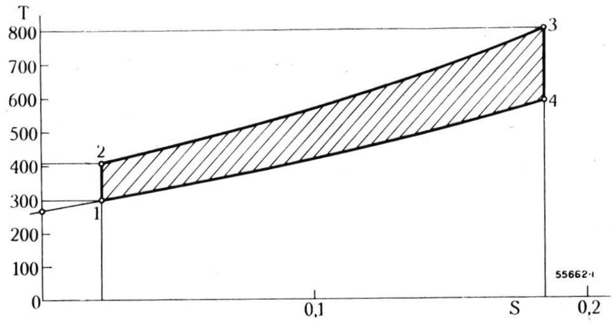


Fig. 9. — T-S diagram of a gas engine.

T. Absolute temperature. S. Entropy.

1. Cold low-pressure gas. 2. Cold high-pressure gas. 3. Hot high-pressure gas. 4. Hot low-pressure gas.

The surfaces of the two diagrams are equal and represent the work obtained in mechanical units (Fig. 8) and heat units (Fig. 9). The mechanical work is best represented in the p-v diagram. The heat quantities are best shown in the T-S diagram.

In the gas engine the heat must be supplied at an increasing temperature and be given out at decreasing temperature.

The heat given out is represented by the surface below the line 5, 1, and the difference, converted into mechanical work, is represented by the surface 1, 2, 3, 4, 5, 1, which, therefore — expressed in heat units — must be equal to the area of the indicator diagram. On the other hand, it is not possible by simple means to show, in the entropy diagram for instance, the work of the feed pump. Figs. 8 and 9 are the corresponding p-v and T-S diagrams for a gas engine.

[1] Some readers may here remember Clausius' law, according to which entropy can only increase or at the best remain constant, but never decrease. The explanation is as follows: When any body gives up heat, this heat must necessarily pass to another body. During this process the temperature of the body to be heated must be lower than that of the body supplying the heat, so that the increase of the entropy of the first is necessarily greater than the decrease of the second. The total entropy of both bodies must, therefore, increase. In the ideal case there is no difference of temperature, and the increase and decrease of entropies just balance each other. A decrease in the total entropy would mean that the colder body had given out heat, which is impossible. The entropy of any single body may, however, either increase or decrease.

The Carnot Efficiency.

The entropy diagram enables the substance of the famous law of Carnot to be illustrated very clearly. The entropy diagram of the saturated steam engine shown in Fig. 7 — except for the left hand upper corner below the points 2 and 3 — is a rectangle. If this corner is disregarded[1] it is at once evident that the heat available at a certain temperature can never be completely converted into mechanical work.

If the two temperatures T_1 and T_2 are given, then of the amount of heat Q available at the temperature T_1 there can be converted into mechanical work at a maximum only the fraction

$$Q \cdot \frac{T_1 - T_2}{T_1}$$

whilst the remainder $Q \cdot \frac{T_2}{T_1}$ must inevitably be given out again at the temperature T_2 if the cycle is to be completed. This is the content of the law of Carnot.[2] The ratio $\frac{T_1 - T_2}{T_1}$ is also denoted as the Carnot efficiency; if a heat engine works between the temperatures T_1 and T_2, the thermal efficiency can never exceed the Carnot efficiency.

II. HEAT PUMPS.

The heat pump is nothing other than the reversal of the heat engine, and the working process of the steam heat pump would be, for instance, as follows (Fig. 6): Boiling water (point 1) is converted to steam

[1] This corner is missing because the process chosen operates without feed water heating.

[2] This is, of course, no "proof" of Carnot's law. The definite relationship between entropy and state postulated previously, without which it would be quite impossible to draw an entropy diagram, is, on the contrary, a consequence of the law of Carnot.

by the heat supplied (point 5). The steam is adiabatically compressed (point 4) and then again condensed by abstraction of heat (point 3). The resulting condensate is afterwards again expanded to the initial pressure.

The heat quantities may once again be read off from the entropy diagram (Fig. 7). The heat supplied is represented by the surface below the line 1, 5, the quantity of heat given off by the surface below the line 4, 3, 2, 1, and the necessary power by the surface 1, 5, 4, 3, 2, 1. By means of this process a certain amount of heat is therefore taken in at the lower temperature and — increased by the heat equivalent of the mechanical work absorbed — given out again at a higher temperature.

The Coefficient of Performance.

The entropy diagram enables us to see immediately what can at the best be expected from a heat pump. The enclosed surface represents the power consumption theoretically necessary. The surface below the diagram is the heat absorbed, and the two together represent the amount of heat which the heat pump can give out. It is customary to express the performance of the heat pump as the ratio of the useful heat to the power absorbed — also expressed in heat units —; the ratio is called the coefficient of performance. The theoretical maximum value of the coefficient of performance may be deduced from Carnot's law; it depends, however, upon which heat quantity is regarded as the useful heat, for a heat pump may operate either as a refrigerator or as a heating machine, and the coefficient of performance differs accordingly.

The Refrigerator.

In the case of the refrigerator the useful output is the heat absorbed at a lower temperature, for this is the heat quantity which is abstracted from the substance to be cooled and is, therefore, the amount of "cold" produced. The maximum ratio of the useful output to the power absorbed is in this case

$$\varepsilon_{th\,K} = -\frac{T_2}{T_1 - T_2}\,*$$

as follows from Carnot's law.

The upper temperature limit T_1 in the case of the refrigerators lies in practice in the neighbourhood of 300^0 abs. It is given by the temperature of the available cooling water. The coefficient of performance is fixed by the choice of the lower temperature T_2, and the entropy diagram shows at once how important it is not to make this temperature a single degree lower than absolutely necessary. An unnecessarily low temperature increases the amount of power required and at the same time reduces the useful output. At very low temperatures as come into question for the liquefaction of air or in particular of hydrogen (20^0 abs) or Helium (4^0 abs) enormous amounts of energy have to be supplied to produce very small outputs of cold.

* The minus sign comes from the fact that the useful output is a heat quantity *taken in.*

The Heating Machine.

In the case of the heating machine the useful output is, on the other hand, the heat *given out* at a higher temperature. The maximum ratio of useful output to the energy absorbed is then according to Carnot's law:

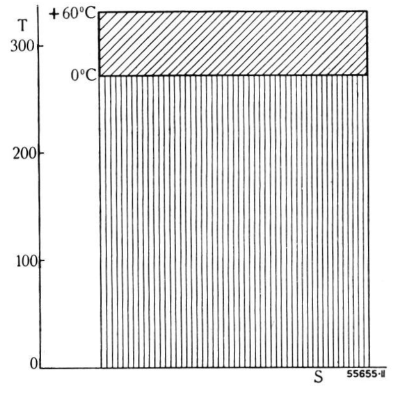


Fig. 10. — Carnot diagram of a heating machine.

//////////. Theoretically necessary energy consumption.

||||||||||. Heat recovered from the surroundings.

The lower the upper temperature, the smaller the energy consumption. **Heating installations for operating with heating machines must be liberally dimensioned.**

$$\varepsilon_{th\,H} = +\frac{T_1}{T_1 - T_2}$$

The available electrical (or mechanical) energy could also be *directly* converted into heat and used for heating purposes. The coefficient of performance indicates, therefore, in this case, how many times more heat is made available for heating purposes by the heating machine.

What values of the coefficient of performance can be attained depends on the operating conditions. In the case of heating machines which make the heat of the surroundings available for room heating, the lower temperature is fixed in the neighbourhood of 300^0 abs (Fig. 10). The higher the upper temperature T_1 is chosen, therefore, the greater is the consumption of energy. It is, hence, futile to connect a heat pump to a inadequately dimensioned central heating system. With coal firing it is possible without much loss to force the temperature up to 80 or 90^0 C; such a temperature would, however, completely nullify the advantage of a heat pump, and for room heating it is therefore essential to employ for the few really cold winter days additional fuel and to dimension the heat pump only for the average heating requirements.

There is, however, for heating machines a further particularly interesting field of application. If, for instance, both temperatures may be raised, then the useful output with constant energy consumption steadily increases (Fig. 11). Such a possibility does indeed exist

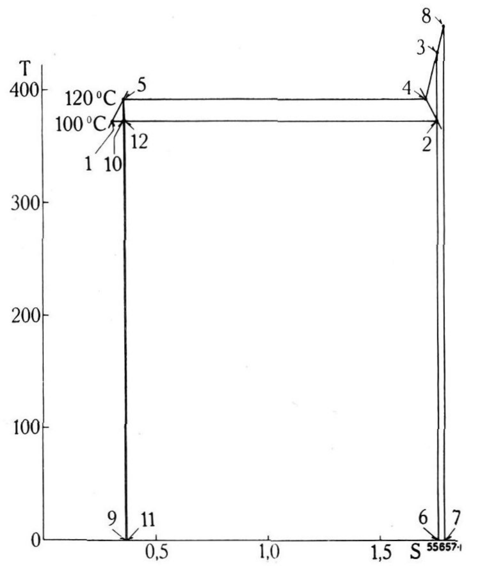


Fig. 11. — Entropy diagram of a thermo-compressor.

Evaporator temperature 100° C.
Condenser temperature 120° C.

1, 2, 3, 4, 5, 1 = Theoretical compression work.
2, 6, 7, 8, 3, 2 = Additional work due to compressor losses.
2, 6, 9, 10, 2 = Theoretically recoverable latent heat of evaporation.
10, 9, 11, 12, 10 = Losses due to throttling and subsequent evaporation of the condensate.

The small amount of energy consumed 1, 2, 6, 7, 8, 3, 4, 5, 1 enables the large part 12, 2, 6, 11, 12 of the latent heat of evaporation to be recovered and to be returned to the evaporation process. The vapour leaves the concentrating plant as condensate and not as steam. The latent heat of evaporation is therefore not lost.

in many cases when exhaust heat is available from any process, e. g., in concentrating, distillating, or drying processes, where large heat quantities are consumed, in order to convert water into steam which is not wanted by anybody. Here it is in many cases possible to recuperate by means of the heat pump the latent heat of evaporation, which would otherwise be lost, and to return it again to the process. Under favourable circumstances it is possible to achieve extraordinarily high coefficients of performance, especially when the steam produced serves at the same time as working medium for the heating machine, so that the heating machine can take its cheapest form of a thermo-compressor.

Efficiencies.

The ideal coefficient of performance ε_{th} according to Carnot cannot be achieved in practice. If ε is the coefficient of performance actually achieved, then the efficiency of the heat pump is

$$\eta = \varepsilon / \varepsilon_{th}$$

The efficiency differs according to whether the heat pump operates as a refrigerator or as a heating machine.

The efficiency is affected mainly by:

(a) The drop of temperature in the heat exchangers.

(b) The working process used and by the nature of the working substance.

(c) The efficiency of the machines used.

These influences cannot, however, be clearly separated, and in any case it is out of the question, as has already been attempted, to express the total efficiency of a heat pump as the product of individual efficiencies, where the latter take into account the effect of the heat exchanger, of the process, of the working medium and of the efficiency of the machine.

It is, of course, always possible in any particular case to determine for instance the effect of the efficiency of the compressor used on the coefficient of performance of the heat pump and to express this effect by a numerical factor. The factor thus obtained does not, however, represent numerically the efficiency of the compressor, and for the same compressor it may assume different values, according to circumstances. The same applies to the other individual factors; in each concrete case, numerical values may be given; they have, however, neither practical value nor physical meaning.

Only by the aid of certain assumptions is it possible to visualize clearly the effect of the above-mentioned conditions. It must, however, always be borne in mind that the considerable simplifications as to the variations of temperature and of the process thus assumed, do not apply in reality. The art of the engineer consists in overcoming or considerably minimizing the deficiencies of the simple processes by suitable measures. In the following, therefore, only the effect of the different conditions is shown in quite a general way.

(a) *Temperature Drop in the Heat Exchangers.*

Let T_0 = lower temperature.
T_1 = upper temperature.
δT_0 = temperature drop in the evaporator.
δT_1 = temperature drop in the condenser.
$\Delta T = T_1 - T_0$ = temperature difference to be overcome.

The theoretical coefficients of performance according to Carnot are:

$$\varepsilon_{th\,K} = -\frac{T_0}{\Delta T} \text{ for the refrigerator.}$$

$$\varepsilon_{th\,H} = +\frac{T_1}{\Delta T} \text{ for the heating machine.}$$

The temperature drop at the heat exchangers causes the temperatures to be displaced; the heat pump must in reality work under the following conditions:—

$T_0 - \delta T_0$ = lower temperature
$T_1 + \delta T_1$ = upper temperature
$\Delta T + \delta T_0 + \delta T_1$ = temperature difference to be overcome

and the corresponding coefficients of performance of an ideal machine are

$$\varepsilon_{1K} = -\frac{T_0 - \delta T_0}{\Delta T + \delta T_0 + \delta T_1} \text{ for the refrigerator}$$

$$\varepsilon_{1H} = +\frac{T_1 + \delta T_1}{\Delta T + \delta T_0 + \delta T_1} \text{ for the heating machine,}$$

from which it follows:

$$\frac{\varepsilon_{1K}}{\varepsilon_{th\,K}} = \frac{\Delta T}{\Delta T + \delta T_0 + \delta T_1}\left(1 - \frac{\delta T_0}{T_0}\right) \text{for the refrigerator}$$

$$\frac{\varepsilon_{1H}}{\varepsilon_{th\,H}} = \frac{\Delta T}{\Delta T + \delta T_0 + \delta T_1}\left(1 + \frac{\delta T_1}{T_1}\right) \text{for the heating machine.}$$

A temperature drop δT_0 at the lower temperature is therefore always more harmful than a temperature drop δT_1 of the same magnitude at the higher temperature.

(b) *Effect of the Process and of the Working Medium.*

Fundamentally, all reversible processes are equivalent, independently of the working medium used. As soon, however, as the cycle becomes irreversible, the working medium has an effect on the coefficient of performance, depending on the process chosen.

1. In the case of steam heat pumps it is usual to base on the following simple process in order to illustrate the effect of the working medium: The working medium is completely evaporated at the lower temperature, the dry-saturated steam is compressed adiabatically to such a pressure that it condenses at the higher temperature. The boiling condensate is then throttled to the pressure of the evaporator.

This process is imperfect in two respects. During the adiabatic compression the steam is heated to a higher temperature than that at which the heat is given up and hence the work of compression is uselessly increased; by the throttling of the boiling condensate a large amount of expansion work is lost, increasing with the degree of evaporation during the throttling. In reality the compressor, therefore, is cooled or working media are employed which have a high molecular weight and a high specific heat in the steam condition, and which therefore become less heated during compression. The condensate is, wherever possible, cooled below the boiling point and is expanded or throttled in stages. The simplified process, therefore, gives a deformed and exaggerated picture of the effect of different working media.

Let

L_V = the ideal work of compression, that is adiabatic to the higher temperature, then isothermal to the condenser pressure,

L_E = the ideal work of expansion of the boiling condensate,

Q_0 = ideal amount of heat taken up,

L_{1V} = the theoretical work of compression during adiabatic compression to condenser pressure,

$\alpha_V = L_V / L_{1V} < 1$,

then for the ideal process

$$\varepsilon_{1K} = -\frac{Q_0/A}{L_V - L_E} \quad \text{for the refrigerator}$$

$$\varepsilon_{1H} = +\frac{Q_0/A}{L_V - L_E} + 1 \text{ for the heating machine}$$

and for the chosen comparison process

$$\varepsilon_{2K} = -\frac{Q_0/A - L_E}{L} \quad \text{for the refrigerator}$$

$$\varepsilon_{2H} = \frac{Q_0/A - L_E}{L_{1V}} + 1 \text{ for the heating machine}$$

and upon rearrangement

$$\varepsilon_{2K} = \alpha_V\left\{\varepsilon_{1K} - (\varepsilon_{1K} - 1)\frac{L_E}{L_V}\right\}$$

$$\varepsilon_{2H} = \alpha_V\left\{(\varepsilon_{1H} - 1) - \varepsilon_{1H}\frac{L_E}{L_V}\right\} + 1$$

Therefore those working media are advantageous for which the ratio L_E/L_V is small, that is, having a high latent heat of evaporation and a low specific heat in the liquid state. In the steam state a high specific heat is desirable in order that α_V may be as large as possible. These conditions are partially contradictory; in general working media with a high molecular weight are to be preferred.

As can be seen, the effect of the working medium on the coefficient of performance also depends on the level of the temperature and on the temperature difference to be overcome. A generally valid "working substance efficiency" or "process efficiency" does not exist; only for certain definite conditions is it possible to give numerical values for each individual case.

2. With gas heat pumps, for practical reasons, the heat is also supplied and abstracted at constant pressure. As, however, no evaporation and liquefaction takes place, the temperatures do *not* remain constant, and the heat is taken in at increasing temperature

and given out at decreasing temperature. If the Carnot efficiency is calculated on the basis of the extreme temperature limits, a poor value is obtained; but in most cases heat pumps serve to cool or to heat some substance, in other words, the heat transfer is not required to take place at constant temperature. Hence, if the temperature variation of the heat pump is adapted to the requirements and counter-flow heat exchangers are used, gas heat pumps may also operate favourably, in spite of the fact that at first sight the entropy diagram appears to be less advantageous.

(c) *Effect of the Efficiencies of the Compression and Expansion.*

Let

L_{1V} = theoretical work of compression.

L_{1E} = theoretical work of expansion of the chosen process.

η_V = adiabatic efficiency of the compressor.

η_E = adiabatic efficiency of the expansion machine.

Then the coefficient of performance becomes

$$\varepsilon_{3K} = -\frac{Q_0/A - (L_E - L_{1E}\cdot\eta_E)}{L_{1V}/_V - L_E\cdot\eta_E} \quad \text{for the refrigerator}$$

$$\varepsilon_{3H} = \frac{Q_0/A - (L_E - L_{1E}\cdot\eta_E)}{L_{1V}/_V - L_E\cdot\eta_E} + 1 \quad \text{for the heating machine,}$$

from which it follows after re-arrangement

$$\frac{\varepsilon_{3K}}{\varepsilon_{2K}} = \frac{L_{1V} - L_{1E}}{L_{1V}/\eta_V - L_{1E}\cdot\eta_E}\left\{1 + \frac{1-\eta_E}{\varepsilon_{2K}}\cdot\frac{L_{1E}}{L_{1V} - L_{1E}}\right\}$$

for the refrigerator

$$\frac{\varepsilon_{3H}}{\varepsilon_{2H}} = \frac{L_{1V} - L_{1E}}{L_{1V}/\eta_V - L_{1E}\cdot\eta_E}\left\{1 + \frac{1/\eta_V - 1}{\varepsilon_{2H}}\cdot\frac{L_{1V}}{L_{1V} - L_{1E}}\right\}$$

for the heating machine

Now here:

$$(L_{1V} - L_{1E})/(L_{1V}/\eta_V - L_{1E}\cdot\eta_E) = \eta_M$$

is directly the efficiency of the machinery installation, and after further re-arrangement we obtain

$$\varepsilon_{3K} = \eta_M\left\{\varepsilon_{2K} + (1-\eta_E)\frac{L_{1E}}{L_{1V} - L_{1E}}\right\} \quad \text{for the refrigerator}$$

$$\varepsilon_{3H} = \eta_M\left\{\varepsilon_{2H} + \left(\frac{1}{\eta_V} - 1\right)\frac{L_{1V}}{L_{1V} - L_{1E}}\right\} \quad \text{for the heating machine.}$$

If we take as an example the simplified process of a steam heat pump described in the previous chapter, then *for this process* $\eta_M = \eta_V$ and $L_{1E} = 0$, therefore

$$\varepsilon_{3K} = \eta_V\cdot\varepsilon_{2K} \quad \text{for the refrigerator}$$

$$\varepsilon_{3H} = \eta_V\cdot\varepsilon_{2H} + (1 - \eta_V) \quad \text{for the heating machine.}$$

In the case of this simplified process it is therefore possible to introduce the adiabatic efficiency of the compressor as a simple factor in the calculation of the refrigerator. Even for the simplest of heating machines this is, however, no longer admissible.

(MS 936) *A. Meldahl. (Hv.)*

THE THERMO-COMPRESSOR INSTALLATION IN LUCENS FOR THE CONCENTRATION OF MILK.

Decimal Index 621.181.63 : 637.142

The article describes a thermo-compressor installation for the concentration of milk enabling an evaporation of 15·25 kg per kWh to be attained.

A. GENERAL.

THERMO-COMPRESSORS for the concentration of solutions belong to the domain of heat pumps which have been used already for several decades for refrigerating as well as for heating purposes.

The thermo-compressor is a heating machine, the use of which is particularly advantageous for the recuperation of heat in concentrating plants. The exhaust heat contained in the steam is recuperated by compression to a higher pressure for heating the evaporator. The heat quantities involved in such concentrating installations are usually large, and by means of the apparatus described, it is possible to recuperate this heat, so that the saving in fuel thus achieved is of considerable economical importance.

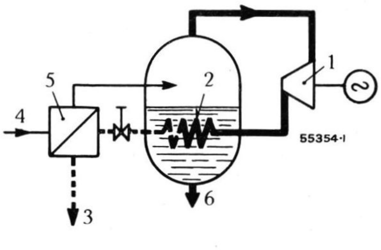


Fig. 1. — Concentrating plant with thermo-compression.

1. Vapour compressor
2. Heating coil
3. Condensate
4. Dilute solution
5. Preheater
6. Concentrated solution

By making the heating surface large, the temperature difference between the boiling and the heating temperature and hence the consumption of electrical energy may be kept small.

Fig. 1 shows the fundamental diagram of such a thermo-compressor plant. The electrically driven vapour compressor pumps the distilled steam into the heating coil 2 of the cooker, where it is cooled and gives up its latent heat of evaporation during liquefaction. The condensate leaving at 3 can advantageously be used to preheat the dilute solution 4 in a heat exchanger 5, thereby making the heat recuperation complete. The amount of driving power required depends on the difference between the heating and the boiling temperatures, which by liberally dimensioning the heating surface 2 may be kept so small that it remains between the limits of 15—25° C. With such temperature differences the evaporation factor is of the order of 15—25, that is, the energy absorbed by the driving motor of the thermo-compressor is from 10—17 times smaller than that of an electric boiler required to achieve the same result. It is, therefore, easy to understand that the thermo-compressor is employed not only in industry for concentrating all sorts of solutions, but also that it has recently found application for the concentration of agricultural products, such as milk, fruit juices, etc.

B. THE LUCENS INSTALLATION.

The Lucens cheese factory of the Fédération Laitière Vaudoise-Fribourgoise gave us the opportunity of installing a thermo-compressor for the concentration of milk.

The installation was planned and supplied by the Aluminium Welding Works of Schlieren, as general contractors, with the collaboration of the technical office of J. Krieg, Zurich. The plant, erected in the centre of a rich milk producing region, was put into service in August, 1942.

The milk production of Switzerland of over $2^1/_2$ million tons per annum is so irregularly distributed over the year, that a large part has to be converted into butter and cheese.

For the manufacture of high-quality butter, the cream is removed by means of centrifugal separators. The remaining skimmed milk was in previous years used as a dairy by-product for feeding cattle, or was even allowed to run off into the drain system. Already at an early date attempts were made to find a technically renumerative use for the skimmed milk. This is, however, only possible if the manufacturing costs of the products obtained do not exceed the world market prices. As, however, all products necessitate the reduction of the water content, even when dried milk is not the final product, all manufacturing processes involved may be looked upon as concentration processes. By extracting the water, a dried, non-perishable and nourishing skimmed milk can be

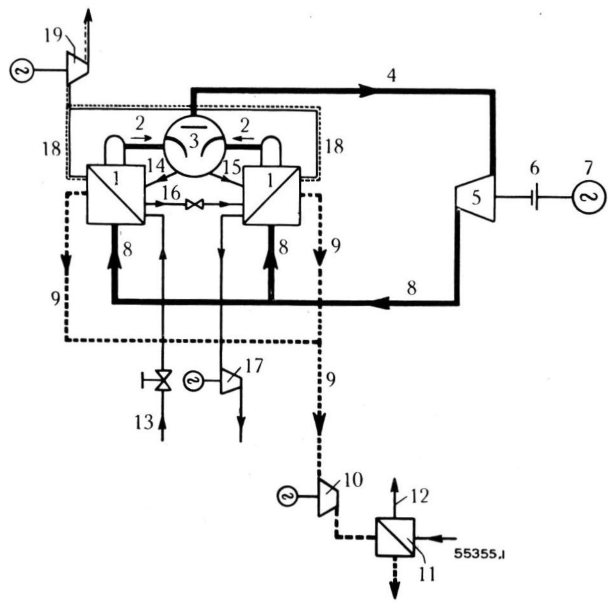


Fig. 2. — Diagram of the Lucens milk concentrating plant with thermo-compression.

1. Evaporator.	10. Condensate pump.
2. Vapour.	11. Recuperation of the condensate heat.
3. Moisture separator.	12. Heated process water.
4. Vapour pipe.	13. Dilute milk.
5. Compressor.	14. 15. Return from separator.
6. Reduction gear.	16. Connecting pipe.
7. Driving motor.	17. Concentrated milk pump.
8. Compressed vapour.	18. Air extraction.
9. Condensate.	19. Air pump.

Concentration is for many food products the best method of conservation. With thermo-compression no fuel and only electrical energy is necessary.

obtained, which may be used both in the foodstuffs industry and as fodder. The economics of the water extraction of the usual concentrating and drying installations depend mainly on the cost of fuel.

The manufacture of milk-sugar, in particular, is only possible with extremely low costs of concentration. This can be achieved with the distilled vapour heat pump, which at Lucens is used alternately by the special technical department for pasteurizing for recovering the albuminoids and the milk-sugar, and for concentrating skimmed milk. The quick circulating concentrating plant enables the milk to be concentrated into milk serum at temperatures below 60° C and with heat application times of maximum 30 minutes.

The subsequent drying of the concentrated skimmed milk is then effected in a vacuum drying oven, heated by circulation of hot condensate from the concentrating plant, which is further heated by fresh steam.

The Lucens installation is built for the following conditions:—

Hourly evaporation G	1000 kg/h
Power at the motor terminals . .	73 kW
Evaporation factor	13·7 kg/kWh

In practice the figures attained are:

	Dried milk manufacture	Milk-sugar manufacture
Quantity of skimmed milk or serum treated per hour	approx. 1500 kg	approx. 1200 kg
Concentration before treatment in parts by weight	9·5	4
Final concentration in parts by weight	65	72

Fig. 2 shows a diagram of the plant. The steam produced on the steam side of the two cookers 1—1 connected in parallel flows via the connection 2—2, the separator 3 and the connection 4 to the thermo-compressor 5. The moisture carried over with the steam is removed by centrifugal action in the separator 3 and returns by gravity via 14—15 back to the evaporators 1—1. The milk to be concentrated is fed by the connection 13 to the left-hand heated space 1, the heated space on the right is fed by the connection 16, that is, by the circulation in the left-hand heated space where a certain concentration is already present. The turbo-compressor 5 forces the compressed and superheated steam to the heating coil 1—1. The condensate pump 10, in the basement, delivers the condensate to atmosphere via the pipe 9, where the heat in the condensate serves for warming process water 12 in the exchanger 11.

The water-ring vacuum pump 19 serves to remove the air leaking into the vacuum system (pipes 18—18). The condensate pump 17 delivers the concentrated milk to atmosphere for further treatment for the recovery of the milk-sugar, which is periodically also effected with the heat pump.

The compressor 5 is driven by a three-phase induction motor 7 of 140 kW at 380 V, 50 cycles, 2936 r. p. m.

Fig. 3 shows the installation completely erected with the thermo-compressor set 3 in the foreground, and the two heaters 1—1 and the separator 2 in the background.

C. TEST RESULTS.

The results of the service tests carried out on site with mercury columns and calibrated thermometers exceeded the specified performance of the set in regard to the amount of water evaporated per hour and the guaranteed concentration, as well as in regard to the specific energy consumption.

A few figures taken from these tests are given below:

Hourly evaporation of water	1370 kg/h
Power at the motor terminals	89·8 kW
Concentration before evaporation about	4 % dry content
Concentration after evaporation	70 % dry content
Evaporation figure	15·25 kg/kWh

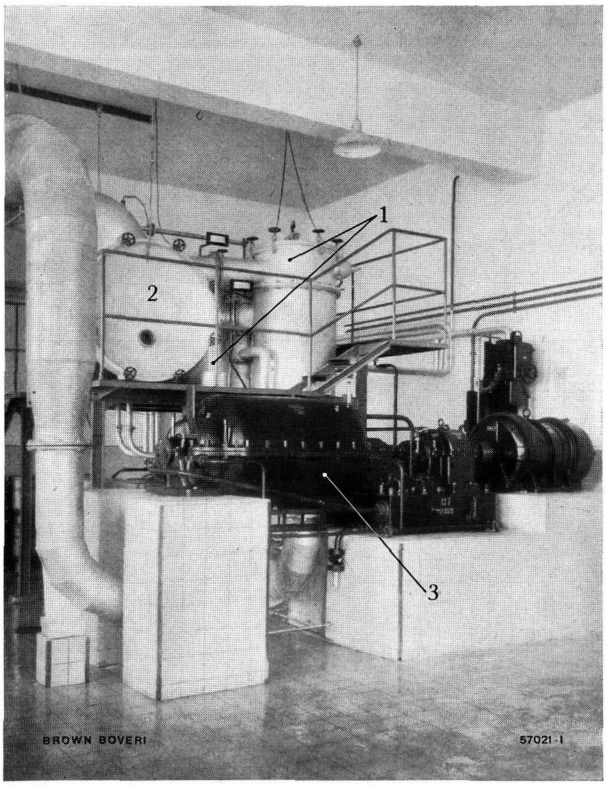


Fig. 3. — The Lucens milk concentrating plant with thermo-compression as installed.

1. Evaporator 2. Moisture separator 3. Thermo-compressor

With this apparatus — evaporator and drip separator — strongly foaming solutions may be concentrated with small energy consumption without danger of fouling the thermo-compressor.

The adjustment of the installation was effected in a relatively short time. The method of starting and the choice of suitable pressure conditions enabled the strong tendency to foaming to be overcome. An effective separator protects the compressor from entrained moisture.

In the planning of concentration installations using heat pumps, careful calculation of the heat and temperature balance is essential. Whereas with direct heating about 600 kcal are consumed for every kilogram of water to be extracted, a heat equivalent of only about 60 kcal/kg has to be supplied from the external source. Mistakes in the heat balance therefore show up tenfold in the latter case.

A thermo-compressor installation has also been acquired by the Nordostschweizerische Milchgenossenschaft, Winterthur, for concentrating milk, as well as fruit and grape juice, in their plant at Uster. This installation was also planned and supplied by the Aluminium Welding Works of Schlieren with the assistance of the technical office of J. Krieg, Zurich, and operates to the entire satisfaction of all concerned. The thermo-compressor set was supplied by us.

(MS 910) *Ad. Baumann. (Hv.)*

A LARGE EXTRACTION TURBINE FOR AN OUTPUT OF 20,000 KW IN A FRENCH INDUSTRIAL PLANT.

Decimal Index 621.165—172

The article describes the power plant of a large paper mill, and reference is made to the special devices for maintaining the frequency constant. The modernisation of this plant enables a considerable amount of fuel to be saved.

THE initiative of the Swiss Holding Co., "A.-G. für Unternehmung der Papierindustrie St. Moritz" led in the year 1928 to the foundation of the Papeteries de la Chapelle S. A. at St. Etienne du Rouvray in France, which has specialized in the production of newspaper. Fig. 1 shows the plant in its present state.

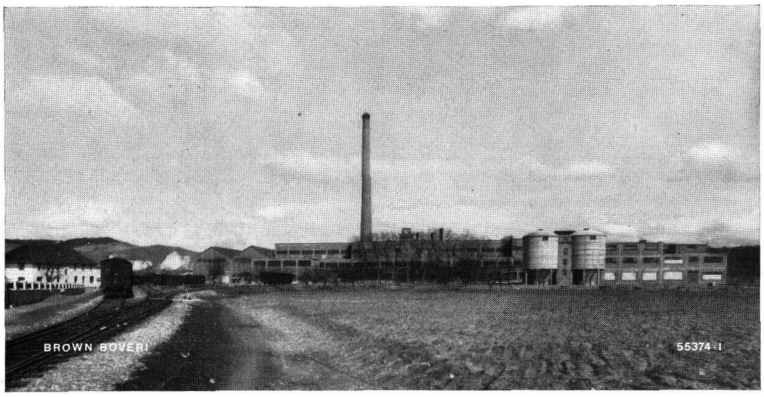


Fig. 1. — General view of the paper mill.
In normal times the daily production of newspaper is 300,000 kg.

All the energy required is generated in a private power station by means of turbo-sets, which, together with the entire remaining electrical equipment for the drive of the mill were supplied by Brown Boveri and their French concessionary, the Compagnie Electro-Mécanique, Paris. The customer has expressed his satisfaction with the Brown Boveri equipment by placing the following orders:—

In the year 1929 a back-pressure turbo-set for 2500 kW at 30 kg/cm^2 abs, 375^0 C and 2·75 kg/cm^2 abs back-pressure, as well as two condensing turbo-sets, each of 4000 kW output.

In the year 1933 a second back-pressure set of the same type and a condensing set for 9000 kW.

In the year 1937 a 22,000 kW extraction turbo-set, which was put into operation shortly before the outbreak of the war, and is described below. At the time of order this was probably the largest extraction turbine with regulated extraction pressure to be built on the European continent.

Fig. 2 shows a view of the engine room. The two 2500 kW back-pressure turbo-sets are in the foreground. These are 3000 r. p. m. machines directly coupled to single-cylinder turbines. Then follow the two 4000 kW and the one 9000 kW condensing turbo-sets, the 22,000 kW extraction set being at the end of the room. The four last units are two-cylinder turbines. It is worthy of note that in spite of the considerable increase in output the dimensions of the set have altered only slightly, while on the other hand the 22,000 kW turbo-set has enabled a considerable improvement in the efficiency of the plant to be obtained.

The steam pressure of the new 22,000 kW turbine is the same as that of the sets previously supplied, namely 31 kg/cm^2 abs; the live steam temperature, however, was raised by modifications in the boiler house to 410^0 C at the turbine inlet. The process steam pressure was fixed by the customer at

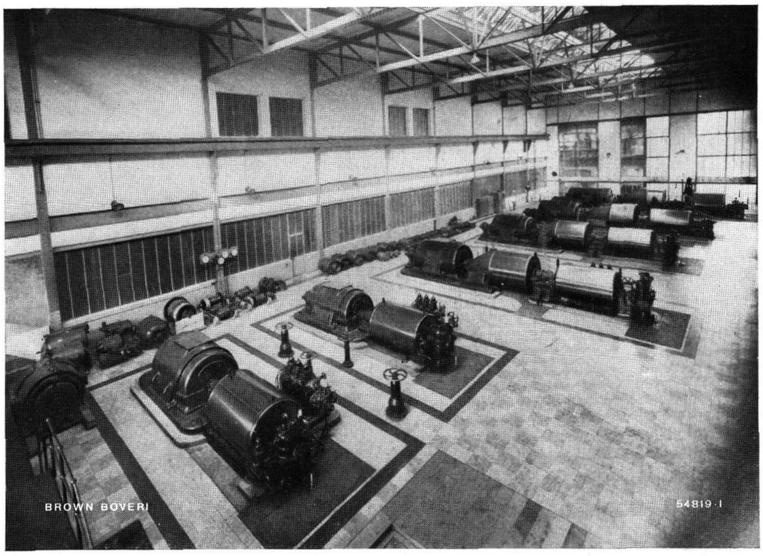


Fig. 2. — General view of the machine room, with six turbo-sets all of which were supplied by Brown Boveri.

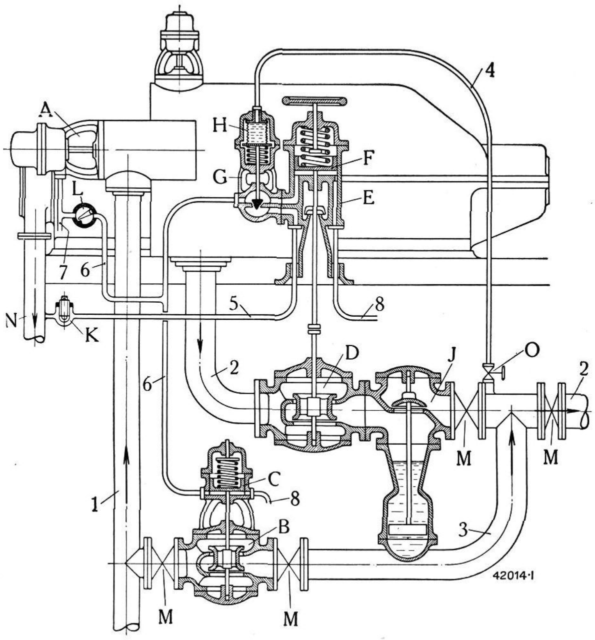


Fig. 3. — Oil pressure regulating system for an extraction turbine with an uncontrolled extraction point and with a live-steam reducing valve.

A. Emergency stop valve.
B. Live-steam reducing valve.
C. Servo-motor for B.
D. Pressure regulating valve.
E. Control for D.
F. Servo-motor for E.
G. Pressure regulator.
H. Diaphragm for G.
J. Non-return valve.
K. Adjusting screw.
L. Non-return valve.
M. Stop valve.
N. Oil pump delivery.
O. Stop valve.

1. Live steam pipe.
2. Extraction pipe.
3. Live steam by-pass pipe.
4. Impulse connection to G.
5. Pressure oil from the pump.
6. Pressure oil from G to B and L.
7. To the starting and tripping device.
8. Oil return to reservoir.

In this way it is possible to extract steam at a constant pressure from a standard condensing turbine.

$2 \cdot 5$ kg/cm^2 abs. with a maximum consumption of 52,000 kg/h. The cooling water is supplied by a private pump station on the Seine, which flows about 500 m distance from the station. The turbine had to be so designed that, when the plant is extended at a later date, up to 20 t/h of process steam can be extracted at a higher pressure of 9 kg/cm^2 abs. A non-controlled auxiliary extraction point was specified, which, however, for the time being is not used. A controlled extraction point always results in a certain pressure loss and hence in a reduction of the efficiency. This second extraction point is located in the wheel chamber, and the distribution of the heat drop is so arranged that even at $^1/_4$ load and with 20 tons of steam extracted per hour the pressure of 9 kg/cm^2 abs can be maintained. At higher loads the pressure at the extraction point increases accordingly. In case the pressure has to be limited to 9 kg/cm^2 abs, a so-called auxiliary extraction point control, in accordance with Fig. 3, can be installed. This is connected to the oil pressure governing system of the turbine, but operates entirely independently and does not affect the turbine governing in any way. This auxiliary extraction point control comprises mainly the oil-pressure operated steam reducing valve D, which is controlled by the pressure regulator G, and the non-return valve J, which serves to prevent the turbine from running away due to steam returning through the extraction pipe.

The 22,000 kW extraction turbine supplied is illustrated in section in Fig. 4. It is a modern design of a two-cylinder machine. It differs from the standard Brown Boveri two-cylinder condensing turbine design in that both the high pressure and the low pressure rotors are provided with dummy pistons. The reaction blading causes an axial thrust to be set up which is proportional to the quantity of steam passing. In the two-cylinder design of turbine the thrusts of the two rotors are opposed to each other, and as in the case of a standard condensing turbine the steam quantities flowing through the high and low pressure cylinders are practically the same, the two thrusts balance each other. Small differences are taken up by the thrust bearing. In the case of an extraction turbine the two quantities may, due to the steam extracted, differ considerably, which makes dummy pistons necessary to enable the resulting thrusts to be compensated in each cylinder separately.

The pressure difference acting on the dummy piston increases with the load. As can be seen from Fig. 4, in the case of the high-pressure cylinder the outer surface is in communication with the exhaust, that is to say, the piston is always subjected to the pressure difference existing between the wheel chamber and the $2 \cdot 5$ kg/cm^2 extraction point. The space on the

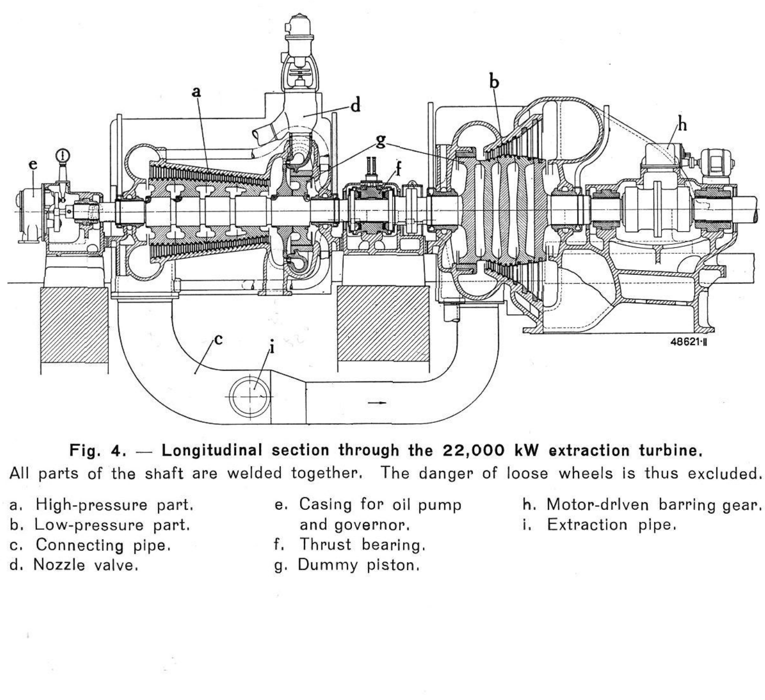


Fig. 4. — Longitudinal section through the 22,000 kW extraction turbine.
All parts of the shaft are welded together. The danger of loose wheels is thus excluded.

a. High-pressure part.
b. Low-pressure part.
c. Connecting pipe.
d. Nozzle valve.
e. Casing for oil pump and governor.
f. Thrust bearing.
g. Dummy piston.
h. Motor-driven barring gear.
i. Extraction pipe.

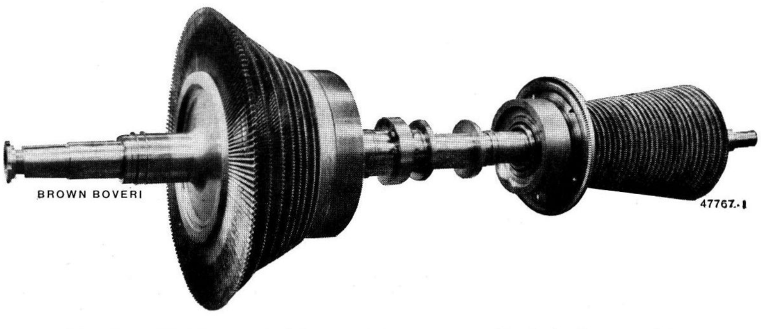


Fig. 5. — Rigidly coupled h. p. and l. p. rotors with their dummy piston.

The thrust bearing is in the centre and allows a free expansion of the shafts in both directions.

outer side of the low-pressure piston is in direct communication with the exhaust chamber of the cylinder and is therefore always under vacuum. In order to keep the losses small, the pistons are provided at their periphery with special labyrinth packings with axial and radial throttling clearances. The two shaft glands of the high-pressure cylinder must seal a pressure of 2·5 kg/cm^2 abs against atmosphere, that is to say the high-pressure gland is subjected to a lower pressure than in the case of a turbine without dummy piston. The shaft glands at both ends of the low-pressure cylinder seal against vacuum, and are therefore supplied with sealing steam from a steam chest so regulated as always to allow a small amount of steam to escape from the vents. Fig. 5 shows the two rotors with the dummy pistons. The rotors are rigidly coupled together and the collar of the thrust bearing can also be seen. The fixed point is located between the two cylinders, from where both shafts and casings can expand freely.

The steam capacity of the high-pressure cylinder is 130 tons/hour. In this cylinder the steam is expanded

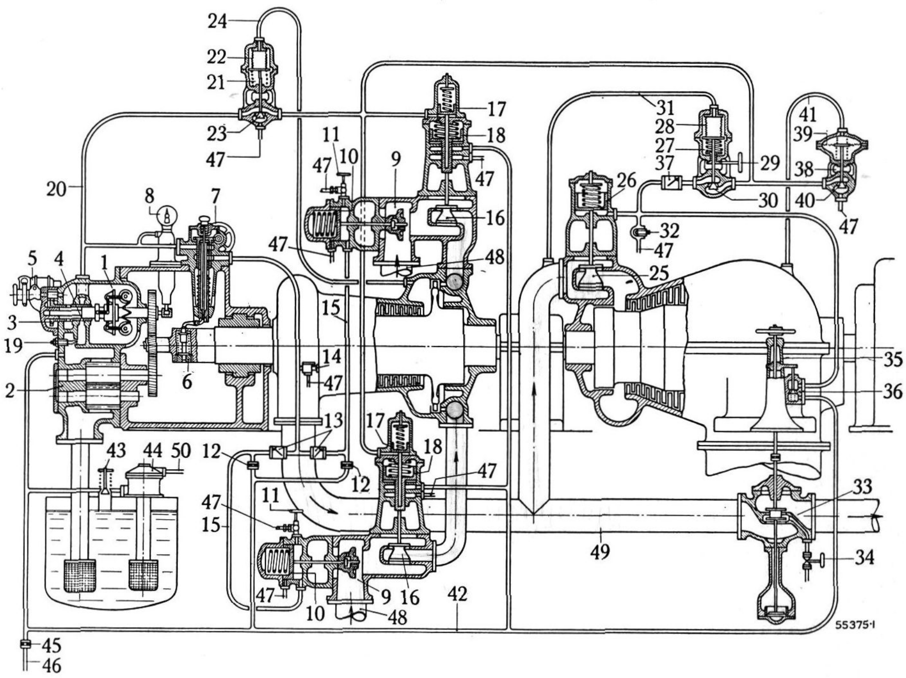


Fig. 6. — Diagram of the turbine governing system.

The steam is extracted at a constant pressure between the h. p. and l. p. cylinders and is independent of the load. For this reason the remaining steam flows through two regulating valves to the low-pressure cylinder.

1. Speed regulator.
2. Main oil pump.
3. Oil regulating sleeve.
4. Oil regulating port.
5. Speed adjusting device.
6. Emergency governor.
7. Starting and tripping device.
8. Tachometer and impulse imparting device.
9. Emergency stop valve.
10. Servo-motors for 9.
11. Test valves for 9.
12. Orifice plates for 9.
13. Non-return valves for 9.
14. Test valve for governing system.
15. Emergency trip oil system.
16. Live steam inlet valve.
17. Relay valve for 16.
18. Servo-motor for 16.
19. Adjusting screw.
20. Oil pressure system for 16.
21. Pressure limiter for wheel chamber.
22. Diaphragm for 21.
23. Control valve for 21.
24. Impulse connection for 21.
25. Regulating valve.
26. Servo-motor for 25.
27. Extraction pressure regulator.
28. Diaphragm for 27.
29. Pressure adjusting device for 27.
30. Control valve for 27.
31. Impulse connection for 27.
32. Outlet throttle.
33. Non-return valve.
34. Vent valve.
35. Stand with operating gear for 33.
36. Oil change-over valve.
37. Non-return valve.
38. Vacuum limiter.
39. Diaphragm for 38.
40. Control valve for 38.
41. Impulse connection for 38.
42. Pressure-oil system.
43. Pressure retaining valve.
44. Auxiliary oil pump.
45. Bearing oil orifice plate.
46. To the bearings.
47. Oil outlet.
48. Live steam valve.
49. Extraction pipe.
50. Steam pipe to 44.

to the extraction pressure of 2·5 kg/cm² abs, at which point a quantity of up to 52 t/h is diverted to the factory. The low-pressure cylinder is accordingly designed for approximately 70 tons of steam per hour. The high-pressure steam is fed to the turbine through two main stop valves (emergency stop valves), arranged on the left and right of the lower casing half. Each emergency stop valve feeds two nozzle or regulating valves, one next to the main stop valve, and one on the top of the cylinder. There are, therefore, four unthrottled inlet steam quantities, so that the throttling losses are reduced to a minimum. Fig. 4 shows a nozzle valve mounted on the high-pressure cylinder. The live steam is led through the nozzle box into the turbine, where it expands in the nozzles to strike on a single-row impulse wheel. It is only then that the steam comes into contact with the cast steel casing of the high-pressure cylinder.

As already mentioned, an extraction pipe for a quantity of 70 tons of steam per hour at a pressure of 9 kg/cm² abs can be connected to the wheel chamber. Nozzle boxes as well as the valve casings for the live steam are of high temperature molybdenum steel. The steam at 2·5 kg/cm² abs, which is not extracted, flows on from the high-pressure to the low-pressure cylinder through the regulating valves arranged laterally on the lower half of the casing.

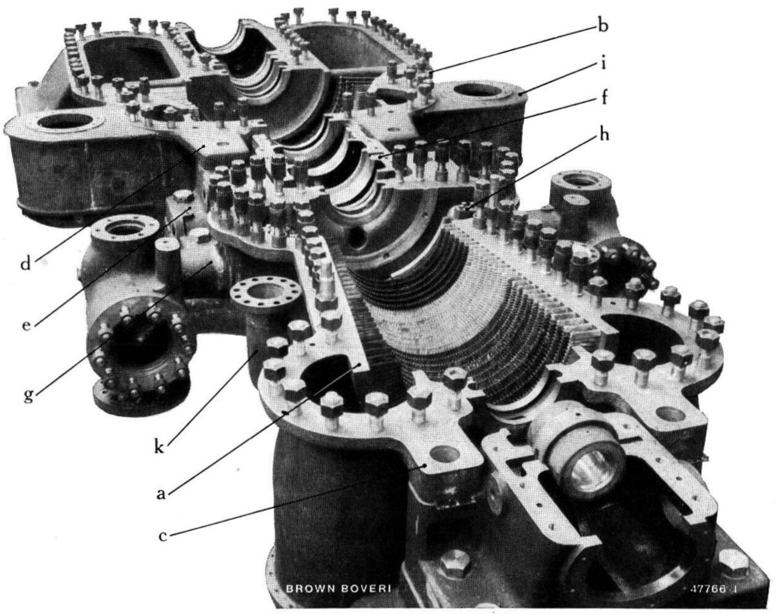


Fig. 7. — High- and low-pressure lower casing half.

The valve chests of the main stop valve are welded to the casing, while the regulating valve chests are cast in one piece with the casing; in this manner the number of flanges are reduced to a minimum. The horizontal separating flange of the two casings has liberally and carefully dimensioned bolts to avoid any leakage.

a. High-pressure part.
b. Low-pressure part.
c. High-pressure supporting feet.
d. Low-pressure supporting feet.
e. Bearing pedestal between high- and low-pressure cylinder.
f. Lower part of casing of thrust bearing.
g. Weld with joint of a valve chest.
h. Nozzle boxes.
i. Regulating valve casings.
k. Live steam pipe to an upper nozzle valve.

Fig. 6 shows a diagram of the governing system. The live steam valves 16 are relay controlled, i. e., the relay piston 17 controls the power piston 18. The governing oil actuates, therefore, only the relatively small relay piston 17, so that the impulses received from the governor are quickly transmitted. The pressure regulator 27 which controls the regulating valves 25 is connected in series with the power piston 26. If, for instance, at constant load the extraction quantity increases, the steam pressure before the low-pressure cylinder begins to fall. The pressure regulator then causes the oil supply to the regulating valves to be throttled, which close slightly; at the same time it increases the oil pressure under the relay piston 17, causing the inlet valves to open. The speed regulator does not have to act, or at the most it has to compensate small differences of power only.

If the valve 33, provided with an operating stand and which is designed as a non-return valve, is closed, all regulating valves receive the full oil pressure and open fully, that is, the turbine operates as a pure condensing machine. It is worth noting that the pressure limiters 21 and 38, the first on the high-pressure cylinder and the second on the low-pressure cylinder, protect the machine from excessive internal pressure. As can be seen from the diagram, the governing oil system is connected to a small sleeve valve mounted on the tachometer shaft, so that the governing oil system is always subjected to small pulsations of pressure to prevent sticking of the valves. Particular care was also given to the question of the speed or frequency regulation.

The dummy piston of the high-pressure cylinder is mounted on the shaft by a lip weld (Fig. 4). The single-row impulse wheel and the drums of the reaction part are similarly mounted on the shaft. The low-pressure rotor has no through shaft, but for both the dummy piston and the reaction drums consists of a number of solid discs with a spigot joint at the periphery, all welded together. The machine has, therefore, two different types of Brown Boveri welded shafts. Both designs have their reasons and are patented. The lip welding enables the transmission of internal stresses to the shaft to be avoided. Residual stresses may be set up in the case of the low-pressure rotors, and for this reason these rotors are annealed after welding.

Fig. 7 shows the complete lower half of the casing of the turbine, in the foreground the high-pressure cylinder with the two readily distinguished lateral valve chests joined to it by welding, in the background the low-pressure cylinder with the integral cast valve chests for the regulation of the valves. Fig. 8 gives a general view of this 22,000 kW extraction turbo-set with the high-pressure cylinder on the left and the generator on the right in the background. The generator is built for an output of 27,500 kVA, 3150 V, 50 cycles. A Brown Boveri quick-acting regulator is connected in the shunt circuit of the exciter.

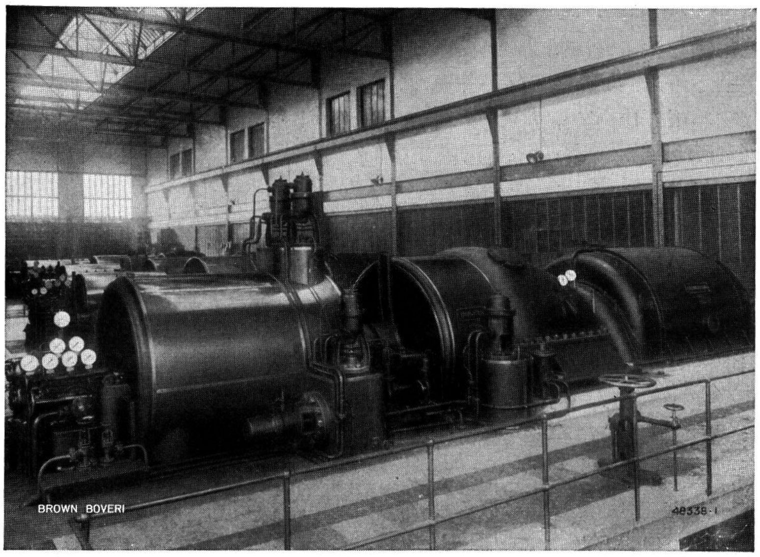


Fig. 8. — View of the 22,000 kW extraction turbo-set.
In spite of the many regulating devices the set is of neat design.
The regulating parts are easily accessible.

The generator voltage is low for such an output and the current correspondingly high. The machine switch must, therefore, handle the full-load current of 5000 A and be capable of dealing with the maximum peak closing current of 100,000 A. Sufficient space was not available for an oil circuit-breaker to satisfy these conditions, so that an air-blast circuit-breaker (Fig. 9) was used. This has, compared with the oil circuit-breaker, the advantage of greater safety against explosion and fire risks, as well as of a lower switching time and smaller contact wear.

The generator protecting gear is shown diagrammatically in Fig. 10. It protects the generator against practically all short-circuits between phases and against faults to earth. The special arrangement of the generator winding with two parallel windings per phase enables a cross differential relay to be used as a very effective protection against phase short circuits. A peculiarity is the method of connection of this relay to special current transformers with two primary windings, which are fed with current from the two winding systems circulating in opposite directions. The winding protecting relay is inserted in the connection between the two star points of the two parallel windings, and in which normally no current flows.

As the generator works directly on to the factory network, without the interposition of a transformer, the earth protecting gear must operate selectively, that is to say, on the occurrence of a fault between the casing and the generator winding, the generator must be immediately disconnected and the excitation cut off, whereas, if a fault occurs on the factory network, or on one of the machines operating in parallel, only an acoustic signalling device operates. The earthing resistance is connected to the busbars, so that the protective device may without any appreciable additional cost be extended to other machines or feeders.

Normally, over-current relays as well as an over-current limiter protect the machines against overload and external short circuits. As there is no question of operation in parallel with an external supply system, the well-known advantages of the current limiter may here be fully made use of. For supplying the larger

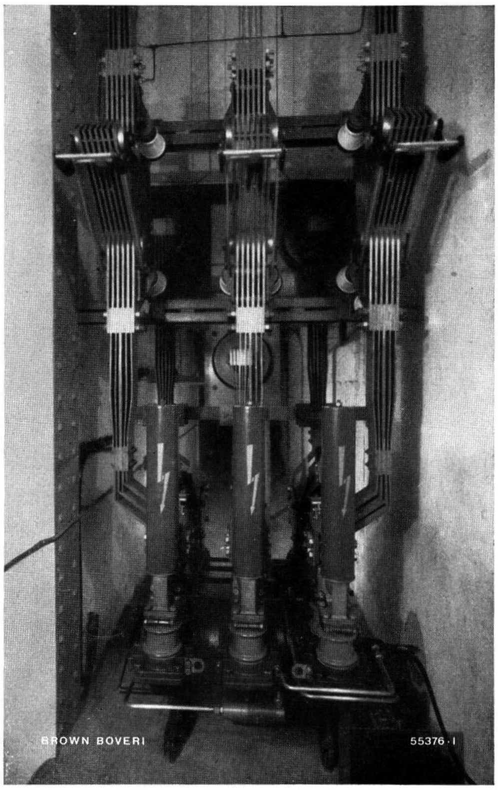


Fig. 9. — High-current air-blast circuit-breaker

for a normal current of 5000 A and a peak closing current of 100,000 A. The space-saving construction of this switch enabled it to be installed in a narrow passage under the turbine.

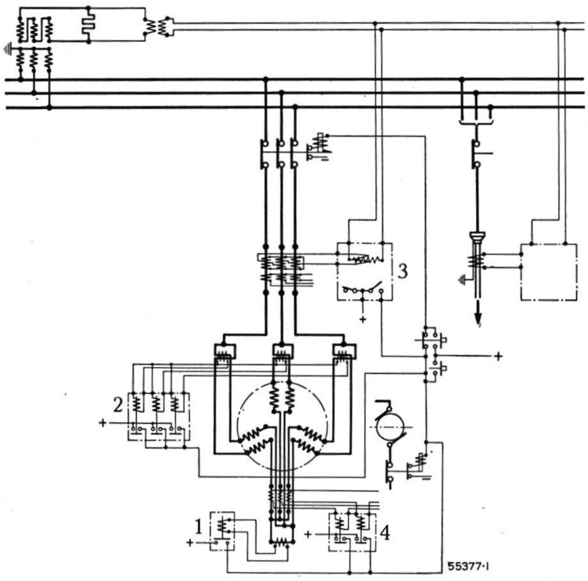


Fig. 10. — Diagram of the generator protecting gear.

1. Winding short-circuit relay.
2. Differential relay.
3. Earth-fault relay.
4. Overload relay.

These devices which partly overlap in their effect protect the generator against internal and external faults.

motors, such as, for instance, the twelve 1000 H. P. synchronous induction motors driving the wood grinders, the full generator voltage is used directly. Smaller motors are fed through transformers at 500 V. Fig. 11 shows diagrammatically the entire distribution system.

The speed of the paper machines must be accurately maintained within close limits and adjustable over a large range. The first stage of construction comprised

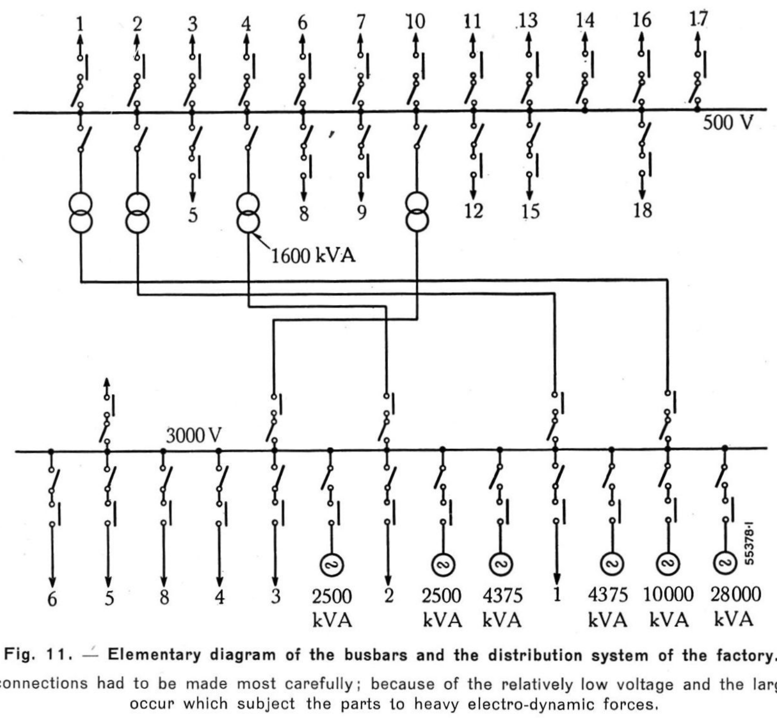


Fig. 11. — Elementary diagram of the busbars and the distribution system of the factory.

The busbars and the interconnections had to be made most carefully; because of the relatively low voltage and the large power, very high currents occur which subject the parts to heavy electro-dynamic forces.

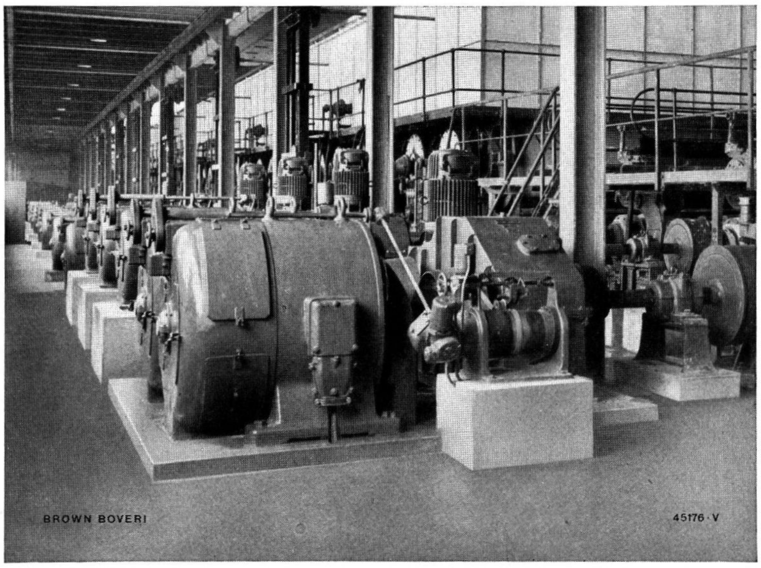


Fig. 12. — Paper-making machine No. 4 with sectional drive by means of shunt commutator motors.

A prove that such drives may be built for alternating current.

the installation of three high-speed newspaper machines of 3·6 m trimmed width, equipped with Brown Boveri sectional drive. Thanks to this drive it was possible to increase the working speed in the course of time from the value of 320 m/min. originally provided to approximately 350 m/min. In the year 1937 a paper-making machine of the same width, but of the most modern design, built for a maximum working speed of 500 m/min. was installed, and provided with a sectional drive, consisting of thirteen three-phase shunt commutator motors having a total power of 1400 kW (Fig. 12). With this drive also it is possible entirely to meet the difficult service requirements of the large high-speed paper-making machine. The pre-set working speed and the relative speed differences between the individual sets was maintained with the closest accuracy. It was thus possible to attain a working speed of 420 m/min., so that this machine represents the fastest paper-making machine in Europe. This very satisfactory result was largely contributed to by the excellent maintenance of the frequency of the supply network.

The 22,000 kW turbine is provided with the well-known Brown Boveri pressure-oil governing system, which maintains a permanent speed drop of 5 % between no load and full load, the momentary increase being somewhat greater. For this reason the turbine is provided with special isochronous frequency regulation. This frequency regulator (Fig. 13) operates on the turbine governor system through the medium of the speed adjusting motor and works on the impulse principle. The frequency regulator as well as other apparatus and instruments for the generators are mounted in a switchboard in the immediate neighbourhood of the set. The impulses from the frequency regulator are longer and more frequent, the greater the difference from the pre-set value. By means of the motor the regulating sleeve and hence the speed characteristic is displaced parallel to itself from the full load position n′ to the no-load position

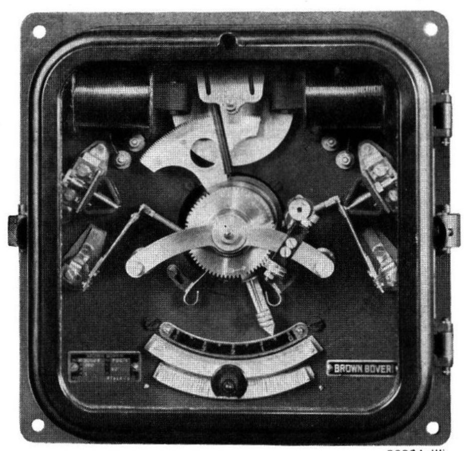


Fig. 13. — Frequency regulator.

In the form shown it controls the position of the sleeve on the turbine speed governor, so that the frequency is kept practically constant at all loads.

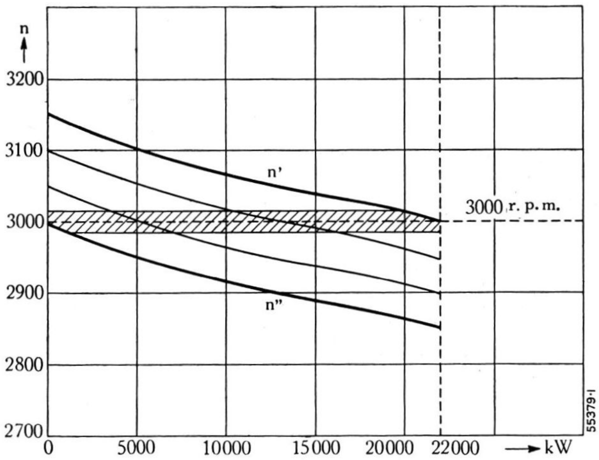


Fig. 14. — Speed characteristics of the turbine governing system with the regulating sleeves in different positions.

n′ Highest position at 22,000 kW.
n″ Lowest position on no-load.

Due to the control by the frequency regulator, the speed is kept within the shaded area for all changes of load.

n″ (Fig. 14), so that the speed is kept the same at all loads. The insensitivity is 0·05 %. The regulator operates so quickly that the greatest momentary variation of frequency does not exceed ± 0·3 %, the speed returning very quickly and without oscillation back to the pre-set value. If necessary, the impulse transmission may be speeded up by allowing the frequency regulator to control the pressure of the governing oil directly. Fig. 15 shows two examples of frequency diagrams taken on a recording frequency meter. The lower diagram was taken in April, 1939 at a time when the paper mill was operating at full load and the 22,000 kW set delivering approximately ¾ of its output. The variations of load were of the order of ± 5 %. As can be seen from the diagram and as confirmed by the readings of the frequency meter, the momentary variations of frequency do not exceed ± 0·15 cycle. The upper frequency diagram was taken in February, 1942 at a time when the load on the set hardly attained 40 % and variations of ± 350 kW took place during the course of a day. The maintenance of the frequency is here still more close and may be considered as perfectly isochronous.

Thanks to the good frequency regulation, the working speed of the paper-making machine could be raised to 420 m/min. for newspaper with small cellulose content (50 gr/m²), and at the same time the amount of waste reduced. To this has to be added the higher efficiency of the 22,000 kW turbo-set compared with the former operation, when several back-pressure and condensing turbines always had to operate in parallel. Before this innovation the customer reckoned with a consumption of 1·05 kg of coal per kg of paper. With a daily production of 300 tons of paper it was possible to reduce this consumption to 0·9 kg, representing a daily saving of coal of 50 tons.

(MS 830) *J. Broggi. (Hv.)*

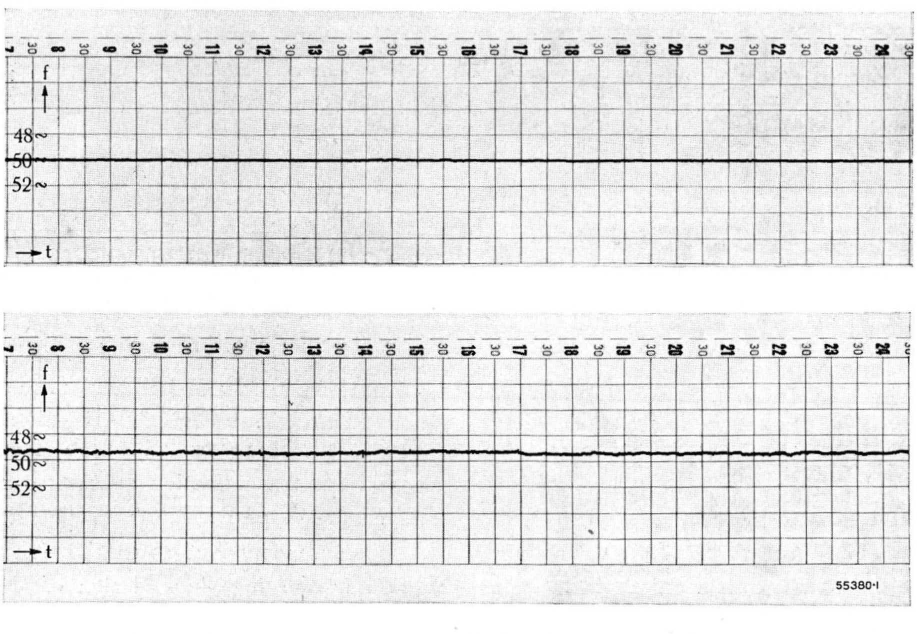


Fig. 15. — Tachograms of the turbine speed showing the effect of the frequency regulator.

Maximum deviation from the base frequency ± 0·15 cycles. f. Frequency. t. Time.
The upper diagram was taken on the 24th February, 1942, the lower diagram on 12th April, 1939.

PNEUMATIC AND MECHANICAL PROBLEMS IN CONNECTION WITH AIR-BLAST HIGH-SPEED CIRCUIT-BREAKERS.

Decimal Index: 621.316.57.064.45

In modern air-blast high-speed circuit-breakers the electrical engineer utilizes the advantages of compressed air which have been exploited by other branches of engineering for a long time past. Compressed air is made to serve both as arc extinguishing agent and high-speed, readily controlled and stored, power transmitting medium. A whole series of interesting problems of a pneumatic and mechanical nature arose in this connection and their solution has resulted in a considerable improvement in power station operating conditions due to the short rupturing times, elimination of explosion hazard, and convenient attendance.

Up till about a decade ago most electrical men knew little about compressed air. The advantages of this extremely adaptable working medium so long exploited in traction, mining, and excavation applications, however, were finally also recognized for electrical apparatus, and its introduction into the switchgear field not only for operating, but also for arc extinguishing purposes, brought a revolution in switchgear design. In one blow the cumbersome operating mechanisms with their thrusting action through power-storage springs, pawls, motors, etc., as well as the extinction liquid were eliminated. Lightweight operating pistons, small control valves, and simple switch chambers took their place, thus giving the circuit-breakers a high speed and making them reliable and easy to maintain.

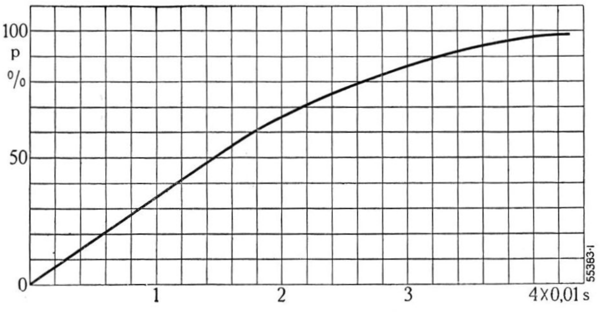


Fig. 1. — Pressure rise in a space of 1 litre capacity when filling with compressed air of p kg/cm² abs through an opening of 1 cm².

In circuit-breaker pneumatics filling phenomena play an important part. The curve facilitates their calculation, which, together with experimental development work, is necessary to achieve high-class apparatus.

Air-blast circuit-breakers are therefore just as much pneumatic as electrical apparatus and their designers must be experienced in both branches of engineering. As to operating engineers, they have quickly become familiar with the new type of switchgear.

A circuit-breaker is only dependable when it carries out all of its electrical, pneumatic, and mechanical functions with the same reliability. The complexity of the pneumatic and mechanical problems which had to be solved in connection with the air-blast high-speed circuit-breaker will be realized simply from their enumeration. The *pneumatic* problems concerned:

- Control of movement.
- Air blast for arc extinction purposes.
- Air conduits to, and passages in, the circuit-breaker.
- Storage of air in circuit-breaker and in compressed-air plant.
- Prevention of water deposits in circuit-breaker.

The *mechanical* problems arose in connection with the valves and arc extinction and isolating contacts, viz.:

- Acceleration processes.
- Impact control (damping devices, buffers, influence of shape on impact resistance).
- Lubricating conditions.
- Temperature effects.
- Reliability of outdoor circuit-breakers under conditions of snow and ice.

A number of these problems are gone into more closely hereafter.

I. SHORT RUPTURING TIMES.

The Brown Boveri air-blast high-speed circuit-breaker partly owes its short rupturing time — in many cases less than 0·05 sec. — to the splitting up of the breaks into arc extinction and isolating contacts. This arrangement, together with the favourable shape selected for the extinction contacts enables the mass and the travel of the latter to be kept small. Another feature contributing to the high speed of interruption is the ingenious design of the valves. The solenoid-operated valves to which the opening impulse is imparted, the intermediate (relay) valve, and the main valve which initiates the blast, are always con-

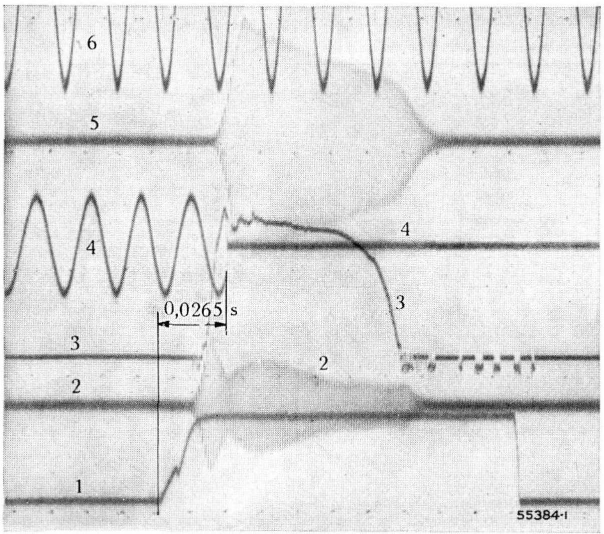


Fig. 2. — Oscillogram of pneumatic functions of a 10 kV, 400 MVA air-blast high-speed circuit-breaker.

1. Current in opening coil.
2. Opening pressure of main valve.
3. *Opening and reclosing* movements of main valve.
4. Auxiliary current across arc extinction contacts showing moment of opening.
5. Pressure in arc extinction chamber.
6. 50-cycle timing wave.

The pneumatic gear of this circuit-breaker operates so rapidly that the arc extinction contacts open 0·0265 sec. after the switching impulse is imparted. The rapid clearing of short circuits reduces their harmful effect.

nected in cascade and function in succession. The big reduction in valve times was achieved in a very simple manner, i. e., through correct mutual proportioning of the valves and their connecting ducts, substantial reduction of the moving masses, etc., which also led to a reduction of the percussive forces and, in consequence, to greater durability of the parts in question.

For the rapid operation of air-blast circuit-breakers the filling times of the cylinders, hollow spaces, etc., play an important part. From the curve in Fig. 1 the time necessary to fill any volume up to a certain pressure (given any air inlet cross-sections) can be readily determined.

The oscillogram of a 10 kV, 400 MVA air-blast high-speed circuit-breaker in Fig. 2 gives an example of the operation of the valves and contacts and their short operating times. In the *opening coil current*, trace 1, the kink represents the moment of attraction of the armature. Trace 2 shows the behaviour of the pressure above the piston of the main valve and trace 3 the motion of this valve. It will be seen that immediately after the functioning of the solenoid-operated valve (and of the relay valve) the opening pressure of the main air-blast valve rises rapidly and the latter is immediately accelerated. The speed of the piston increases so rapidly that the supply of compressed air cannot keep pace with the increase in volume in the cylinder, whereupon the pressure drops back and does not rise again until the end position is attained. Trace 5 shows the pressure cycle in the arc extinction chamber. This does not begin until a little after the initial valve movement, due to the time taken by the air to pass through the ducts. The pressure rapidly attains its maximum value and thereupon slowly falls back, due to the air leaving the receiver. The arc extinction contacts open when the pressure in the extinction chamber has reached a value of about 50 %, as shown by trace 4 for the auxiliary current through these contacts. Trace 6 represents a 50-cycle voltage as timing wave. The inherent mechanical operating time of the circuit-breaker in this diagram is 0·0265 sec. to which must also be added the duration of the arc of about 0·01 sec.

II. AIR FLOW CONDITIONS.

The velocity of air through valves, ducts, etc., is governed by the relation between the absolute inlet and outlet pressures; it does not exceed the velocity of sound. Fig. 3 shows the velocity of air at 20° C; it does not depend on the pressure and is proportional to the square root of the absolute temperature.

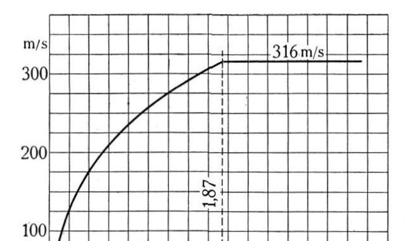


Fig. 3. — Velocity of compressed air through narrowest cross-sections at 20° C.

It never exceeds the velocity of sound, i. e., 316 metres/second, but attains it when $\frac{p_1}{p_2} = 1 \cdot 87$.

$$\frac{p_1}{p_2} = \frac{\text{Initial absolute pressure}}{\text{Final absolute pressure}} = \text{Expansion ratio.}$$

From the velocity the quantity of compressed air passing through openings, ducts, etc., can be calculated. The flow coefficients are obtained from a large amount of test material.

The drop in temperature accompanying adiabatic expansion, a phenomenon well-known from steam-engine practice, contributes to the rapid evacuation of spaces in valves, receivers, etc., the absolute temperature dropping as the 0·286 power of the pressure ratio.

In the course of the research work on the air blast for arc extinction purposes interesting and important information was obtained concerning the flow of air to the arc extinction chamber, through the hollow contact for the extinction process proper, and through the exhaust pipe. The question of the cooling and silencing of the exhaust was also investigated. Tests showed, for instance, that the shape of the air passages in the extinction chamber has quite a big influence on the switching capacity, whereas the form of the hollow contact is of less importance.

At present a large amount of experience is available concerning flow coefficients, most favourable passage forms, etc., of air ducts.

III. AIR DEHYDRATION.

Another problem was the elimination of the bane of all high-voltage equipment, i. e., condensation. Moisture is invariably present in the air supply to the compressor and is carried over into the compressed-air installation. The greater part (i. e., about

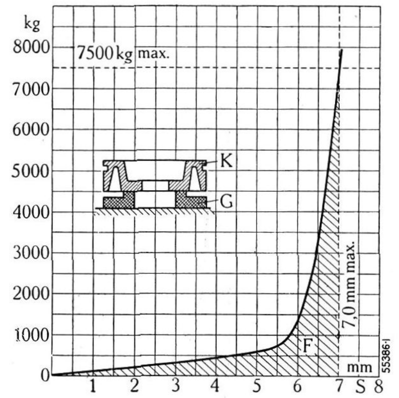


Fig. 4. — Compression characteristic of rubber buffer of main valve.

S. Compression path.
F. Hatched area = 600 cm/kg work of impact.
K. Valve piston.
G. Rubber buffer.

The maximum force of 7500 kg leads to dangerously high material stresses, thus showing that the buffer is incorrectly proportioned. Carefully selected and tried out impact damping devices are imperative if high-speed designs are to have a long life.

96 % of the water content, assuming a pressure of 25 kg/cm² g) is automatically condensed in the cooler and air receiver through the cooling of the hot compressed air. Although the compressed air only contains 4 % of the original water it is still 100 % saturated and will condense should the temperature drop. The condensation caused by temperature changes is avoided, for instance, by supplying the circuit-breaker at a gauge pressure of 15 kg/cm² through a reducing valve from the 25 kg/cm² g air receiver, whereby, due to the increase in volume of the air, the moisture is distributed throughout a greater space. This arrangement moreover conforms to standard practice, inasmuch as it greatly increases the store of air available. The air in the circuit-breaker then only has a humidity of about 60 %, and a drop in temperature of about 10° C will result in no condensation.

The same principle also enables insulators to be kept thoroughly dry inside. By scavenging them with a small quantity of compressed air interiors are obtained in which, with a compressor pressure of 25 kg/cm² g for instance, the relative humidity is only 4 %. Such insulators will therefore remain free from condensation even should the temperature drop by as much as 40° C, which is never likely to be the case.

IV. IMPACT CONTROL.

The increase in switching speed has rendered impact control more and more essential. Friction brakes, pneumatic damping devices, and frequently also rubber buffers have given good results, but great attention must be paid to their dimensioning. The example shown in Fig. 4 represents an investigation into the forces in the rubber buffers of a main valve, the work of impact being 600 cmkg, as determined from the mass and the impact speed. Although the impelling forces are only of the order of a few hundred kilograms the compression characteristic (the hatched part of which must equal the work of impact) involves a maximum force of 7500 kg and correspondingly high material stresses. By correctly proportioning the buffer the stressing has been reduced to a fraction of its original value. Continuous switching tests have proved the excellent effect of the improvements incorporated on the basis of these investigations.

Since a circuit-breaker must be able to withstand thousands of switching operations it is essential to shape all active parts so that shearing effects and local over-stressing will be avoided which from experience greatly impair creep strength.

Due to the ingenious solution of all of these problems the circuit-breakers now constructed rupture the heaviest short circuits in a few hundredths of a second, thus mitigating the effects of faults or, if the high-speed reclosing feature is provided, even rendering them entirely innocuous.

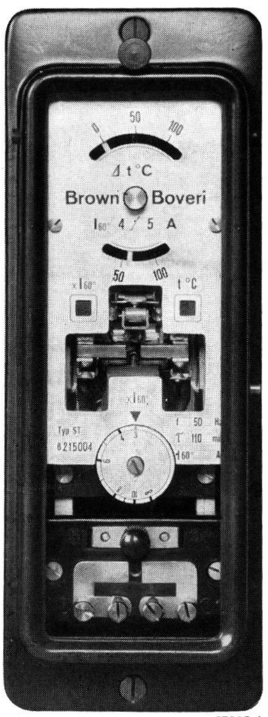
(MS 928) *G. Brühlmann. (E. G. W.)*

THE TYPE "ST" SECONDARY THERMAL RELAY.

Decimal Index 621.316.925.44

The type ST thermal relay for overload protection purposes enables installations to be efficiently exploited.

IT goes without saying that a high-class electrical machine is all the more efficient the longer it can operate without interruption. This period, however, depends to a great extent on the condition of the conductor insulation, which is the more quickly impaired the longer the maximum admissible temperature is continuously exceeded. In this respect, therefore, overload protection is tantamount to obviation of excessive temperatures in the conductors. Inasmuch as the temperature rises approximately as the square of the load current, only a slight continuous overload can lead to trouble in course of time. This is, moreover, the reason why over-current relays afford no real measure of overload protection. The safe overload capacity is therefore relatively restricted. On the other hand, a machine is all the more efficient the better it is utilized. Service overloads are permissible as long as the critical temperature limit is not exceeded. The only criterion is the temperature of the conductor which forms the hottest part.



57835·I

Fig. 1. — Secondary thermal relay type ST for the protection of machines, transformers, and cable against overload.
The relay indicates both the instantaneous temperature of, and maximum temperature attained by, the protected object.

The different methods of protection against overloads such as temperature measuring equipment for generators, built-in thermal images for transformers, metering wires in cables, etc., all have the supervision of the conductor temperature in view. Thermal relays have the same function; they reproduce the temperature of the conductor on a model and then measure it with mechanically robust thermometers. Here, however, something more is aimed at. Whereas, the protective devices mentioned above were specially designed for the individual case and were tied to the site of the object to be protected, the thermal relay is a self-contained, separate, overload relay, capable of universal application, similar to the over-current time-limit relays for short-circuit protection. Here, too, there are two forms, series and secondary relays, entailed solely by the method of installation.

The type HT relay, the first series or primary-current thermal relay to be introduced on the market, was brought out in 1938.[1] Since then the choice between over-current and thermal relays is generally made according to the object of protection. This is best proved by the big proportion of type HT thermal relays among the series relays so far supplied.

In the meantime, manufacture of the type ST secondary thermal relay (Fig. 1) has been taken up on mass production lines. Both series and secondary relays serve to trip circuit-breakers or give warning of dangerous conditions, and to indicate the temperature.

Differences in construction compared to the type HT relay result in low inherent power consumption — an important factor where secondary relays are concerned — and a substantially greater maximum time constant. Both properties can be obtained with the same means, viz., efficient lagging of the thermal image. Fig. 2a shows the outer anti-radiation casing of the thermal image which encloses the heating element, metering column, and heat accumulator. The heating element (a strip of resistance material) heats the metering column and the heat accumulator. The latter comprises a series of metal plates (Fig. 2b) which can be changed as required on the finished apparatus. Variation of their number and value enables the time constant to be adapted to the object to be protected in steps of 20, 30, 40, 60, 80, or 110 minutes. From temperature curves of machines this so-termed steady time constant corresponds to the time taken to attain 63·4 % of the steady temperature. The relay, however, also faithfully follows the

[1] J. Stoecklin: "The Primary-current Thermal Relay Type HT", The Brown Boveri Review 1937, p. 323.

deviation from the theoretical temperature rise curve, which, as is common knowledge, is invariably particularly pronounced in the initial stage and forms a criterion for correct operation on heavy overloads. In Fig. 3 the tripping time of the type ST relay in relation to the steady time constant is shown with the overload current as parameter. The times apply to the attainment of a temperature of 60° C. As will be seen, with increasing overload the curves follow less and less faithfully the time constant which is intended for a slowly rising temperature. The quicker the temperature of the conductor rises the less the surroundings of the conductor (insulation, iron, oil) absorb heat, until, finally, in the boundary case, only the conductor itself with its slow inherent time constant applies. This is also the reason why protective gear not based on the temperature of the conductor itself, e. g., contact thermometers in the oil of transformers, are unsuitable as protection against overloads.

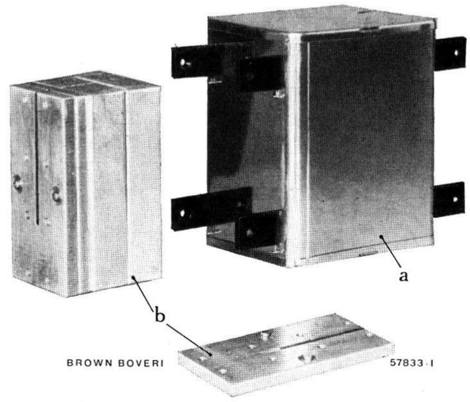


Fig. 2. — Thermal image of type ST relay.

a. Anti-radiation casing which encloses the thermal image (comprising heating element, metering column, and heat accumulator) and substantially reduces the inherent power consumption.
b. Changeable plates of heat accumulator permitting of adaptation to time constants of both small generators, large transformers, and high-voltage cables.

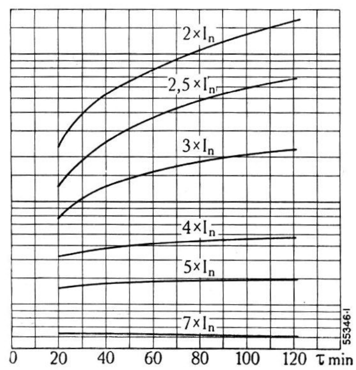


Fig. 3. — Tripping time of type ST relay in relation to steady time constant τ.

With rising overload the influence of τ increases in the relay to the same extent as in the object to be protected. The temperature is thus more or less faithfully reproduced on all overloads likely to be encountered.

The thermal relay is also provided with a magnetic limit-current instantaneous release (d in Fig. 4) adjustable for 3—10 times the rated current. This can be cut out if desired. The contacts of the thermal and time-limit elements have separate indicators (i and b in Fig. 4) and terminals. Under service conditions, therefore, the contacts can be made to actuate a warning signal or the tripping coil of a circuit-breaker. In attended stations, for instance, the thermal contact is only connected to the signal. Upon the latter functioning the attendants can decide whether load can or must be thrown off, or whether in case of emergency the load may be allowed to exceed the set limit and to what extent. In cases where instantaneous operation is desired on short-circuits the limit-current contact causes the tripping coil of the circuit-breaker to function. It frequently happens

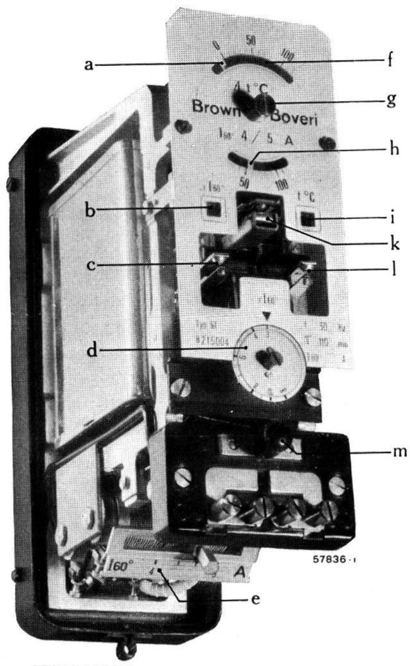


Fig. 4. — Type ST relay, cover removed.

a. Temperature pointer.
b. Signal for limit-current release.
c. Auxiliary contact for short-circuiting heating element.
d. Limit-current instantaneous release.
e. Current adjustor.
f. Maximum temperature pointer.
g. Resetting knob of maximum temperature pointer.
h. Adjusting pointer for tripping temperature.
i. Signal for thermal release.
k. Tripping contact of thermal element.
l. Contact of limit-current instantaneous release.
m. Screwed plug for interrupting tripping circuit and short-circuiting current transformer when relay tested in situ.

that the relays of a transformer have to be included in the graded protective system of the network, in which case the limit-current contacts of the thermal relays fitted in two or three phases are made to operate in parallel through a separate over-current time-limit relay. In this manner combined short-circuit and overload protection of the transformer is achieved (Fig. 5).

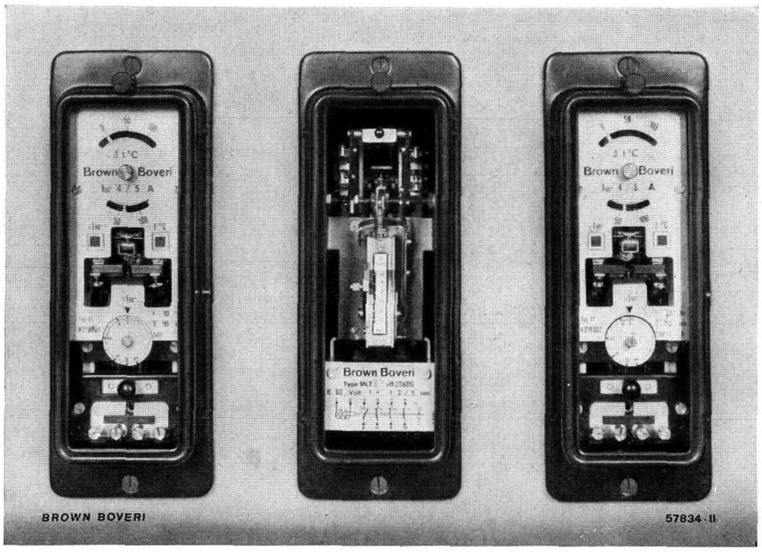


Fig. 5. — Combined short-circuit and overload protection for distribution transformers ensures full protection and temperature indication without extra apparatus.

Upon the limit-current armature operating, the limit-current contact is closed and since the thermal contact is already open, the auxiliary contact (c in Fig. 4) short-circuits the heating element. Even when the limit-current release is cut out, however, this contact prevents unnecessary stressing of the heating element above twelve times the rated current. As a result, the thermal relay is short-circuit-proof to a high degree.

The inherent power consumption of the type ST relay lies between 7·2 and 9 VA according to the current setting. The mean value is thus 8 VA, i. e., just as good as with the type S secondary over-current time-limit relay.

The type ST relay is designed for a secondary current of 5 A and must always be adjusted to the rated current of the object to be protected. Standard practice is to select the primary rating of current transformers equal to, or slightly higher than, the rated current of the object to be protected. Under rated load conditions, therefore, the secondary current is 4—5 A and the scale of the balancing shunt (e in Fig. 4) is calibrated for this range.

The suitability of the type ST relay for the overload protection of motors, transformers, and cables has been checked by direct temperature measurements under working conditions with excellent results. The maximum time constant of 110 minutes now also enables the temperature rise in large transformers to be reproduced. Fig. 6 shows the time necessary to attain the maximum temperature in the winding of a 200 kVA transformer in relation to the tripping time of a type ST relay with a time constant of 100 minutes under different conditions of overload. Prior to the measurement the transformer had been operating at half-load for ten hours.

The temperature indicating feature is improved upon through the provision of a maximum pointer which indicates the highest temperature attained until it is re-set. In the mechanical design of the type ST relay great care has been taken to ensure permanent accuracy.

The thermal relay is operated solely by the current of the object to be protected and since the ambient temperature is usually compensated for, the relay reproduces the temperature rise in the conductor in relation to its surroundings. For cable, for instance, indication is correct over the whole scale, being the temperature rise in the conductor compared to the temperature of the insulation. In the case of machines and transformers, however, the iron losses have a certain basic heating effect which is superposed on the actual temperature rise in the winding (Fig. 7). Inasmuch as the thermal relay is so adjusted in service that its temperature rise at full load is equal to that in the winding — usually 60 °C — temperature indication is correct in the region of full load, thus also explaining the excellent measure of protection afforded. Above and below rated load conditions, however, higher and lower values, respectively, are indicated, as will be seen from Fig. 7. It would be an easy matter to reproduce the heating effect of the iron losses in the relay with a second heating element connected to the system voltage and so eliminate this indicating error, as has been corroborated by test. The same object can be achieved in a still simpler manner by beginning the temperature scale of the relay at the no-load temperature instead of at zero, and calibrating accordingly (Fig. 8 b). In this case, however, the relay still indicates

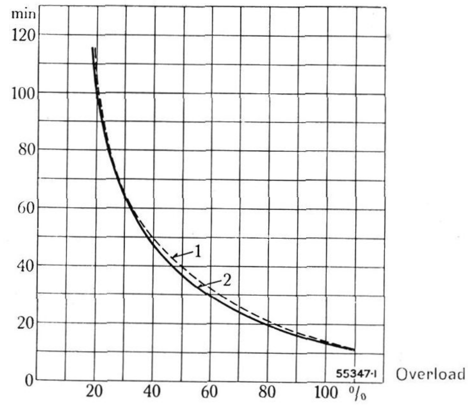


Fig. 6. — Tripping time of relay in relation to overload compared to admissible overload period of a 200 kVA transformer.

1. Relay. 2. Transformer.

The curves show how readily the type ST relay can be adapted to the object to be protected.

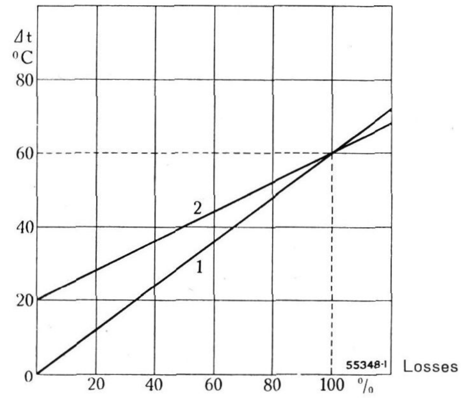
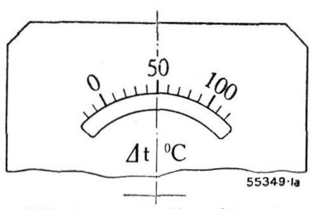
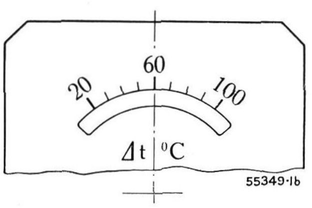


Fig. 7. — Temperature rise in conductor in relation to losses.

1. Without preliminary heating due to iron losses.
2. With preliminary heating due to iron losses.



8 a. Without compensation of iron losses.



8 b. With compensation of iron losses.

Fig. 8. — Scale of temperature indicator.

Compensation for iron losses through special calibration of scale.

no-load temperature when the machine is switched out, but this slight discrepancy is of little importance from an operating point of view. The special calibration of the temperature scale of type ST relays is employed where accurate indication under low-load conditions is required. The indicating error in this case is then only the matter of a few degrees Centigrade over the whole scale.

The more important properties of the type ST relays are given in table I.

The present big demand for electrical energy due to the shortage of coal has increased the risk of overloads in many districts. The difficulties experienced in obtaining raw materials make it imperative that high-class insulating materials should be preserved as much as possible, although existing plants must be employed up to their economic limit. The thermal relay enables these requirements to be fulfilled to an extremely high degree, while none of the finer points which are frequently also necessary in order fully to meet operating conditions have been left out of consideration in its design.

TABLE I

Secondary Thermal Relay Type ST.

Technical data	50 cycles
Rated current	5 A
Short-circuit strength	200 A
Range of adjustment for 60° C temperature rise	4–5 A
Time constants available for	20, 30, 40, 60, 80, 110 min.
Limit-current instantaneous release	
Range of adjustment	3–10×I 60° (can be cut out)
Inherent power consumption	
Current setting 4 A	7·2 VA
Current setting 5 A	9 VA
P.F. = 1	
Admissible contact rating	
Thermal making contact	
Rating at making up to 220 V≃	10 A
Rating at breaking, inductive	
D. C. 110 V	0·3 A
D. C. 220 V	0·2 A
A. C. 220 V	10 A
Limit-current making contact	
Rating at making up to 220 V≃	10 A
Rating at breaking, inductive	
D. C. 110 V	0·5 A
D. C. 220 V	0·4 A
A. C. 220 V	10 A
Indication of operation	
of thermal release	Signal
of limit-current release	Signal
Temperature indicator	Instantaneous and maximum pointers

(MS 939) *J. Stoecklin. (E. G. W.)*

EARTH-FAULT PROTECTION WITH ARC SUPPRESSION COILS. THE BROWN BOVERI ARC SUPPRESSION COIL WITH PROGRESSIVE CURRENT REGULATION.

Decimal Index 621.316.935.3

The arc suppression coil with progressive current regulation described hereafter has important advantages over existing coils with off- or on-load tapping switches, e. g., simple winding without tappings or increase in voltage, large range of regulation (up to 1 : 10), secondary winding for practically constant voltage, and possibility of testing large units with graded insulation. A number of these coils has been in operation for a long time past.

INTRODUCTION.

THE extension, interconnection, and density of supply systems have to keep pace with the ever-increasing industrial, trade, and domestic demand for electrical energy. The layout of most systems is therefore subject to considerable alteration in the course of time through the running of new lengths of line and the increasing of the section of existing feeders to enable a larger load to be carried. Contracts are sometimes also concluded between neighbouring undertakings with a view to a mutual exchange of energy, and, as a result, a system may be temporarily or permanently extended fairly considerably.

Apart from these alterations involved by the growth and development of networks there are the normal service changes entailed by switching operations due to fluctuating loads or faults. In such cases long or short sections of line may be connected or disconnected. A supply system is thus not a rigid, unchanging formation, but is subject to temporal and local alterations in length of more or less great magnitude.

For the protection of networks against the noxious effects of earth faults, reactance coils, so-termed arc suppression coils, the inductance of which is adjusted to offset the capacitance of the system to earth, have proved very successful. Inasmuch as the earth capacitance of a system, however, is governed by the length of the lines and, as already stated, this is liable to vary, such earth-fault protective gear must be adaptable to these changing conditions. It is immaterial whether the increase in system capacitance occurs gradually, following the growth of the network, or whether the change is of a sudden nature, i. e., caused by a fault or through the intervention of an attendant.

At first sight the simplest method of keeping the inductance of the coil tuned to the system earth capacitance would appear to be to equip each line with a separate arc suppression coil which would be cut in and out with the line. Even given a relatively simple system layout, however, this would involve a large number of coils and cannot be entertained for reasons of economy. In consequence, coils of higher rating, each allotted to a complete section of a system, must be employed, whereby alterations in the part of the system in question will entail re-adjustment of the coil current. In this case, therefore, all of the coils connected to the system must be capable of regulation. Another possible arrangement is to install a number of coils with a fixed current setting at different points in the system and only to provide adjustable coils where attendants are available for the regulation of the coils and the supervision of the protective gear. Here it is advisable to select the adjustable coils with a wide range of regulation. Upon large sections of a system being connected or disconnected the cutting in or out of one or more non-adjustable coils results in a kind of coarse regulation. Finer regulation can then be effected with the adjustable coils.

Until a few years ago it was the practice to employ off-load tapping switches for the adjustment of the current, so that the coil had first to be disconnected from the system before adjustment could be effected, i.e., before the tapping switch could be changed over from one tapping to another. Apart from the fact that the disconnection of a coil involves special switches, such a method is not only cumbersome, but entails great care on the part of the attendant. For this reason, coils with on-load tap-changing switch have become more and more common of recent years. Although this arrangement has proved satisfactory it has a number of drawbacks, which will be touched upon later. The design with progressive regulation of the current under load evolved by Brown Boveri incorporates many interesting features and at the same time affords big advantages in many respects. It can therefore be considered an important advance in the development of adjustable arc suppression coils.

The aim of this article is to describe this new equipment, whereby special stress will be laid on its advantages. The different arrangements will therefore be discussed in sequence, viz:—

I. Arc suppression coils with off-load tapping switch.
II. Arc suppression coils with built-in on-load tap-changing switch.
III. Arc suppression coils with progressive current regulation.

I. ARC SUPPRESSION COILS WITH OFF-LOAD TAPPING SWITCH.

The current is adjusted by selecting a suitable number of turns.

If U = the voltage applied to the coil (the phase voltage of the system in question),
w = the number of turns on the coil winding,
J = the current corresponding to the number of turns w,
Φ = the magnetic flux linked with the turns w,
R = the magnetic resistance of the closed iron circuit,
C_1, C_2, C_3 and C = constants,

the relation between the number of turns w and the applied voltage U will be

$$w = \frac{U}{C_1 \Phi} \tag{1}$$

From the equation

$$Jw = C_2 \Phi R \tag{2}$$

for the magnetomotive force driving the flux Φ through the iron circuit with resistance R it follows that

$$w = C_2 \frac{\Phi}{J} R \tag{3}$$

From the equations (1) and (3)

$$w^2 = \frac{C_2 U R}{C_1 J} \tag{4}$$

For a given system with a constant voltage U, a given coil with an invariable magnetic resistance R, and when $C = \frac{C_2 U R}{C_1}$ it results that

$$\boxed{w = C\sqrt{\frac{1}{J}}} \tag{5}$$

From the foregoing formula the number of turns w for any desired current J can be determined. Even the relation between the maximum and minimum number of turns is laid down, i. e.,

$$\frac{w_{max}}{w_{min}} = \sqrt{\frac{J_{max}}{J_{min}}} \tag{6}$$

Moreover, certain directives must be followed for the arrangement of the tappings in the case of reactance coils with iron core. In consideration of the leakage flux occasioned by an air gap the ampere-turns should be produced as far as possible at the point where they are required to overcome the magnetic resistance through the flux. With a locally concentrated air gap (denoted by the line a—b in Fig. 1a) it would therefore be incorrect to distribute the winding uniformly along the whole length c—d of the limb. In this case a state of equilibrium would only exist between the generated ampere-turns Jw and those consumed in overcoming the magnetic resistance (proportional to ΦR) at the points c, d and e. It is at a and b, the very points where the edges of the laminations are located, that the deviation between Jw and ΦR would be the greatest. As a result, the leakage fields leaving the end laminations here would cause an inadmissibly intense local heating effect. By splitting up the air gap as depicted in Fig. 1 b this drawback is obviated. The finer the sub-division the smaller will be the leakage fields.

The application of the principle of the local opposition of the ampere-turns generated and consumed

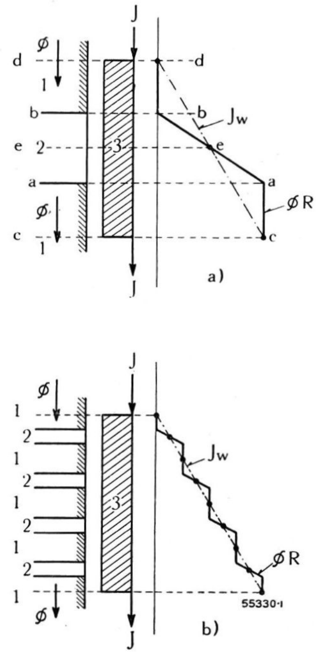


Fig. 1. — Local distribution of ampere-turns Jw and of magnetic drop ΦR.

1. Core. 2. Air gap. 3. Winding.

a. Concentrated air gap. Big deviation of ΦR from Jw along edges of air gap, hence big flux leakage and danger of excessive heating.

b. Air gab divided. Small deviation of ΦR from Jw, therefore small leakage fields. No risk of excessive heating.

involves uniform distribution of the tapping turns over the whole length of the limb, exactly as in the case of the parent winding. This is where the design difficulties begin. For regular grading of the current (interval between successive steps uniform) winding steps with different numbers of turns are required. This is shown hereafter by means of an example.

An arc suppression coil is required to be graded within the range of 0·2 *J* to *J* with steps equivalent to 0·1 *J*. The number of turns required for each tapping can be calculated with the help of formula (5) if it is assumed that the number of turns *w* of the parent winding corresponds to the maximum current *J*. The result is shown in table I and again in Fig. 2

TABLE I.

Current in %	Number of turns	Number of turns per step
100	w	
90	1·054 w	0·054 w
80	1·118 w	0·064 w
70	1·195 w	0·077 w
60	1·291 w	0·096 w
50	1·414 w	0·123 w
40	1·581 w	0·167 w
30	1 826 w	0·245 w
20	2·236 w	0·410 w

in the form of a curve. The grading of the winding is not uniform, which was only to be anticipated, inasmuch as the relation between *w* and *J* in formula (5) is non-linear. The tapping turns vary between 0·054 *w* and 0·410 *w*, i. e., practically in the ratio of 1 : 8.

The correct arrangement would be to distribute each winding step over the whole length of the limb, but this has the drawback of complicating the winding,

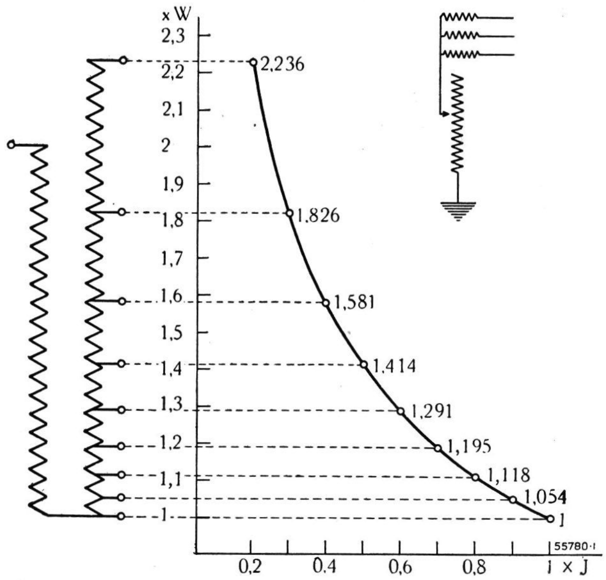


Fig. 2. — Arrangement of tappings of an arc suppression coil with uniform tapping intervals and a range of regulation of 0·2 *J* to *J*.

Parent winding:
Number of turns . . . *w*
Current . . . . *J*
Voltage . . . . *U*

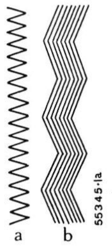
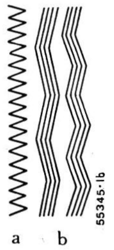
Regulating winding:
Number of turns . . 1·236 *w*
Current . . . . . 0·2 *J*–*J*
Tappings . . . . . 0·1 *J*
Smallest step . . . 0·054 *w*
Largest step . . . 0·41 *w*

Uniform current grading involves irregular tapping intervals.

for it is no easy matter to support a parent winding and eight tapping windings sufficiently rigidly and at the same time provide for satisfactory cooling conditions. Above all, the distance between the outer winding and the core must not be too great, otherwise the principle of opposition of the ampere-turns will be achieved only in the longitudinal direction, and not transversally.

A second possible arrangement is to combine the tapping windings to form one or two multiple-spiral windings, which, however, would involve abandoning the uniform current grading. Table II shows two

TABLE II.

Tapping winding Spiral winding (octuple)				Tapping winding Two spiral windings (quadruple)			
Connection	Number of turns	Current in %		Connection	Number of turns	Current in %	
		Actual value	Required value			Actual value	Required value
	w	100	100 90		w	100	100
	1·1545 w	75	80 70		1·073 w	87	90
	1·309 w	58	60		1·146 w	76	80
	1·4635 w	47	50		1·219 w	67	70
	1·618 w	38	40		1·291 w	60	60
	1·7725 w	32	30		1·527 w	43	50 40
	1·927 w	27			1·763 w	32	30
	2·0815 w	23			1·999 w	25	
	2·236 w	20	20		2·236 w	20	20

a. Parent winding; b. Tapping winding.

such arrangements. The deviations from the specified current steps are up to 37 % in the first case and up to 20 % in the second. Nevertheless, with the first arrangement the desired current can be adjusted with a maximum deviation of 10 % (100 instead of 90), while in the second case the greatest difference is 7 % (43 instead of 50). Multiple-spiral windings, however, have certain drawbacks. They have a relatively large pitch so that space is wasted at the beginning and end of the winding. The turns of the tapping windings must be well insulated, inasmuch as the full voltage of the windings in question lies between them. Finally, the manufacture of such multiple windings, no matter whether of small or large cross-section, is comparatively difficult. Apart from isolated cases with very few tappings, where a suitable current grading was possible with a spiral winding, this arrangement has been very rarely adopted.

In practice, the rigorous application of the principle of the local opposition of the generated and consumed ampere-turns has usually been dispensed with. Even though this involves certain leakage fluxes the heating of the laminations along the edges of the air gap can be kept within reasonable limits by finely subdividing the air gap, avoiding excessive induction in the core, suitably arranging the tapping windings, and incorporating certain design features based on the more than twenty years' experience of our firm in the construction of reactance coils.

Leads connect the tappings of the windings to the terminals of a built-in face-plate or tubular switch. Inasmuch as such a switch may only be operated off-load it is imperative that the coil should be disconnected from the system neutral beforehand. For sites affording the possibility of checking the coil to see whether it is alive and to determine whether an earth fault exists, a single-pole isolating switch can be used to interrupt the coil circuit. There is nevertheless always a risk of an earth fault occurring while the isolating switch is being opened, in which case an arc would be struck. Since, moreover, most systems are not completely symmetrical the isolating switch will have to interrupt the asymmetry current, even when there is no fault in the system. The safest policy, therefore, is to employ a single-pole circuit-breaker (oil or air-blast high-speed circuit-breaker) to disconnect the coil, notwithstanding the not inconsiderable extra expense entailed.

It is particularly this difficulty of disconnecting arc suppression coils that led to the search for other arrangements with which the change-over from one tapping to another can be effected under load. The coil with built-in on-load tap-changing switch meets this requirement.

II. ARC SUPPRESSION COILS WITH BUILT-IN ON-LOAD TAP-CHANGING SWITCH.

The design of the coil and the arrangement of the winding are the same as for coils with off-load tapping switch, but the latter is replaced by a switch for changing from one tapping to another under load. At first sight the tapping change-over problem would thus appear to be completely solved. From an operating point of view this is actually the case, but from an economical standpoint the arrangement has disadvantages. These are gone into below on the basis of the example already employed.

The coil with tappings as per table I is connected, together with the parent winding (w turns), to the supply voltage U. In the tapping winding with $1{\cdot}236\ w$ turns a voltage of $1{\cdot}236\ U$ is induced and it is for this voltage that the range of regulation of the on-load tap-changing switch must be selected. Taking a mean, the maximum regulating voltage of a modern on-load tap-changing switch is of the order of one half of its rated voltage. Hence a switch with a voltage rating of $2 \times 1{\cdot}236\ U = 2{\cdot}5\ U$ would have to be employed. Even when it is considered that the coil is connected to a system with a line voltage of $U\sqrt{3} = 1{\cdot}73\ U$ and must be insulated accordingly, a switch with a higher voltage rating will have to be provided in many cases, especially where the range of regulation is large. Such a switch

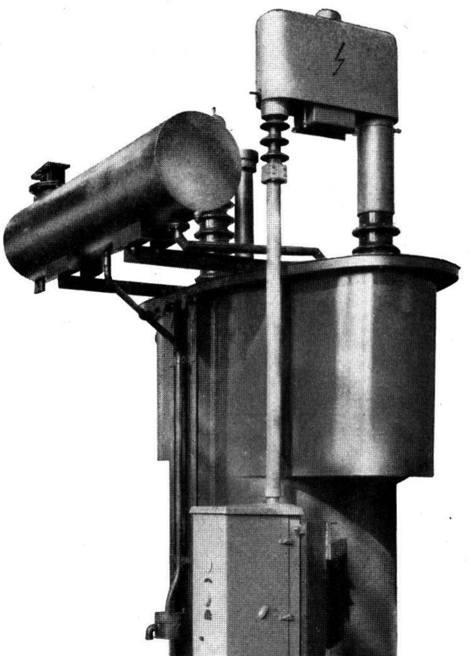


Fig. 3. — Arc suppression coil with built-in on-load tap-changing switch for a 127 kV system.

Rating 7500 kVA, range of regulation 65—102 A.
The on-load tap-changing switch is suitable for small ranges of regulation.

is not only expensive, but requires a large amount of space and, in consequence, increases the cost of the coil and in particular of the oil filling. For the lack of anything better, however, arc suppression coils with on-load tap-changing switch for current regulation have found wider and wider application. Fig. 3 shows such a coil rated 7500 kVA for two hours. The current can be regulated from 65 to 102 A with the on-load tap-changing switch. For the sake of completeness it might be mentioned that the change-over resistors of on-load tap-changing switches are very bulky (due to the voltages between the tappings) and for this reason cannot be mounted on the bushing of the switch.

With modern on-load tap-changing switches for transformers the principle of combined coarse and fine regulation is generally adopted. The switches built by Brown Boveri have seven fine steps and up to three coarse steps. With these switches a maximum of thirty steps can be obtained with only ten tappings. By reason of this property and especially on account of the compact design with the three phases superposed, together with the coarse and fine selectors (star-point switch), this switch is particularly suitable for regulating transformers. In the case of arc suppression coils, however, the repetition of the fine steps on each coarse step gives irregular current grading with large steps in the maximum current zone and small steps at the other end of the winding.

An example will serve to illustrate this disadvantage. Assume a coil with a range of regulation of $0{\cdot}15\ J$ to J, divided into twenty-three steps. The winding comprises a parent winding with two tappings and a regulating winding with seven fine steps. Each step has the same number of turns so that the regulating winding can be considered to be of the multiple-spiral type. The eighth step is formed by the change-over to the first coarse step (tapping of parent winding); from here the seven fine steps are repeated, so that upon transition to the second coarse step sixteen steps are obtained. With the further repetition of the seven fine steps a total of twenty-three steps results.

The effect of the described grading is shown in Fig. 4 by curve 2. It deviates considerably from the straight line 1 which represents the desired, ideal current grading. If an effort is made to improve the grading by selecting another number of turns for the fine steps, so that, for instance the currents of the eighth or sixteenth step (position 9 or 17 of on-load tap-changing switch) lie on the straight line 1, this could only be achieved by substantially reducing the range of regulation. As shown by curves 3 and 4 the lower limit of regulation is only $0{\cdot}4\ J$ and $0{\cdot}3\ J$, respectively, instead of the specified $0{\cdot}15\ J$. Even the extension of the parent winding to include a third coarse step would not suffice to obtain the $0{\cdot}15\ J$ limit.

The unsatisfactory current grading, especially in the case of coils with a wide range of regulation, has led to a search for a solution of the problem in another direction. The result is the coil with progressive current regulation.

III. ARC SUPPRESSION COILS WITH CONTINUOUS CURRENT REGULATION.

Fig. 5 illustrates the design of this arc suppression coil in diagrammatic form. Two cores a of circular cross-section are mounted on a spindle. When

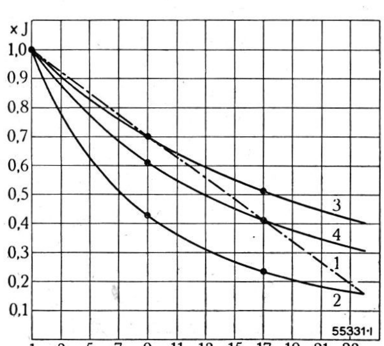


Fig. 4. — Regulation curves for arc suppression coils with built-in on-load tap-changing switch.

1. Ideal characteristic.
2. Practical curve obtained by adhering to range of regulation.
3, 4. As 2, but with slight deviation from ideal curve and sacrificing part of range of regulation.

The larger the range of regulation the more difficult it is to obtain satisfactory current grading.

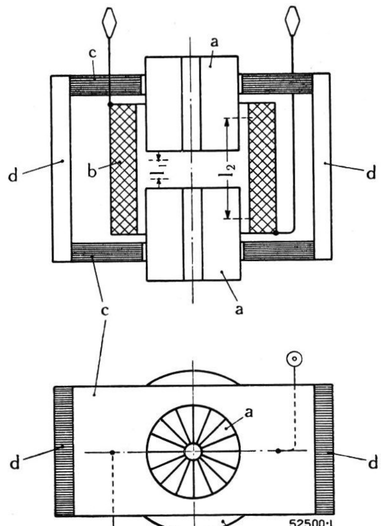


Fig. 5. — Diagrammatic design of arc suppression coil with progressive current regulation.

a. Moving cores.
b. Winding.
c. Yoke plates.
d. Longitudinal yokes.
l_1, l_2. Minimum, maximum air gap.

In addition to a large range of regulation an ideal regulating characteristic and a winding without tappings are obtained.

the latter is rotated the cores move towards or away from each other, thus varying the air gap between the limit values l_1 and l_2. Top and bottom the magnetic circuit is closed by horizontal yoke plates c and on the sides by two longitudinal yokes *d*. During the rotative movement the two cores turn in circular recesses in the yoke plates. The winding *b* and the insulating cylinder are easily lodged in the space between the cores and the external longitudinal yokes.

The adjustment of the current is achieved by varying the air gap. Since the winding has a given, constant number of turns w and the phase voltage U of the system can also be considered as being practically constant, this arc suppression coil operates with constant flux Φ, inasmuch as from (1)

$$\Phi = \frac{U}{C_1 w} \qquad (7)$$

Since U, C_1, and w are constant the flux Φ is also constant. The variation of the current is now achieved entirely by alteration of the air gap, i. e., of the magnetic resistance R. From formula (2)

$$J = C_2 \frac{\Phi R}{w} \qquad (8)$$

With Φ constant the current J is proportional to the magnetic resistance R.

The magnetic resistance R is chiefly concentrated in the air gap, for the resistance of the remainder of the magnetic circuit can be safely neglected, inasmuch as the joints and the clearance between the cores and the yoke plates are kept small. Along the edge of the air gap there is an indentation of the flux which varies somewhat with the length l of the air gap. If this alteration is also neglected the magnetic resistance R becomes proportional to the length l, so that from formula (8)

$$\boxed{J = C_4\, l} \qquad (9)$$

If the limit values l_1 and l_2 of the air gap are in the relation of, for instance, 1 : 6, the current can also be regulated more or less within this range.

In contradistinction to the earlier constructed coils with heavily divided air gap (entailed by the parallel layers of laminations) the coils with progressive regulation have an undivided air gap. To prevent the leakage fields along the edge of the gap producing excessive local heating the parallel layers of laminations have heen abandoned and radially-laminated moving cores adopted. Since with this arrangement the leakage fields enter around the whole periphery in the direction of the layers of laminations the danger of local heating is eliminated.

For the drive of the spindle, motor operating gear with double reduction gear is provided on top of the active part. A position indicator and a limit switch for reversing the direction of rotation of the driving motor are mounted on the outside of the tank (Fig. 6).

A special spindle guide keeps the humming of the coil down to a very low level over the whole range of regulation. The intensity of the humming will not alter after lengthy periods of operation.

The advantages of this type of arc suppression coil are as follows: —

(a) Since the winding has no tappings and is moreover not subject to short-circuit forces, it forms an absolutely reliable element. What is more, there are no free winding ends having a higher voltage and which could swing with travelling waves. The winding without tappings, which is only earthed on the one side, will not reflect over-voltage waves entering at the star point of the transformer and is thus subject to very little stress. Moreover, with very high voltages and powers it is an advantage to connect the supply to the centre of the winding, thus resulting in a reduction of the steepness of wave-fronts.

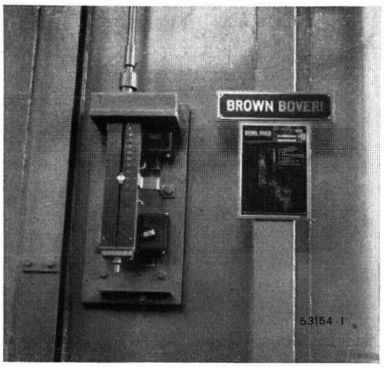


Fig. 6. — Mechanical position indicator on arc suppression coil.
Scale calibrated directly in amperes. Electrical remote position indication is also possible.
These devices facilitate the checking of the coil setting.

(b) This type of coil is particularly suitable for regulation within a wide range, normally up to 1 : 8, but in exceptional cases even up to 1 : 10. In the case of coils regulated by means of switches such a range would involve a voltage on the tappings of the order of the line voltage and the switch would therefore have to be rated for twice the service voltage. Moreover, the number of tappings of the standard switches would not suffice for the large range of regulation.

The progressive regulation enables the most favourable current setting to be selected for the suppression of the earth fault arc in all cases; the coil may be either in resonance tune or slightly out of tune. An advantage particularly to be stressed is the possibility of altering the current setting without prior disconnection of the coil, even under load conditions.

(c) Notwithstanding the large range of regulation the coil can be incorporated in a voltage or power winding the voltage of which remains practically constant no matter what current setting is selected for the coil. Such a voltage winding may be employed not only for measuring the voltage of the neutral, but for the operation of earth-fault relays or a warning signal. The power winding is generally used to reinforce the active component, in that a non-inductive resistance is connected. The object of this measure is either to limit the displacement to earth of the system neutral point due to system asymmetry or to ensure the earth-fault relays receiving sufficient active power under all conditions of service, and thus augment their discriminating properties.

(d) By employing graded insulation to earth large units can be constructed with a minimum amount of material. The savings which can be effected, especially in the case of high voltages, are considerable. A proviso for the design, however, is that an induced voltage be employed to test it. If the test voltage is twice the rated voltage U the power taken by the coil is 4 UJ at the rated frequency f, when J denotes the minimum current involved by the total number of turns of arc suppression coils with tappings. If the frequency is increased to ten times the rated value during the test the power taken will drop to 0·4 UJ. Large units, however, usually have no provision for regulation, with the exception of a few tappings for the adjustment of the current when initially setting the coil to work. A coil rated 20,000 kVA, therefore, requires a supply of 8000 kVA with a power factor of approximately 0. With the progressively regulated coils the cores can be screwed completely together, thus reducing the power to a fraction of this figure and enabling existing testing equipment to be employed for an induced-voltage test.

Fig. 7 shows the different possible methods of testing. Models A and B with full insulation to earth are tested with an applied voltage. The test entails either two terminals for the full test voltage (A) or temporary insulation of the end of the winding on the earthed side (B), a very awkward and time-wasting job. With models C (low ratings) and D (high ratings) with graded insulation to earth an induced voltage test is possible without difficulty; moreover, the terminal on the earthed side of the coil can be selected for a lower test voltage. Since with the last-mentioned designs, weights and dimensions are lowest and the turn insulation is also covered by the induced voltage test this arrangement should be given preference.

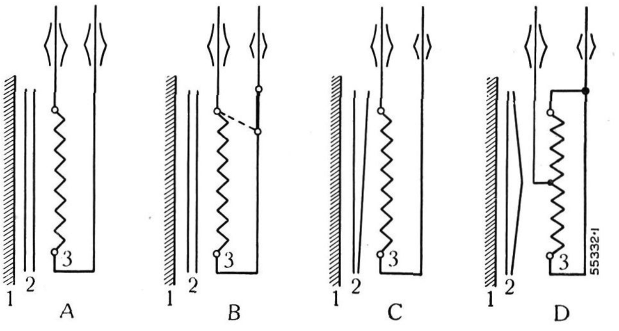


Fig. 7. — The insulation of the winding to earth is tested in the case of A and B with an applied voltage, in the case of C and D with an induced voltage.

1. Iron. 2. Insulation. 3. Winding.

A is fully insulated and has two similar bushings for the rated voltage.
B as A, but with the terminal on the earthed side for a lower voltage. For the voltage test one end of the winding is insulated.
C Insulation graded on one side. Earthing terminal smaller.
D Insulation graded on both sides. Earthing terminal smaller.

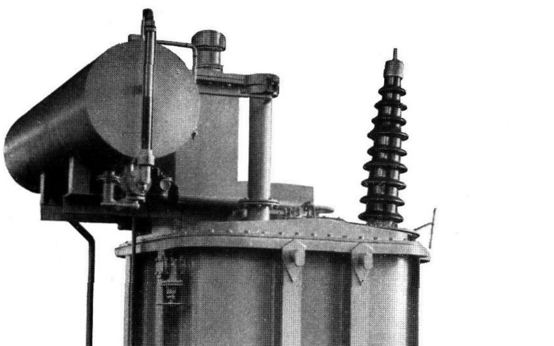


Fig. 8. — Arc suppression coil with progressive current regulation for a 120 kV system.

Rating 5500 kVA. Range of regulation 18 to 78 A.
Arc suppression coils with progressive current regulation permit of accurate adaptation to system conditions and therefore give the best protective effect.

The Brown Boveri arc suppression coil with progressive current regulation is not to be considered as an attempt to put something new on the market at any price. The majority of its components have already been tried out in other apparatus. Moreover, a number of coils of this new type have already been in operation for a long time past. Experience to date is excellent without exception. One of the coils supplied is shown in Fig. 8; its rating is 5500 kVA when connected to a 120 kV system.

In conclusion, the progressively regulated arc supression coil is particularly suitable for the completely automatic adjustment of the current with the extension of a system. The earth-fault protection problem is thus completely solved, inasmuch as automatic regulation is possible both for individual coils and coils operating in parallel (in one and the same system or in interconnected systems) with little extra material and without complicated connections.

(MS 957) *A. van Gastel. (E. G. W.)*

A 3000 KW MOBILE MUTATOR SUBSTATION FOR TRACTION-SERVICE AND REGENERATIVE BRAKING DUTY.

Decimal Index 621.316.264-182.3

The Compania Paulista de Estradas de Ferro, São Paulo, Brazil, has acquired a mobile substation for the conversion of a three-phase 90 kV supply to d. c. at 3 kV. The plant, which is noteworthy both on account of its rating and by reason of its design for regenerative braking, is described hereafter.

INTRODUCTION.

THE C. P. E. F., one of the most important railway undertakings in South America, owns about 1500 km of track. In 1922, in anticipation of traffic developments, the company decided to undertake the electrification of the Jundiahy-Campinas section, being the first Brazilian railway undertaking to put an electrification scheme into effect. To-day, more than 400 km of the C. P. E. F. system is electrified. Due to the continual extension of the electrified services it was finally found necessary to acquire a substation which could be transferred to different points of the system in the event of breakdown, repair, or overhaul of the existing stationary plants and which, in particular, could be rushed to any part of the railway during temporary periods of heavy traffic (Fig. 1).

On the basis of results obtained with similar plants supplied by Brown Boveri earlier for other undertakings the company in question ultimately placed an order for the supply of a 3000 kW mobile substation for the conversion of a three-phase 90 kV supply to d. c. at 3 kV with our company. A condition to be taken into consideration was that the power recuperated through the regenerative braking of trains running down the gradients on the line should be paid back into the primary system, thus involving re-conversion.

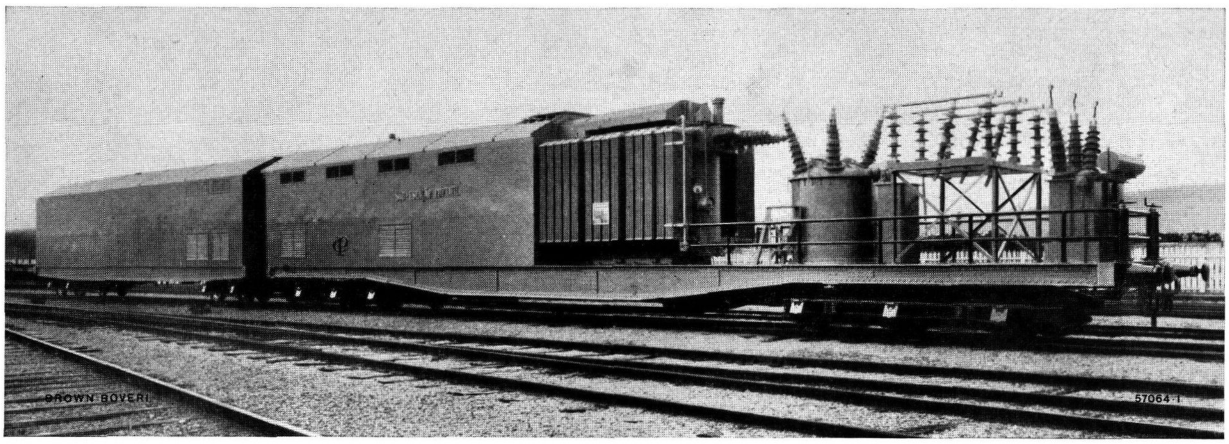


Fig. 1. — The mobile substation of the C. P. E. F., Sao Paulo.

Rated 3000 kW, it is designed for the conversion of a 90 kV three-phase supply into d. c. at 3 kV. Technically, this plant is in a class of its own and is, moreover, the largest mobile mutator installation in the world.

I. CONSTRUCTION.

The design of the set was dictated on the one hand by the requirement that it should form a complete standby for any of the mutators supplying the contact-wire system and on the other by the fact that it had to provide a link for the return to the primary system of the energy recuperated from the regenerative braking of trains running downhill. With unchanged polarity of the contact-wire voltage alteration of the direction of the power through the set involves a change of direction of the current in the contact wire. Inasmuch as reversal of the direction of the current is impossible with a single mutator unless the main circuit is changed over in relation to the voltage or energy and since this arrangement did not meet the requirements of the case in question, separate mutators for each direction of flow of current, cross-connected by the well-known method and each rated for the full output of the stationary mutators, were selected. The main circuit of the set is shown in Fig. 2. Mutator I converts the three-phase supply into direct current for the contact wire, whereas mutator II converts the recuperated direct current into three-phase current to enable it to be paid back into the primary system. These two mutators are supplied from the secondary and tertiary windings of the common main transformer which depend on the same primary winding. The winding delivering the energy to the contact wire, as well as the interphase transformer, is of very simple design and is connected by a new method with which the harmonics in the primary currents and d. c. voltage lie between those entailed by six and twelve-phase operation, respectively. The tertiary winding for the power recuperated from the contact wire is connected on the well-known six-phase fork principle; it is designed for a third of the d. c. rating of the secondary winding. The primary winding of the main transformer is connected through an oil circuit-breaker to the 90 kV supply system. Since the primary voltage may vary with the point of connection of the set in the system four tappings are provided on the primary winding of the main transformer to enable its ratio to be adapted to the prevailing conditions by means of a change-over switch; the same applies to the secondary winding of the auxiliary transformer supplying the auxiliaries. The mutators are water-cooled on the closed-circuit principle, the water being re-cooled by means of an air-cooler with fan.

Both units also have controlled grids for voltage regulation. The corresponding control gear, built up from static parts which are not subject to wear, imparts steep-front impulses with a variable phase displacement controlled by means of automatic, quick-acting voltage regulators. To interrupt the short-circuit current in the event of backfires or short circuits on the contact wire or in the motor-coaches simple protective gear is provided. This incorporates a high-speed relay and in the event of an over-current in the cables to the mutator interrupts the current within approximately three-quarters of a cycle of the a. c. voltage through the intermediary of the controlled grids. Reverse or over-currents caused by backfires or faulty ignition are cut out in the shortest possible time by means of d. c. high-speed circuit breakers. To limit the harmonics in the contact-wire voltage and current, caused by the harmonic voltage on the d. c. side, a wave absorber in the well-known arrangement with limiting choke coil and several voltage filter circuits is provided. In the event of the a. c. - d. c. mutator having to be taken out of commission the other mutator can be switched over by

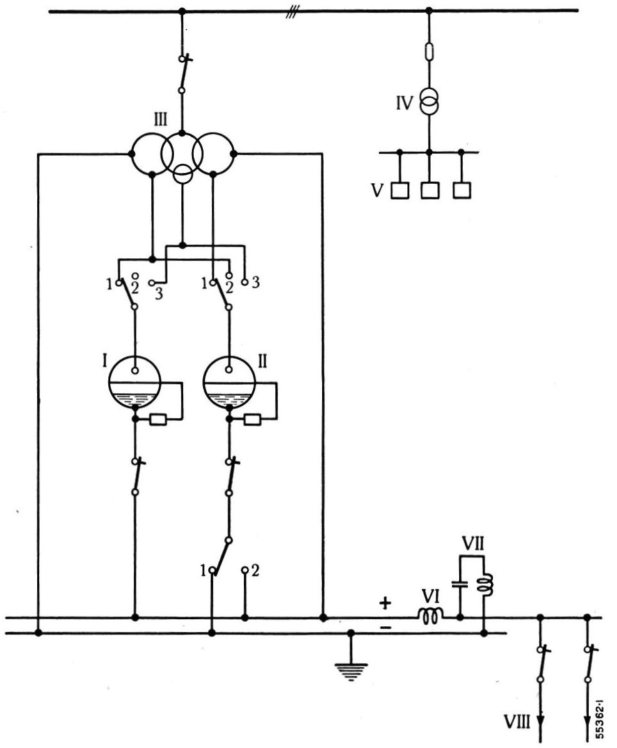


Fig. 2. — Simplified diagram of main circuits and auxiliaries.

The cross connection of the two mutators I and II permits of continual transition from power supply to regenerative braking service, or vice versa, without any change-over operations having to be carried out. Position 1 of the change-over isolating switch corresponds to normal service, 2 to emergency service with only one mutator, and 3 to formation of a mutator.

III. Main transformer.
IV. Auxiliary transformer.
V. Auxiliaries.
VI. Reactor.
VII. Voltage filter circuits.
VIII. D. C. feeders.

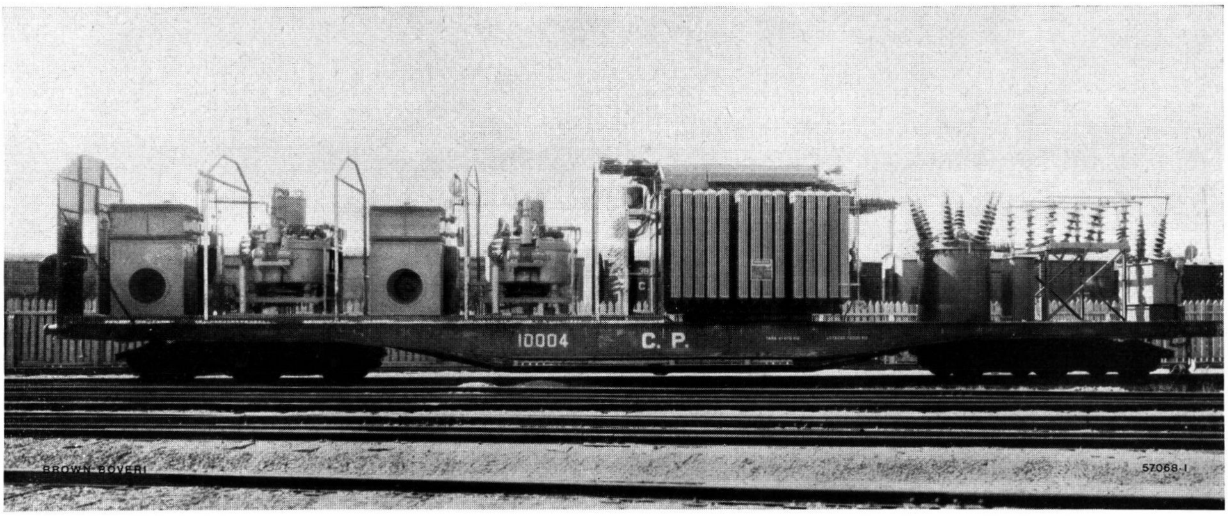


Fig. 3. — Wagon 1 with body removed.

From right to left: Auxiliary transformer, high-voltage isolating switch, 90 kV high-voltage circuit-breaker, main transformer, mutators I and II each with recooler.

One of the mutators supplies the direct current, while the other serves for the recuperation of energy from trains running downhill.

means of isolating switches to take its place, thus enabling the supply to the contact-wire system to be fully maintained. A further winding embodied in the main transformer permits mutators to be thoroughly re-formed, independently of the site of the plant, before being re-set to work after overhaul.

The entire installation is designed for overloads as per class C, i.e., 50 % for two hours and 200 % for five minutes.

To permit the auxiliaries to be tested and operated independently of the primary supply a special emergency generator driven by a small petrol engine is incorporated in the set. Fig. 3 shows the a. c. switchgear, the main transformer with the two mutators, and the re-cooling plants on one wagon, Fig. 4 the remote control, metering, and regulating switchboard, d. c. switchgear with two outgoing feeders, and the wave absorber on the other.

The whole equipment weighing approximately 56 tons is mounted on two wagons with two two- and two three-axle bogies, respectively, the total area required being 124 m^2. The effective volume of the plant is only 340 m^3.

II. METHOD OF OPERATION.

As already stated the new mutator substation had to be adapted to the existing railway plants. To ensure satisfactory load distribution when operating directly in parallel with motor-generators both mutators had to have a voltage-current characteristic independent of fluctuations in the supply voltage and giving a virtually constant voltage at the d. c. terminals in the range between no-load and 100 % overload and the natural voltage drop of the set above this load. This characteristic is achieved with automatic quick-acting regulators acting on the grid control gear of the mutator. Inasmuch as the power delivered to the contact wire system is naturally much greater than that recuperated the d. c.—a. c. mutator is generally only lightly loaded for a short period. The mutators could be made to deliver intermittently, one delivering power and the other remaining off-load. To obtain maximum reliability of the two mutators under all load conditions a basic load, if only a low one, had to be arranged for both mutators. As a result the two voltage regulators are so adjusted that, apart from the current flowing to or from the contact wire system, a low basic load flows from one mutator to the other, thus ensuring maximum availability with very little additional loss, because the energy thus employed returns to the three-phase supply system. During regenerative braking there is a slight rise in the d. c. voltage which can be adjusted arbitrarily on the regulator. In the event of breakdown of the a. c.—d. c. mutator that normally operating in d. c.—a. c. service can be employed in its stead. The change-over is effected by means of change-over isolating switches simultaneously with the corresponding control gear. During this emergency service, pneumatic braking must be resorted to in lieu of regenerative braking on trains running downhill in the section of the system affected. In the case of backfires the arc on the main anodes is extinguished

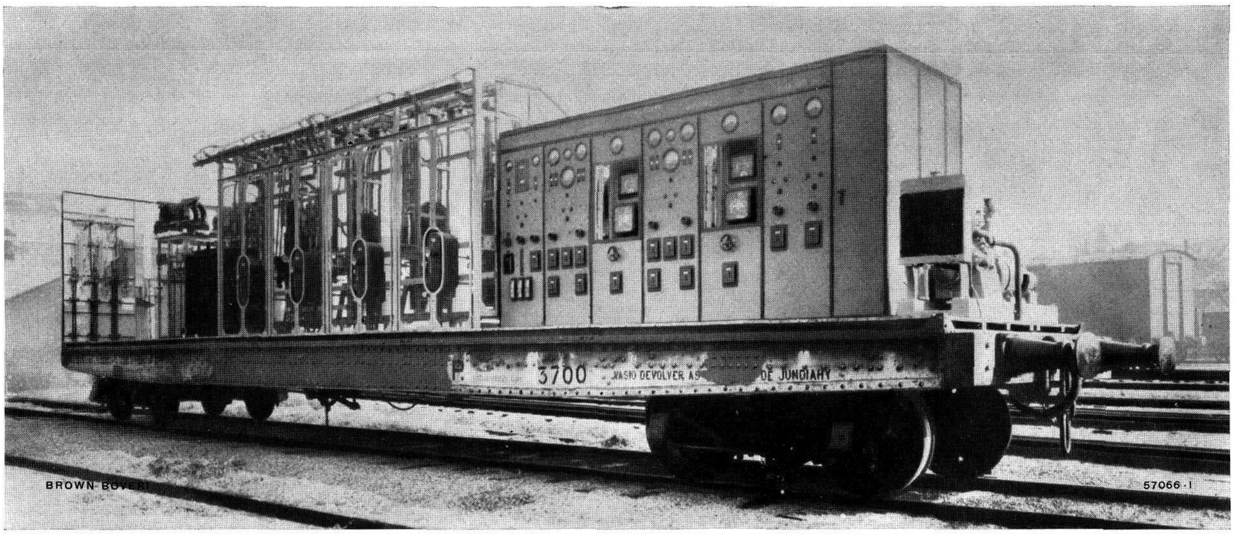


Fig. 4. — Wagon 2 with body removed.

From right to left: Auxiliary set, switchboard for control and supervisory purposes, d. c. switchgear with mutator and feeder circuit-breakers and wave absorber.

The comprehensive switch equipment is not only entailed by the size of the substation, but also by the exacting technical requirements (recuperation, compounded d. c. voltage, and interchangeability of the two sets).

through the combined action of the grid control gear and a high-speed over-current relay, while the corresponding d. c. circuit-breaker trips out and is immediately automatically re-closed. As a result, the over-current in the supply system only lasts for about 1·5 hundredths of a second and interruption on the d. c. side only 1—2 seconds. A similar sequence of operations takes place when short circuits occur on the contact wire or in the motor-coaches, although in this case the d. c. circuit-breaker cuts out the section of contact wire affected and thereupon automatically recloses. This rapid suppression of the short-circuit currents in both cases not only reduces the stresses in the mutators themselves to a harmless minimum, but in all other parts of the plant through which the main current flows as well. Both the set and its auxiliaries can be switched in and out in a fraction of a minute. Unskilled attendants can start up the plant or change it over from normal service with two mutators to emergency operation with one mutator, or vice versa, by following a simple switching plan. Due to the continuous basic load on both mutators, the voltage increase otherwise involved by the use of the interphase transformer and wave absorber under conditions of no-load operation of the plant is entirely obviated without additional loss. Transition from power supply to regenerative braking service, or vice versa, is continually possible, inasmuch as no change-over operation or actuation of relays or the like is entailed. Both mutators are always ready to deal with any current likely to be required in service. As a result the characteristic of the voltage at the d. c. terminals is always entirely progressive in relation to the magnitude and direction of the current and is thus exactly the same electrically as that of a motor-generator (Fig. 5). The mean annual efficiency of the entire

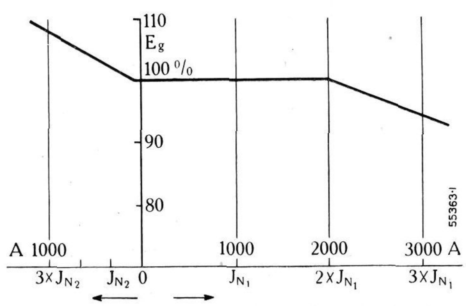


Fig. 5. — Voltage characteristic of set in function of load.

The voltage-current characteristic of the two cross-connected mutators is maintained constant in the normal load range by suitable regulating gear and is entirely progressive, i. e., as with rotary convertors.

Eg D. C. voltage.

J_{N_1} Rated current of mutator I.

J_{N_2} Rated current of mutator II.

plant, including all auxiliaries and assuming average load conditions, is of the order of 96 %. The power factor of the set referred to the non-regulated d. c. voltage, is 95 %. The plant has been in operation since February, 1942, to the entire satisfaction of the purchaser and has already proved its high degree of mobility and availability for service on many occasions.

(MS 927) *E. Kern. (E. G. W.)*

THREE-PHASE VARIABLE SPEED DRIVES FOR WIND TUNNEL BLOWERS.

Decimal Index 621.34 : 533.6.07

The speed of the air in wind tunnels for aero-dynamic research must be capable of being varied over a very wide range. For this purpose the blowers are driven by motors with a large range of speed regulation. This article deals with such wind tunnel drives employing Brown Boveri Scherbius cascade sets. Because of the "fan-torque characteristic" very large regulation ranges may be handled in an economical manner with these cascade regulating sets. The elementary diagram of connections is described in detail.

LONG years of experience in the field of mechanics of fluids gained in the manufacture of steam turbines, turbo-blowers and turbo-compressors, have caused Brown Boveri also to turn their attention to the affiliated problems of modern aero-dynamics and to construct aero-dynamic research installations. A number of wind tunnels for working at velocities below and above sound velocity have already been built by Brown Boveri and their concessionaries. In such plants, the speed of the air in the test chamber must be capable of being regulated between wide limits according to the requirements, which is best achieved by the use of variable-speed drives for the blowers.

Where small and medium powers are involved, three-phase commutator motors can be used, whereas for high powers, cascade arrangements of induction motors with commutator regulator machines come into consideration. The most widely used commutator motor to-day is the rotor-fed shunt commutator motor in which the speed regulation is achieved by displacement of the brushes, whilst for the speed control of induction motors with a cascade regulating machine the so-called Scherbius set is generally used.

In the case of constant torque the price of these drives increases with the range of regulation. Thus for instance, in the case of the rotor-fed commutator motor the size of the commutator together with the regulating winding and brush gear is fixed by the slip load, that is, by the range of regulation, assuming the torque to remain constant. The greater this range, the larger the above-mentioned regulating parts, and hence the larger the motor. In the same way, in the case of the Scherbius cascade unit, the size of the Scherbius machine with its accessories is fixed by the slip load, that is, by the range of regulation. This is the reason why Scherbius cascade machines have up to the present been used only for ranges of at the most 2 : 1.

The conditions are, however, different when for instance as with drives for fans and centrifugal compressors the torque decreases rapidly when the speed is reduced. In such drives the required torque is usually proportional to n^2 (n = r. p. m.), that is to say the driving power is proportional to n^3. We will designate this case by the name "fan torque". Fig. 1 shows the driving power (curve a) and the synchronous power (curve b) for speed regulation with constant torque,

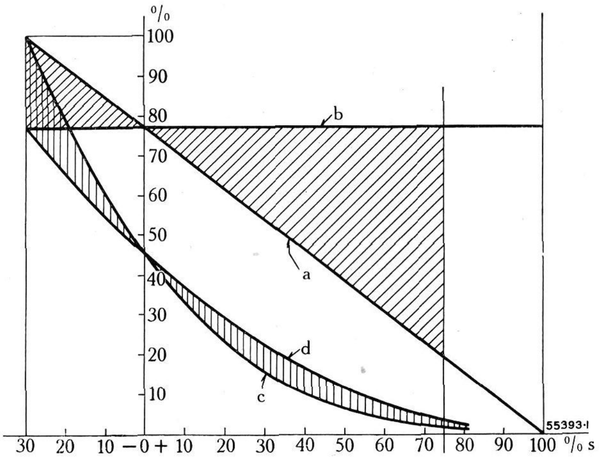


Fig. 1. — Slip load with variable speed three-phase drives.

s. Slip.
a. Driving power
b. Synchronous power } Constant torque.
$b-a$. Slip load
c. Driving power
d. Synchronous power } Fan torque.
$d-c$. Slip load
a, b, c and d in % of the driving power at n_{max}.

and also the driving power (curve c) and the synchronous power (curve d) for speed regulation with fan torque, drawn as a function of the slip (s). The difference of the ordinates b and a in the one case, and a and c in the other case, represents the slip load.

If, for instance, the speed is regulated at constant torque between 30 % above synchronism and 75 % below synchronism (regulation range 5·2 : 1), the maximum slip load (at n_{min}) is 58 % of the driving power at n_{max}. For the same range of regulation, but with fan torque the maximum slip load (at n_{max}) is according to Fig. 1 only 23 % of the driving power. From this it can be seen that in the case of speed regulation with fan torque it is possible to use even for large ranges relatively small commutator motors or Scherbius sets. These drives are, therefore, particularly suitable for centrifugal compressors and pumps, etc. where particularly large regulation ranges are required. The connections of these drives are then specially arranged as described in detail below.

The German patent 635,308 describes the connection for rotor-fed three-phase commutator motors which is excellently adapted to large ranges of regulation with a fan torque. The connection is shown diagrammatically in Fig. 2; the drawing includes all the brushes a_1 to a_6 and b_1 to b_6 of the double brush yoke, which in this particular case is six-phase. Of the six phases of the stator winding only one phase (S_1) is shown. The rotor windings (primary and regulating windings) have been omitted from the diagram for the sake of simplicity. Each phase of the stator winding consists of two parts (for example, phase S_1 of S_1' and S_1''), the axis of the component windings being displaced relative to each other by 60 electrical degrees. Fig. 2 shows the brush position for operation below synchronism, where it is possible to switch over without breaking the circuit and without shock from the "normal regulation range" to the "extended regulation range" (see also patent description). For the normal range the change-over switches U_1 to U_6 are moved in the clockwise direction, and for the extended regulating range they are thrown over in the anti-clockwise direction. By means of this change-over the effective number of turns of the secondary winding is in the extended range $\frac{1}{\sqrt{3}}$ smaller than in the normal range, and the regulating range is increased accordingly. The change-over itself does not cause any change of speed, but it does, however, provide the possibility of further reducing the speed by additional displacement of the brushes.

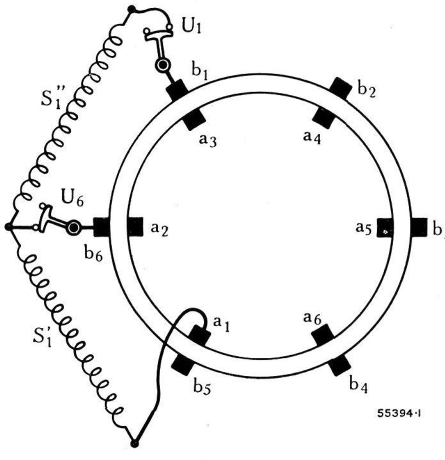


Fig. 2. — Elementary connection diagram of the rotor-fed three-phase shunt commutator motor with change-over switching arrangement for extending the range of regulation.

a_1—a_6 and b_1—b_6 represent the two sets of brushes of the six-phase double brush yoke.
S_1' and S_1'' are two component windings of one of the six phases of the stator winding.
U_1 and U_6 are two of the six change-over switches for switching over to the extended regulation range.

The change-over switches U_1 to U_6 can conveniently be combined in a controller built on to the motor; this can then be operated by means of a small pilot motor controlled by an auxiliary contact on the brush yoke. The increase in price of the motor due to the controller is small, so that in this way it is possible to obtain the extended range of regulation much more cheaply than if the motor had to be built for the large regulation range without change-over switch. The arrangement comes into consideration for motors of outputs of about 100 to 500 H.P.

As a rule, however, driving powers of such plants are of the order of several thousand H.P., so that it is worth while employing a system of regulation which reduces the losses to a minimum. In such cases the Brown Boveri Scherbius cascade arrangement with its very high efficiency is particularly suitable.

Scherbius cascade arrangements for drives with fan torque requiring speed regulation over a large range, can be provided for increased regulation range downward by interposing between the slip-rings of the induction motor and the main terminals of the Scherbius machine a regulating transformer, which we might call "the rotor circuit transformer". Scherbius cascade units for the ranges usual up to the present (between about 30 % above synchronism and 30 % below synchronism) are regulated exclusively in the exciter circuit of the Scherbius machine, in that their field is varied by means of a transformer ("excitation transformer") fed from the slip-rings of the main motor. In this "normal regulation range" the Scherbius machine receives the full slip-ring voltage of the main motor; for excitation in the neighbourhood of synchronism, a small additional frequency changer is necessary. This connection for Scherbius regulation above and below synchronous speed may be assumed to be known.

The commutation of Scherbius machines is dependent essentially on the "transformer voltage" e_{tr} between neighbouring segments in the commutation zone, this transformer voltage being due to the alternating field of the machine. Let e_{tr} = constant $f_s \cdot \Phi_S$ where

f_s = slip frequency

Φ_S = flux per pole of the Scherbius machine,

and since in the normal regulation range Φ_S is proportional to f_s,

$$e_{tr} = \text{Const. } f_s^2$$

Although e_{tr} is practically compensated by an auxiliary field, experience shows that e_{tr} must for reasons of commutation not exceed a certain definite value (E_{tr}). E_{tr} therefore fixes the normal regulation range of the

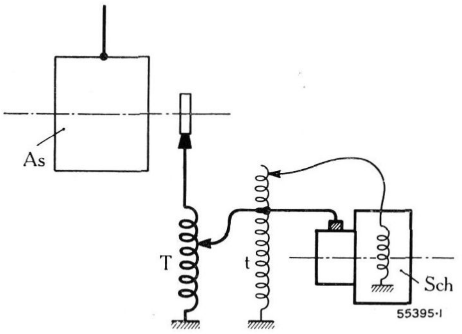


Fig. 3. — General fundamental diagram for the extended regulation range of the Scherbius cascade.

As. Main induction motor.
Sch. Scherbius machine.
T. Rotor circuit transformer.
t. Excitation transformer.

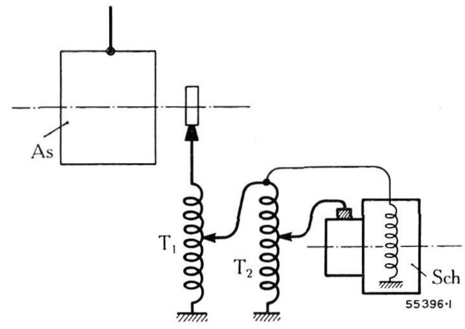


Fig. 4. — Theoretical diagram for the extended regulation range of the Scherbius cascade.

As. Main induction motor.
Sch. Scherbius machine.
T_1 and T_2. Two identical rotor circuit transformers.

cascade arrangement. Beyond the lower limit of the normal range of regulation (where $e_{tr} = E_{tr}$), it is possible to increase the range only by reducing Φ_S, that is, by reducing the voltage of the Scherbius machine by means of the above-mentioned "rotor circuit transformer". The elementary diagram for the "extended regulation range" is shown in Fig. 3, where t is the excitation transformer and T the rotor circuit transformer. It is convenient to regulate t and T simultaneously, so that e_{tr} is always equal to E_{tr}. The Scherbius machine has then for every value of f_s the maximum admissible voltage with regard to commutation; the losses of the Scherbius machine are then a minimum. Moreover, it is possible to compensate a constant e_{tr} with simple means.

The following symbols are employed in the subsequent discussion:

ε_R = Slip-ring voltage of the main motor.
ε_S = Terminal voltage of the Scherbius machine.
ε_e = Excitation voltage of the Scherbius machine.
s = Slip of the main motor.
α = Transformation ratio of the transformer T.
β = Transformation ratio of the transformer t.

Let for the upper limiting speed of the extended regulation range

$$\alpha = 1 \qquad \beta = 1 \qquad \varepsilon_R = E_R \qquad s = S \qquad e_{tr} = E_{tr}$$

If now first only transformer T is regulated, in that α is made smaller than 1, then s remains practically unaltered, but ε_s, Φ_s and e_{tr} decrease in the ratio of α to 1, then

$$\varepsilon_e = \varepsilon_S = \alpha E_R \qquad s = S \qquad \varepsilon_{tr} = \alpha E_{tr}$$

If now transformer t is also regulated, in that β is made larger than 1, then the slip and the slip-ring voltage increase in the ratio of $\beta:1$, and hence $s = \beta S$ $\varepsilon_R = \beta E_R$.

Further:

$$\varepsilon_S = \alpha \beta E_R \qquad \varepsilon_e = \alpha \beta^2 E_R \qquad e_{tr} = \alpha \beta^2 E_{tr}$$

If, therefore, e_{tr} is always to maintain the value E_{tr}, then α and β must be regulated simultaneously so that

$$\alpha \beta^2 = 1 \text{ or } \beta = \frac{1}{\sqrt{\alpha}}$$

A purely theoretical possibility of automatically achieving the desired dependency of ε_R, ε_S and ε_e is shown in Fig. 4. T_1 and T_2 are here two identical regulating transformers, which both have simultaneously the same transformer ratio ($=\sqrt{\alpha}$). The connection has, of course, no practical significance.

The same effect is, however, very closely approximated to with the practically feasible connection according to Fig. 5, in which the Scherbius excitation

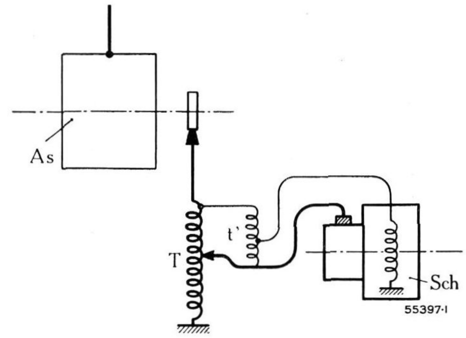


Fig. 5. — Elementary diagram for the extended regulation range of the Scherbius cascade as suggested by the author.

As. Main induction motor.
Sch. Scherbius machine.
T. Rotor circuit transformer.
t'. Auxiliary transformer.

is connected to a fixed tap of the auxiliary transformer t′ fed from the voltage $\varepsilon_R - \varepsilon_S$. If the transformation ratio of t′ is of the order of $3:1$, then ε_{tr} remains approximately constant over a large range of slip during regulation of the transformer T. For a ratio of $3:1$ we have the relation

$$\varepsilon_e = \left[\alpha + \frac{1}{3}(1-\alpha)\right]\varepsilon_R = \frac{1+2\alpha}{3}\varepsilon_R = \frac{1+2\alpha}{3\alpha}\varepsilon_S$$

and hence

$$\beta = \frac{\varepsilon_e}{\varepsilon_S} = \frac{1+2\alpha}{3\alpha}$$

and

$$s = \beta S = \frac{1+2\alpha}{3\alpha} \cdot S$$

Further

$$e_{tr} = \alpha \beta^2 E_{tr} = \frac{1}{9}\left(\frac{1}{\alpha} + 4 + 4\alpha\right) E_{tr}$$

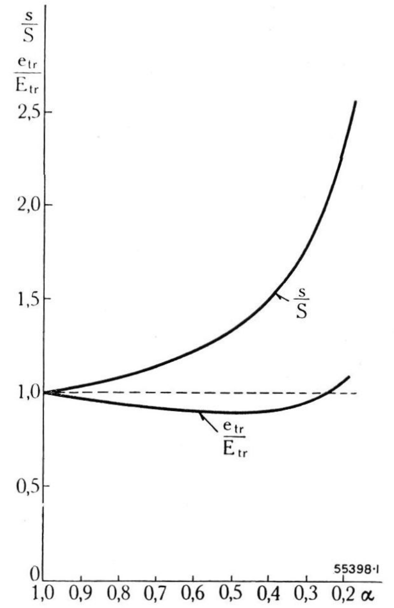


Fig. 6. — Variation of the slip and transformer voltage per commutator segment as a function of the regulation position of the rotor circuit transformer.

α Transformation ratio of the rotor circuit transformer.
s. Slip.
S. Slip at $\alpha = 1$.
e_{tr}. Transformer voltage per segment.
E_{tr}. Transformer voltage per segment at $\alpha = 1$.

Fig. 6 shows the quantities $\frac{s}{S}$ and $\frac{e_{tr}}{E_{tr}}$ drawn as a function of α. A regulation of the transformer T from $\alpha = 1$ to $\alpha = 0{\cdot}18$ corresponds to approximately a 2·5 times increase of the slip, during which e_{tr} remains practically constant (variation $\pm$ 10 %).

Fig. 7 shows the complete connection of such a Scherbius cascade with normal and extended regulation range, including the necessary switching apparatus. The Scherbius machine has the following three windings in the stator:—

1. The compensating winding k, which compensates not only the rotor winding, but also causes the actual reversal of current.
2. The excitation winding e.
3. The interpole winding w for producing the auxiliary field and neutralizing the transformer voltage e_{tr}.

The change-over switch r enables the excitation winding e to be reversed when passing through synchronism.

In the normal regulation range the change-over switches u_1, u_2, u_3 are in the right-hand position, the terminals of the Scherbius machine are then connected

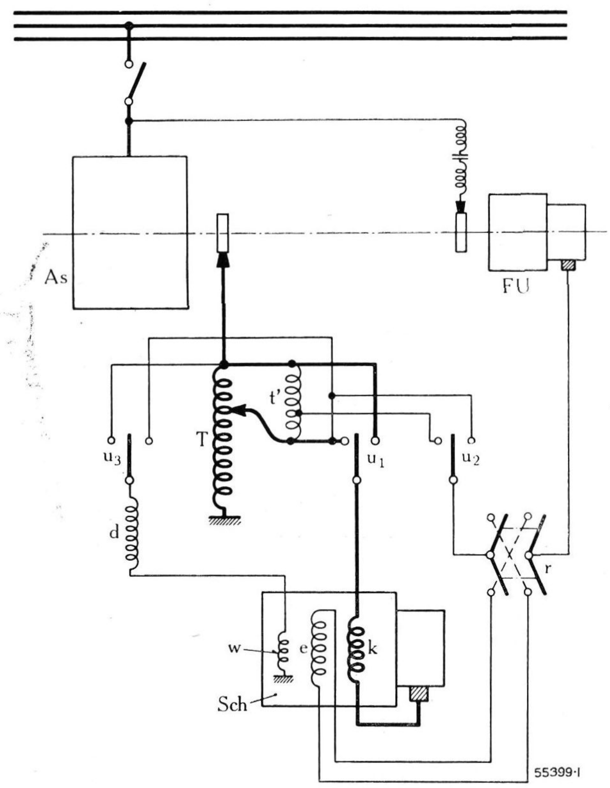


Fig. 7. — Complete diagram for the Scherbius cascade with change-over switching from normal to the extended regulation range.

As. Main induction motor.
Sch. Scherbius machine.
FU. Frequency changer.
k. Compensating winding.
e. Excitation winding.
w. Interpole winding.
T. Rotor circuit transformer.
t'. Auxiliary transformer.
d. Choke coil.
r. Reversing switch.
$u_1\ u_2\ u_3$. Change-over switches.

directly to the slip-rings of the main motor, and the excitation winding e to the regulating contacts of the transformer T. Except for the arrangement of the auxiliary winding w, further described below, the connection corresponds to that of the normal Scherbius regulation above and below synchronism.

In the extended regulation range the change-over switches u_1, u_2, u_3 are to the left. The terminals of the Scherbius machine are then connected to the regulating contacts of the transformer T and the exciter winding e to the taps of the auxiliary transformer t'. The connection corresponds to that of Fig. 5.

The current in the auxiliary winding w is determined mainly by the apparent resistance of the choke coil

d. When operating in the extended regulation range, this circuit is fed directly from the slip-rings of the main motor, whereby a constant current, that is to say, a constant auxiliary field is obtained which ensures the compensation of the practically constant voltage e_{tr}. When operating in the normal regulation range, the auxiliary circuit is connected in parallel to the excitation winding e, so that, provided the choke coil is not saturated, a current proportional to the slip results. It would, however, be desirable to have a current proportional to the square of the slip, which can be achieved approximately by giving a suitable saturated characteristic to the choke coil.

The connection of the Scherbius cascade according to Fig. 7 enables not only a very wide regulation of the speed of drives with fan torque, but also, provided the transformer T is designed as a continuously variable regulating transformer with sliding contacts, an absolutely continuous regulation of the speed, which is particularly advantageous with automatic control.

The switches u_1, u_2, u_3 and r can conveniently be combined in a controller which also contains the control contacts for the pilot motor of the transformer T. Each position of the controller must correspond to a definite position of the transformer T.

We may here mention the order in which the switches close for regulation of the speed from maximum down to minimum.

At maximum speed the change-over switch r is in the upper position and u_1, u_2, u_3 to the right, the transformer T is adjusted for $\alpha = 1$. By regulation of the transformer T from $\alpha = 1$ to $\alpha = 0$, the speed can be brought down to synchronism. After reversing the Scherbius excitation by r, the transformer T is again brought from $\alpha = 0$ to $\alpha = 1$, whereupon the lower limit of the normal regulation range is attained. After switching over the change-over switches u_1, u_2, u_3 to the extended range, it is possible further to regulate the speed down to the limit of this extended range by regulating the transformer T.

A picture of a wind tunnel for aero-dynamic investigation of aero engines and aeroplanes of full size, is shown in Fig. 8. A variable-speed Brown Boveri Scherbius set drives the blower, which absorbs a power of 4750 H.P. Air is drawn in from the atmosphere and is ejected again to the atmosphere at the end of the tunnel. This is, therefore, a so-called open wind tunnel.

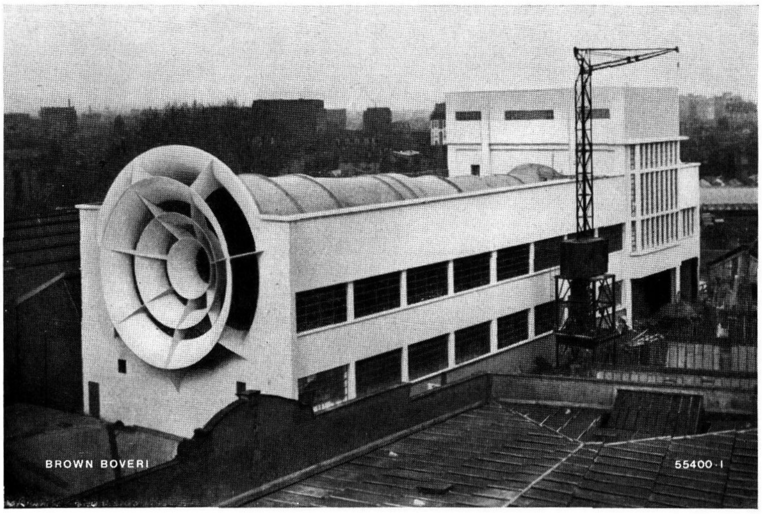


Fig. 8. — Large wind tunnel for aero-dynamic investigations on aero-engines and aeroplanes of full size.

With this open tunnel air is drawn in at one end and ejected to the atmosphere at the other. A Brown Boveri Scherbius regulating set drives the blower which absorbs a power of 4750 H. P.

The maximum air speed in the measuring chamber is 100 m/sec., that is 360 km/h. The blower, which has a diameter of 8 m, delivers at 300 r. p. m. the enormous air quantity of 1950 m^3/sec. It is, together with its induction motor, mounted directly in the wind tunnel, The speed is varied practically without loss by means of the Scherbius machine above and below synchronous between the limits of 330 and 230 r. p. m.

Long years of experience in the field of mechanics of fluids enable us to supply complete plants for aero-dynamic wind tunnels with air speeds above sound velocity or below sound velocity as well as high altitude test plants for aeroplane engines.

(MS 875) *H. K. Schrage. (Hv.)*

DYNAMOMETERS.

Decimal Index 621.317.788

Electric dynamometers are electric machines specially adapted to measure the input or output of prime movers or driven machines.

GENERAL.

ELECTRIC dynamometers are usually provided to brake prime movers and measure simultaneously their torque, in which case they operate as generator. If employed as a motor, however, they can be used for the testing of driven machines and the measurement of their input.

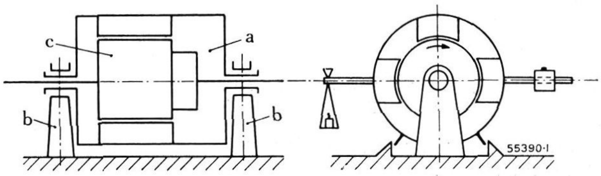


Fig. 1. — Diagrammatic illustration of fundamental layout of a dynamometer.

a. Swinging carcase. b. Bearing pedestals. c. Armature.

Very accurate measurements are possible with an electric dynamometer in an extremely simple manner providing the balance and speed counter are of high-class design.

I. FUNDAMENTAL LAYOUT.

Electrically, dynamometers operate exactly like direct-current shunt-wound machines, but mechanically there is an essential difference in that the carcase is mounted so as to swing freely about the shaft axis. The principle of the layout is shown in Fig. 1 where a is the carcase mounted in the pedestal bearings b (usually ball or roller bearings) and free to swing through a certain angle. Following standard direct-current machine practice the armature c is supported in the end shields of the carcase. Similarly to a balance, the carcase oscillates about its axis, the degree of deflection being limited by a stop. It is usually provided with two lever arms, one of which carries a sliding weight to enable the swinging carcase to be accurately balanced when the machine is unexcited and at rest, while the other serves for the measurement of the torque when the machine is running, either by means of weights suspended from it or by transmitting the torque to suitably arranged spring or sliding weight balances. Compared with other designs this fundamental layout is probably also the most appropriate from a practical point of view.

For the sake of completeness, however, another layout is shown in Fig. 2.

In this case the friction in the pedestal bearings does not affect the swinging carcase either when the dynamometer is generating or when it is motoring,

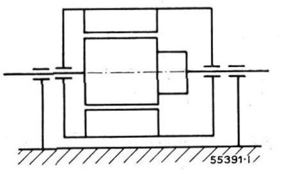


Fig. 2. — Another possible arrangement for the swing mounting of dynamometers.

i. e., in the latter case is not transmitted to the shaft of the driven machine. The resulting metering error could be compensated with the help of correction curves, but according to the sign (plus or minus) of the correction this is not practical. In view of these drawbacks the layout in Fig. 2 is of less importance and not to be recommended where a high degree of accuracy is required.

II. TORQUE.

The machine on which measurements are to be made is usually directly coupled (flexibly or rigidly) to the dynamometer, for the losses involved by belts and the like cannot readily be determined. With the fundamental layout in Fig. 1 the torque imparted by the prime mover to the armature or transmitted from the latter to a driven machine acts entirely on the freely swinging dynamometer carcase. The torque transmitted by the armature to the carcase comprises chiefly the magnetic torque resulting from the current through the armature and the excited carcase field, together with the reaction moment due to bearing and brush friction and the loss of energy due to the windage impinging on projecting parts of the carcase. When operating as generator, therefore, the dynamometer correctly indicates the torque imparted to it by adding the bearing and brush friction and windage torque to the magnetic torque; all of these are in the same direction. On the other hand, a dynamometer in use as a motor will subtract the friction and windage torque from the magnetic torque and thus also indicate the torque transmitted to the machine coupled to it. The product of the length of the lever arm (in metres) and the pull or pressure acting on it (in kg) gives the torque in mkg imparted to or transmitted by it.

The reaction of the windage can be obviated by suitably controlling the ventilating air in the dynamometer, thus rendering correction unnecessary. A simple method of achieving this is to arrange the air inlet and outlet on the carcase in the axial direction and to provide them with nozzles (Fig. 8).

The slight inaccuracy involved by the ball or roller bearings of the swinging carcase can be reduced to a minimum by pivoting the swinging part of the dynamometer on knife-edges. This, however, entails mounting the dynamometer carcase on a special frame, as shown diagrammatically in Figs. 3 and 4.

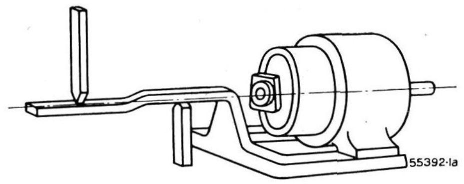


Fig. 3. — Dynamometer with swinging carcase supported on knife-edges for laboratory installations.

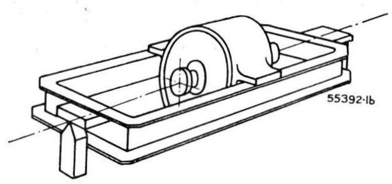


Fig. 4. — Dynamometer with swinging carcase supported on knife edges for laboratory installations.

The overhung arrangement in Fig. 3 is suitable for low powers, whereas the layout with a complete frame in Fig. 4 is intended for high powers.

The reaction in the tangential direction due to the unrestricted outlet of the ventilating air to atmosphere is not transmitted to the dynamometer carcase and so may cause slight errors.

Notwithstanding the use of ball or roller bearings slight inaccuracies may creep in due to the swinging carcase. Although these errors are relatively small — generally only amounting to a fraction of 1 % — they can be entirely avoided as described hereafter when an extremely high degree of accuracy is required.

The first class of error can be corrected where considered necessary, i. e., in the case of high-speed machines, with the help of efficiency curves. Such corrections for windage torque must be added to the measured torque when the dynamometer operates as a generator and subtracted when it functions as a motor.

The correction torque is dependent on the speed and must be experimentally determined for various speeds by accurately balancing the dynamometer when at rest and allowing it to run light at different speeds. The reaction torques then developed will give the corrections to be applied to the load readings. Actually, however, the knife-edges are on the balance beam.

III. SPEED.

To ensure accurate measurements with the dynamometer high-class speed counters must be used. These may be belt or band driven from the machine shaft, although direct coupling is preferable on account of the possibility of slip. The speed can also be measured with an a. c. generator or a frequency indicator connected to the dynamometer shaft, in which case measurements are not restricted to the installation site of the dynamometer. In order correctly to take account of the power required to drive the speed counter, which must be considered as a dynamometer loss, it is again necessary to resort to curves for correction purposes. These small losses, however, are of little importance and can in most cases be entirely neglected.

IV. POWER.

The torque measured by the dynamometer multiplied by the speed counted on the shaft gives the power imparted to or transmitted by the shaft. With a torque M_d in kgm and a speed n in r. p. m. the power N is obtained from the following formula:—

$$N = \frac{M_d \cdot n}{973} \text{ kW}$$

$$\text{or } N = \frac{M_d \cdot n}{716} \text{ H. P. (metric)}$$

a simple and rapid manner. Apart from the influences of a mechanical nature the accuracy of such power measurements also depends on the errors inherent in every metering instrument. Given the present state of development of instrument construction, however, these errors are generally very small and can usually be neglected.

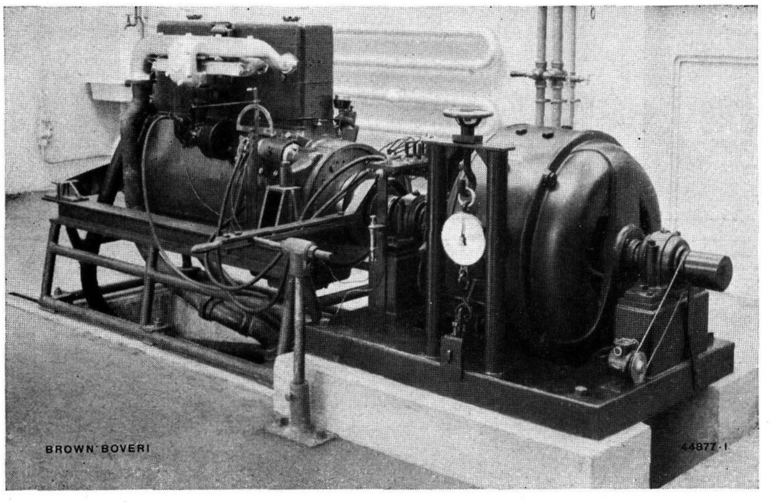


Fig. 5. — Dynamometer for medium powers and speeds.

Rating 60 kW, speed 1000—1700 r. p. m.

With a standard machine the method of oscillating suspension shown in Fig. 2 can be employed.

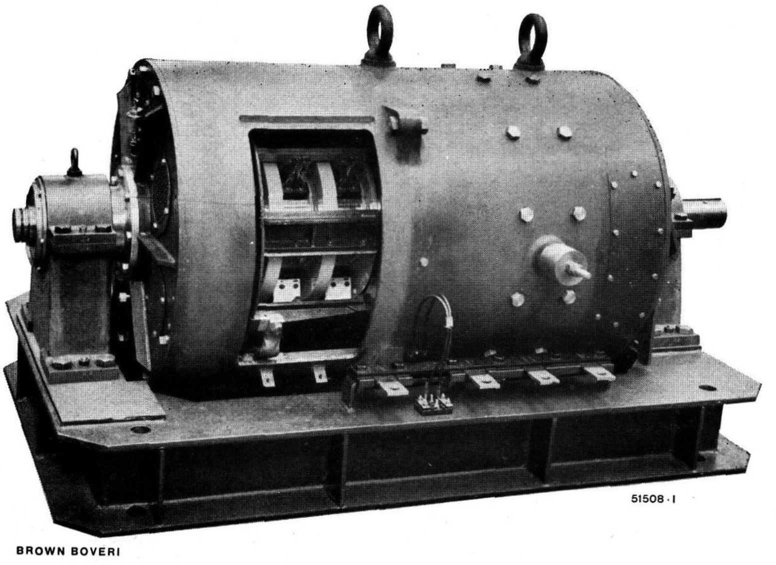


Fig. 6. — Dynamometer for measuring the torque of the propeller of aeroplane engines at various speeds.

The dynamometer is combined with a sliding-weight scale on which the torque can be read off with great accuracy. It is also employed for measuring the power of and loading aeroplane engines.

Maximum rating 350 H. P., speed range 500—4500 r. p. m.

Except for the quite unimportant forces not transmitted to the swinging carcase the mechanical power on the shaft can thus be accurately determined in

When ball or roller bearings are employed for the swinging carcase, as in the fundamental layout in Fig. 1, the error is hardly likely to exceed $\pm$ 0·2 % at the normal torque of the dynamometer, but will be greater when measuring very low torques. In large

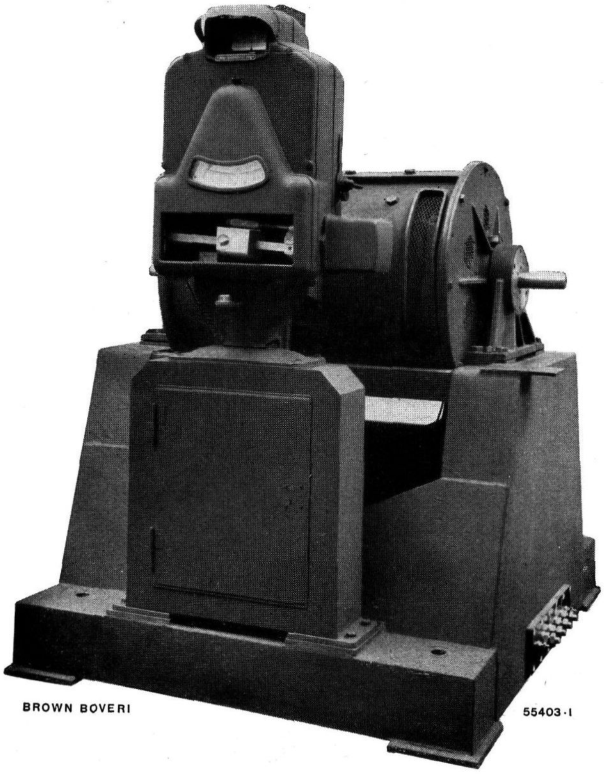


Fig. 7. — Dynamometer with built-on sliding-weight scale for simply and accurately measuring the torque of turbo-compressors.

(Manufactured by Brown, Boveri & Cie. A. G., Mannheim.)

The torque at various compressor speeds can be read off directly on the sliding-weight scale.

Maximum rating 180 kW, speed range 2500—3500 r. p. m.

works where the torques to be measured fluctuate between wide limits and importance is attached to a high degree of metering accuracy over the entire torque range, it is advisable to purchase a number of dynamometers to cover the whole of the desired metering range.

V. CONTROL.

The dynamometer can be employed as motor or generator alternately. Its speed and load can be very easily controlled. The necessary accessory equipment for control purposes depends on the field of application and the degree of control required.

In the simplest case, where exclusively prime movers have to be braked and their output measured, only a hydraulic resistance for the dissipation of the electrical energy generated is required for a wide speed and torque range, in addition to the auxiliary supply for the excitation of the dynamometer. In works where machines have to be driven and their power consumption measured, or where braked energy has to be recuperated, a power supply system is of course necessary. Since a wide range of speed variation is generally specified for testing installations Ward-

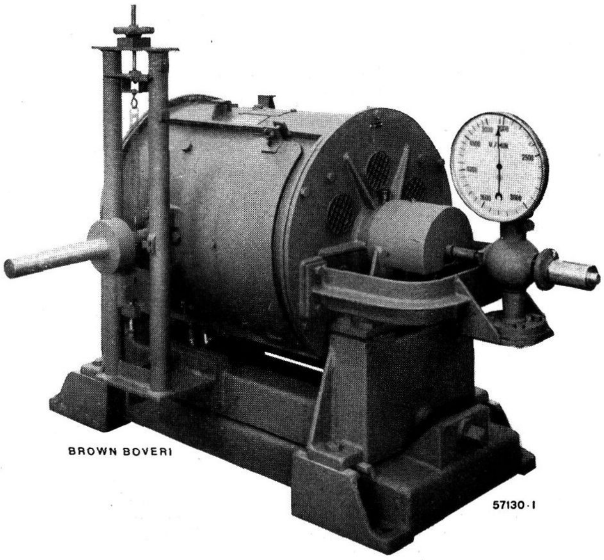


Fig. 8. — Dynamometer for measuring the torque of small blowers. The necessary weights can be displaced on the arm of a lever on the swinging stator.

The air inlet and outlet in the axial direction avoid metering errors through windage.

The mounting of the speed counter on the swinging carcase obviates the metering error due to friction in the speed counter.

Rating 40 kW, speeds 2000—4500 r. p. m.

Leonard control is usual for a. c. systems and boosters for d. c.

VI. TYPES OF DYNAMOMETERS.

For low and medium powers and where a high degree of accuracy is not imperative standard d. c. machines, arranged as shown in Fig. 2, can be employed, very little alteration being involved to enable them to be used as dynamometer (Fig. 5).

The increased speeds and outputs of internal combustion engines have led to a demand for dynamometers suitable for testing them accurately. Examples of such machines for the braking and measurement of outputs up to 260 and 180 kW at speeds of 4500 and 3500 r. p. m., respectively, are shown in Figs. 6 and 7.

These models correspond to the fundamental layout in Fig. 1, the well-known d. c. turbo designs being employed for the high-speed dynamometers.

A precision-type dynamometer for the measurement of high-speed, low-power machines is shown in Fig. 8. With this design not only are the ventilating air inlet and outlet arranged axially and provided with nozzles, but the casing of the speed counter is also rigidly connected to the swinging carcase of the dynamometer to avoid all error from reaction torques. The high speeds required led to the turbo design being selected, but for tests at medium speed the "barrel" construction (Fig. 9) has also proved very suitable for dynamometers.

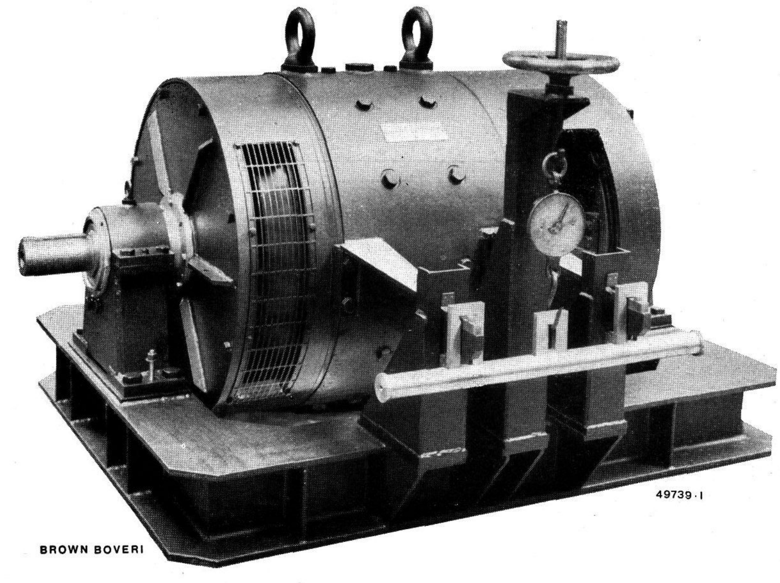


Fig. 9. — Dynamometer for measuring the torque of electric motors.
The torque can be read off directly on a built-on spring balance.
Maximum rating 260 kW, speed range 1000—1800 r. p. m.

VII. SPHERE OF APPLICATION.

Dynamometers are suitable for the measurement of the output of prime movers or of the input to driven machines. In addition to the measurement of power and the braking of internal combustion engines, turbines, steam engines, etc., dynamometers are also used for starting internal combustion engines. The dynamometer is the most scientifically accurate and easily applied instrument for measuring the power required by pumps, blowers, gears, aeroplane propellers, and the like. It can also be used to advantage for running in engines and for no-load friction and compression loss measurements.

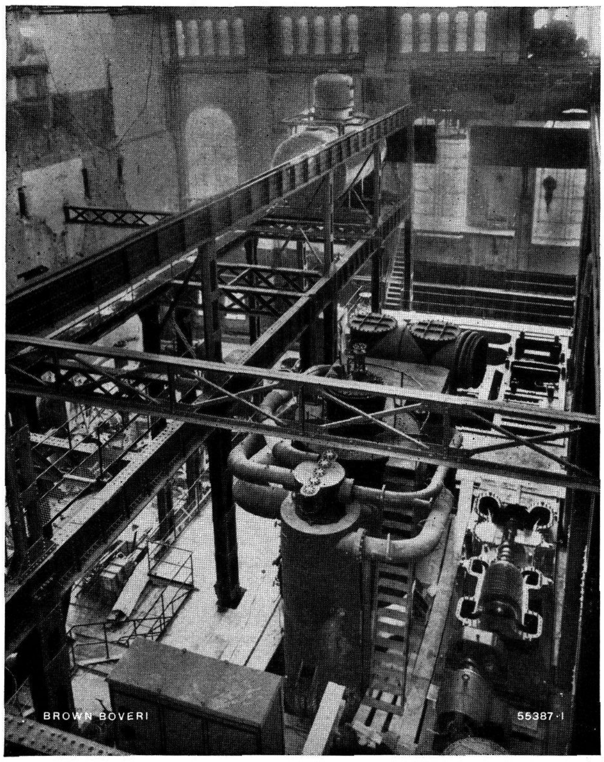
(MS 917) *N. Widmer. (E. G. W.)*

BRIEF BUT INTERESTING

Erection of large Velox Boilers Overseas.

Decimal Index 621.181.65

TWO of the largest Velox boilers so far constructed are at present in course of erection at the Pedro Mendoza Power Station of the Cia. Italo-Argentina de Electricidad at Buenos Aires. Both boilers are designed for a continuous evaporation of 80 t/h. The accompanying view



Two Velox boilers, each with an evaporation of 80 t/h, in course of erection at the Pedro Mendoza Power Station of the Cia. Italo-Argentina de Electricidad at Buenos Aires.

Note the small space requirements: Area covered by both boilers 25×11 m, necessary total height including basement 12·5 m.

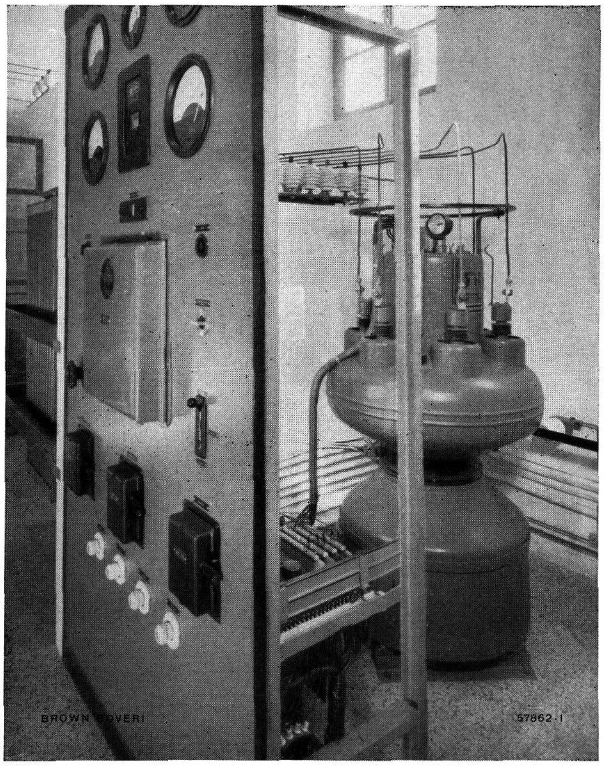
of the erection site depicts the first boiler towards the end of the erection period. The site for the second is also visible in the background. The illustration shows very clearly how little space a Velox boiler requires. Plant with an aggregate evaporation of 160 t/h, corresponding to an output of approximately 35,000 kW, is arranged on a surface of 25 × 11 m. The height of the basement is 4·5 m and the boilers only project 8 m above the floor of the turbine room. This represents a big saving on building costs.

(MS 953) *A. Spoerli. (E. G. W.)*

Pumpless Mutator operates 14,000 Hours without Backfire.

Decimal Index 621.314.65.004

AFTER a period of exhaustive research and design work the first tests with pumpless mutators were carried out by us some years ago and led to excellent results within a short time.



Automatic pumpless mutator plant rated 350 kW, 1500 V, at Mesocco on the Rhætian Railways.

The small space requirements, little attendance necessary, and high efficiency make the pumpless mutator the ideal traction convertor.

Thereupon, we got into touch with a number of customers with a view to trying out in suitable installations several units of the first model constructed and thus proving the results obtained in our test bay. Thanks to the comprehension shown by the parties approached and the great interest aroused by this addition to our range of mutators it was found possible to install a whole series of trial pumpless units in railway and tramway substations.

Apart from a few initial difficulties invariably inherent in new designs and which were quickly surmounted, the pumpless model proved extremely satisfactory, so that it was possible immediately to accept orders with full guarantees.

Of the many plants supplied in the meantime a mutator feeding a foreign municipal tramway is worthy of special mention. The working day of the undertaking in question is very long and as a result the plant has already operated over 14,000 hours. It has given entire satisfaction, not a single backfire having occurred during the long working period which has only been interrupted by short daily intervals. This gratifying result not only proves the excellence and appropriateness of the design of the equipment, but shows that a good vacuum can be continuously maintained in our pumpless mutators under onerous working conditions.

(MS 952) *A. Odermatt. (E. G. W.)*

Safety First!

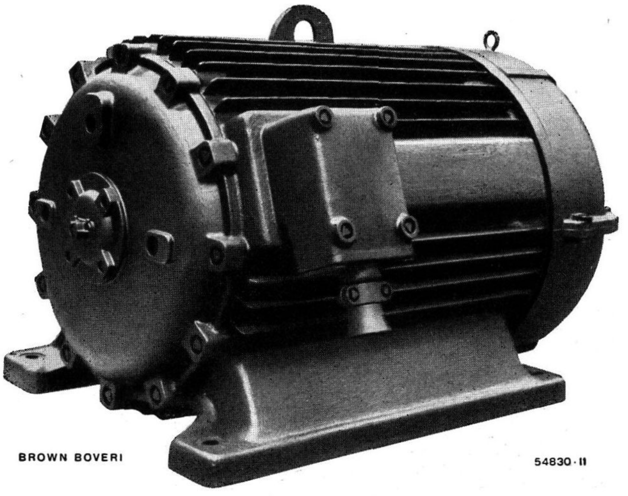
Decimal Index 621.313.13—213.44

GRAVE risks may be run if standard electric machines are installed in locations where the atmosphere contains mixtures of explosive or inflammable gases. Such conditions may obtain in oil refineries, the chemical industry, works processing by-products of coal, munition works, etc., as well as in mines where fire-damp may occur. Sparking of the slip rings, winding faults, accidental contact with the terminals, scraping of the rotor against the stator, etc., can easily lead to the ignition of an inflammable gas-mixture if the necessary precautions are not taken to prevent an explosion within the machine being transmitted to the surrounding atmosphere.

In view of the wide application of electric drives to industries manufacturing explosive or readily inflammable products in recent years Brown Boveri have put on the market a new series of three-phase explosion-proof motors which give complete protection against the transmission of flame from the interior to the atmosphere. Exhaustive investigations of the conditions governing explosions which were carried out in a test room built specially for the purpose have enabled high-quality motors to be designed that fully meet the exacting specifications for this class of material.

The illustration shows a motor which can be used without hesitation in explosive atmospheres. Such machines are of the squirrel-cage or slip-ring type and have ratings up to 260 kW and 1100 V. They are totally-enclosed, have an external fan for surface cooling, and withstand internal pressures up to 10 kg/cm^2 abs, thus conforming to the severest specifications. The casing is very liberally dimensioned and is attached to the end shields by means of strong bolts which can only be unscrewed with a special spanner. All joints and in particular the shaft bore are very accurately machined, so that internal explosions cannot possibly be communicated to the exterior. The terminal boxes are likewise explosion-proof, while the various screws are all locked to prevent their working loose.

During the manufacturing process every motor is pressure tested at 10 kg/cm^2 abs. Each type or size of motor has also been subjected to an explosion test in conformity with the exacting regulations. For this purpose the interior of the motor was filled with a mixture of explosive gas which was caused to ignite. The motor was considered to have passed the test when no flames were transmitted to the exterior. These far from simple tests were carried out in a special test chamber and afford a guarantee of the quality of the machines.



Three-phase explosion-proof motor.

This motor conforms to the most exacting specifications and gives maximum safety in explosive or inflammable atmospheres.

In all locations where explosive or inflammable gas mixtures may occur and standard motors are installed, they should immediately be replaced by explosion-proof motors, which give 100 % safety even in the most dangerous atmospheres.

(MS 904) *G. Rochat. (E. G. W.)*

The first Electric Bus in Switzerland.

Decimal Index 629.113.65—45
621.335.9

WITH the present shortage of liquid fuels it might have been expected that all automobiles would disappear from the road. This, however, is not the case, for new types of vehicles now help to maintain road traffic. Whose attention has not been drawn by a passing producer or compressed-gas operated lorry or car? One of the new-comers, however, the *electric vehicle*, has made its appearance practically unnoticed by the general public. Who would suspect that the passing elegant and silent car is operated by a storage battery and not by petrol, or producer or compressed-gas? Within a period of eighteen months Brown Boveri alone have supplied over 160 equipments for electric vehicles. In this way, electricity, the Swiss national source of energy, has found a new field of application hitherto dominated practically exclusively by the internal combustion engine.

After conversion of numerous lorries, delivery vans, and private cars to electric drive attention was turned to the motor buses of transport undertakings. The first vehicle of this type to be equipped was the new electric bus of the Société des Autotransports du Pied du Jura Vaudois depicted in the accompanying illustration.

The special conditions of the case in question, where approximately 100 km have to be covered daily, made it necessary to render the vehicle more or less independent of its depot. Moreover, it was imperative that the specified schedule, including several halts of one to two hours, be adhered to. An obvious step was to endeavour to employ these intervals for re-charging the battery, whereby the weight of the latter and, in consequence, also that of the whole bus could be considerably reduced.

To avoid having to provide a charging station at each lengthy halt Brown Boveri suggested mounting the charging set directly on the vehicle. To put the charging set to work a plug merely has to be pushed into a socket in the supply system. All other operations are effected automatically. The advantage of this arrangement which occasions no additional work and involves no supplementary instruction of the driver is obvious.

The electric bus in question operates over the 18·7 km long Morges-Cossonay route. It has a tare of 6·46 t, a seating capacity of eighteen, and a mail and cycle compartment at the rear. The 19 kW traction motor enables a speed of 40 km/h to be attained on the level.

All control gear hitherto employed, i. e., accelerator, clutch, and brake pedals, as well as the change gear have been retained, so that the bus is just as simple to drive as a petrol vehicle and a fresh period of instruction is unnecessary for the drivers.

(MS 933) *H. Bachelin. (E. G. W.)*

Electric bus recently put into service by the Société des Autotransports du Pied du Jura Vaudois.

The first battery-operated bus in scheduled service in Switzerland with charger on vehicle. The bus is independent of fixed charging stations and can re-charge its battery wherever a three-phase supply is available, thus considerably increasing its radius of action.

A New Method of Voltage Regulation.

Decimal Index 621.316.722

THE Wimmis Substation (Switzerland), recently taken into commission, is connected to the new 150 kV transmission line erected between the Innertkirchen Power Station and the Mühleberg Power Station of the Bernese Power Co. along the southern shores of the lakes of Brienz and Thun. Its fundamental layout is shown in Fig. 1.

The 65 kV line is provided for an exchange of energy in both directions. The auto-transformer with on-load tap-changing switch, which interconnects the 50 and 65 kV systems, regulates the voltage automatically. Independent of the direction of flow of energy two methods of operation are possible:

1. No generating plant is in operation in the receiving system.
2. Generating plant is in operation in both systems.

With the usual method of voltage regulation the voltage is raised both when active and reactive power is being delivered. In the latter case this leads to intolerable working conditions when power is being supplied to a system having generating plant of its own in operation. In the case of the new method of regulation the voltage is reduced to such an extent when reactive power is being delivered that the energy is transmitted with the highest possible power factor. The equipment can be employed unchanged in both of the above-mentioned operating cases,

i. e., both when energy is being supplied to a system with no generating plant of its own in operation and when the two interconnected systems each has generating plant in service. This method of regulation has been developed in collaboration with the Bernese Power Co.

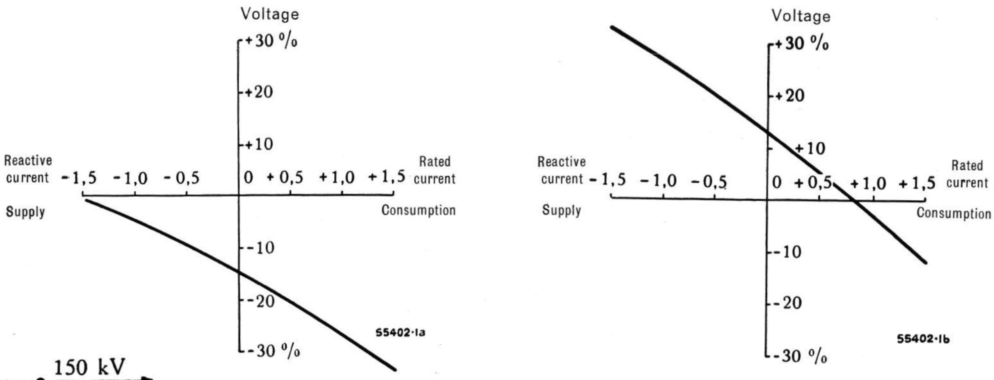


Fig. 2. — Voltage characteristic with constant active and variable reactive current.

(a) Active current taken from 65 kV line.
(b) Active current delivered to 65 kV line.

From the curves it will be seen that the automatic voltage regulating equipment enables the energy to be transmitted at the highest possible power factor.

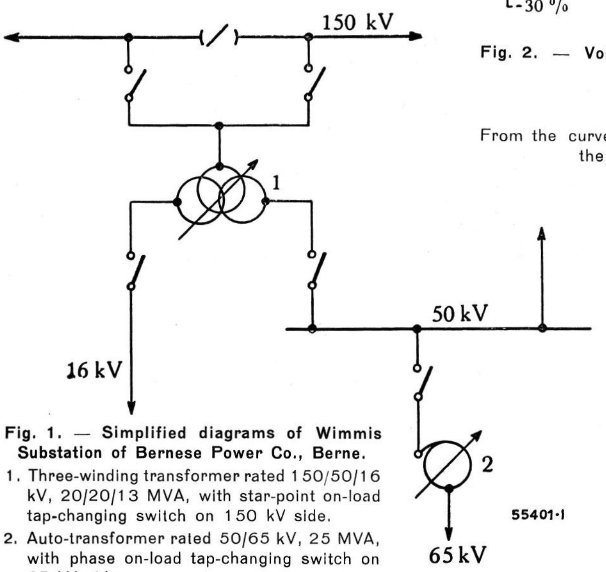


Fig. 1. — Simplified diagrams of Wimmis Substation of Bernese Power Co., Berne.

1. Three-winding transformer rated 150/50/16 kV, 20/20/13 MVA, with star-point on-load tap-changing switch on 150 kV side.
2. Auto-transformer rated 50/65 kV, 25 MVA, with phase on-load tap-changing switch on 65 kV side.

With the arrangement employed the required value of the regulated voltage is dependent on the direction and magnitude of the active and reactive current transmitted. The curves in Fig. 2 show the characteristic with constant active current and variable reactive current. By appropriately setting the adjusting rheostats employed to obtain this characteristic the effect of the active and reactive components of the current on the required voltage can be adjusted within wide limits and regulation thus adapted to the system conditions.

Fig. 3 depicts the two transformers with on-load tap-changing switch erected in the outdoor substation.

(MS 960) *P. Russenberger. (E. G. W.)*

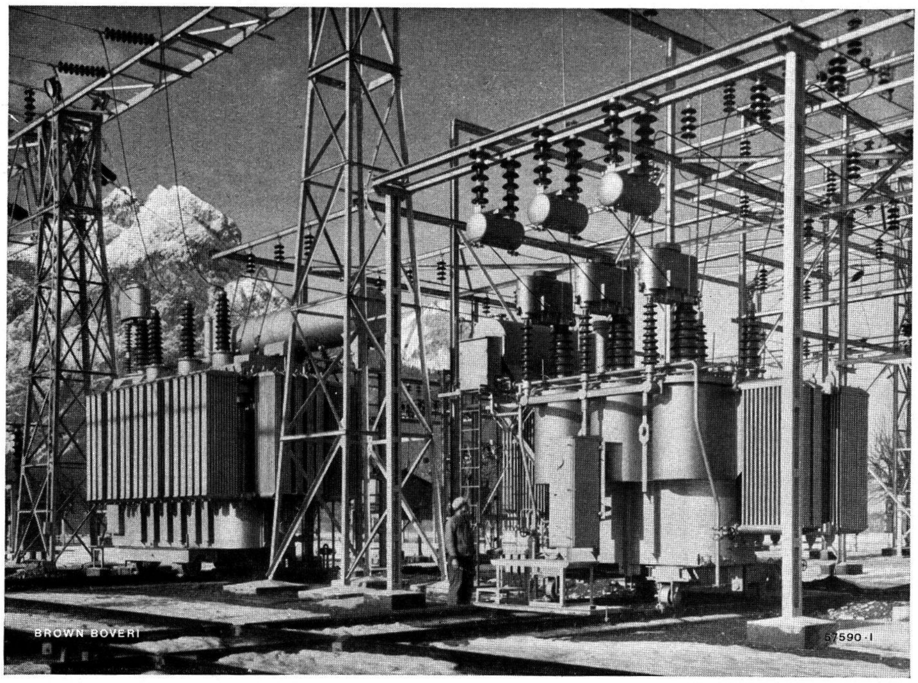


Fig. 3. — 20 MVA three-winding transformer and 25 MVA auto-transformer, both with on-load tap-changing switch, in the Wimmis Substation of the Bernese Power Co., Berne.

Without voltage regulation by means of reliable on-load tap-changing switches the necessary exchange of energy between the different systems would be inconceivable.

BROWN BOVERI

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