

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)



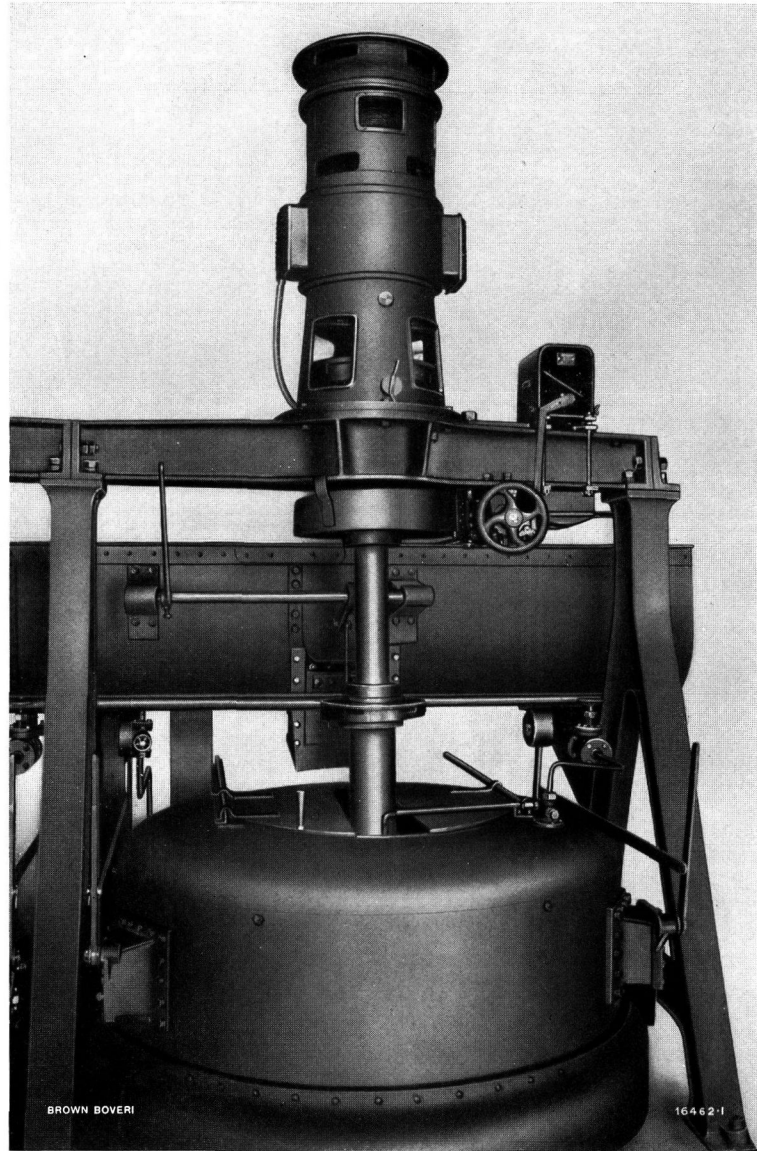
NYON-ST. CERGUE-MOREZ RAILWAY.

Motorcoach with trailer on the section below St. Cergue. Trolley-wire voltage 2000 V direct current.

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ELECTRIC DRIVES FOR INDUSTRIAL PLANTS



AARBERG SUGAR FACTORY, SWITZERLAND.

Weston centrifuge driven by a Brown Boveri three-phase alternating-current motor with centrifugal starter.

CHOCOLATE AND SUGAR FACTORIES - BREWERIES
AGRICULTURE - SMALL INDUSTRIES - MACHINE TOOLS

THE BROWN BOVERI REVIEW

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HIGH-VOLTAGE RECTIFIER INSTALLATIONS.

Decimal index 621. 313. 73.

MERCURY arc rectifier installations for converting alternating current to high-tension direct current are particularly noteworthy for their economical operation; firstly on account of the fact that the fall of potential across the arc remains approximately constant irrespective of the voltage applied, and secondly because a rectifier of a given size is capable of dealing with a much heavier load at high voltage than when the voltage is low. Further, with an increase in voltage great difficulties are encountered with rotating machines; this is not so with rectifiers, which are pre-eminently suitable for such a case and are therefore probably the converter of the future. The use of rectifiers for the conversion of alternating current to high-tension direct-current, opens up fresh possibilities for the electrification of suburban and interurban railways.

Brown, Boveri & Co. have, for some time, built a rectifier which is particularly suitable for high-tension direct current. Fig. 1 shows this piece of apparatus, Type GRZ 156, and Fig. 2 the manner in which its load capacity varies with the voltage. At 500 V on the direct-current side, the continuous rating is 670 A, and at 5000 V the rating is 250 A. The same type is therefore capable of different continuous outputs dependent on the direct-current voltage, e. g., from 500 V to 5000 V the output varies between 340

Experience shows that rectifiers behave very satisfactorily on overload. The guaranteed overload capacity of a rectifier, Type GRZ 156, plotted to a base giving the duration of the overload is reproduced in Fig. 3.

With these rectifiers, specially constructed for high tensions, exhaustive tests have been carried out both in the testing department of Brown, Boveri & Co. and in some of the plants installed, the results obtained furnishing ample proof of the reliability of the apparatus (see also The Brown Boveri Review 1922, No. 9, page 195).

A particular advantage of rectifiers is their insensitiveness to short circuit. Direct short-circuit tests have been carried out on rectifiers in the shops up to a maximum of 5000 volts D. C. Fig. 4 shows the current and voltage oscillogram of a rectifier during a short-circuit test. In this experiment the basic load applied was 820 A at 1780 V, and a Brown Boveri quick-acting circuit breaker was employed.

As already mentioned, the voltage drop in the rectifier is practically constant for all loads and working voltages. Hence it follows that, the higher the voltage the greater will be the economy of operation. Fig. 5 shows the increase of efficiency with pressures between 500 and 5000 volts. Even on the lightest loads the rectifier maintains its high efficiency,

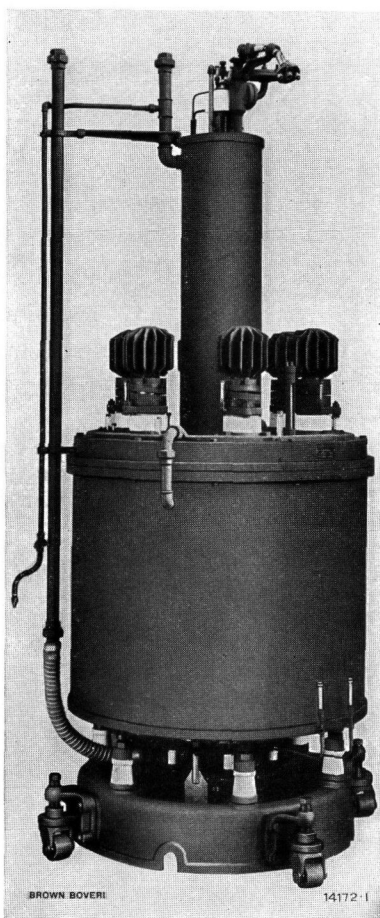


Fig. 1. — Mercury arc rectifier Type GRZ 156.

and 1240 kW.

a marked contrast to the rotary converter. This fact renders the rectifier particularly suitable for use where the load fluctuates as in the case of railway work.

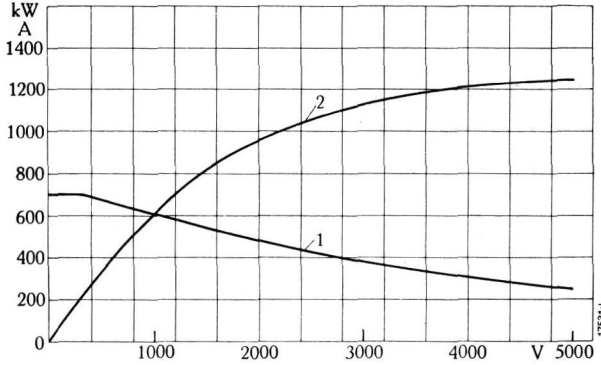


Fig. 2. — Load capacity for rectifiers GRZ 156.

1 = Current at continuous rating.
2 = Output.

The rectifier casing must not be earthed although this is the general practice with other electrical machines; consequently the whole of the cylinder is supported by six insulating feet which stand on a cast-iron foundation ring. When, owing to the conditions at the place of erection is impossible to use a crane to lift the rectifier into position, castors by means of which the rectifier may be moved are fitted to the foundation ring. These castors are so constructed that they enable the foundation ring, together with the rectifier, to be raised a few centimetres from the floor when it is desired to move the apparatus (Fig. 1). The air-pump set is similarly mounted on insulating feet, as has been the practice of Brown, Boveri & Co., for a considerable time past. The high vacuum essential for the operation of the rectifiers is produced in two stages by the Brown Boveri air-pump set Type GRLW as illustrated in Fig. 6. The set consists of two separate

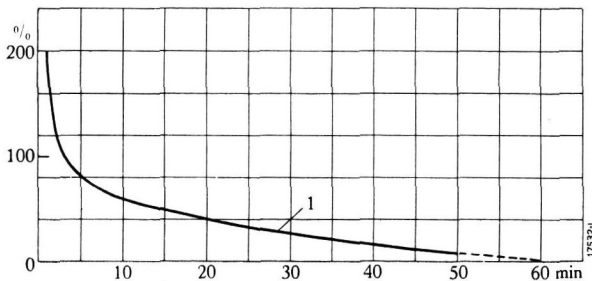


Fig. 3. — Overload capacity of rectifier Type GRZ 156 as a percentage of full load to time base.

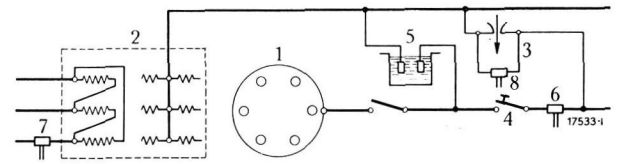
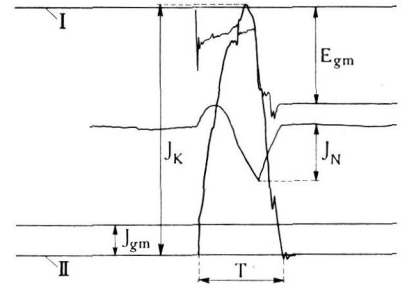


Fig. 4. — Current and voltage of power rectifier on short circuit, and diagram of connections for short-circuit test.

- I. Zero line for D. C. voltage. $E_{gm} = 1780$ V direct current.
- II. Zero line for the direct current. $J_{gm} = 820$ A direct current basic load.
- 1. Rectifier. $J_k = 6700$ A direct current on short circuit.
- 2. 1500-kVA transformer. $J_n = 1020$ A primary current in transformer.
- 3. Short-circuiting apparatus.
- 4. Quick-acting D. C. circuit breaker.
- 5. Water resistance.
- 6, 7, 8. Connections for oscillograph.
- $T = 0.0165$ sec duration of short circuit.

pumps and a vacuum gauge mounted on a common baseplate. In the first stage, a vacuum of about 0.015 mm of mercury, is produced by an oil-immersed slide-type rotary pump driven by a 0.3-kW motor. This motor is electrically isolated from the baseplate by insulating washers, and from the pump by a flexible insulating coupling, in order to prevent any possibility of disturbance in its supply arising as a result of the high D.C. voltage. An automatic float valve with an oil chamber above it is fitted on the suction side of the rotary vacuum pump. The object of this float is to close the vacuum pipe as soon as the pump or its driving motor stops. The float

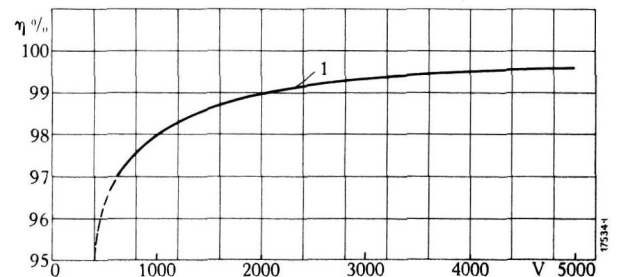


Fig. 5. — Efficiency as a function of working voltage for rectifier Type GRZ 156.

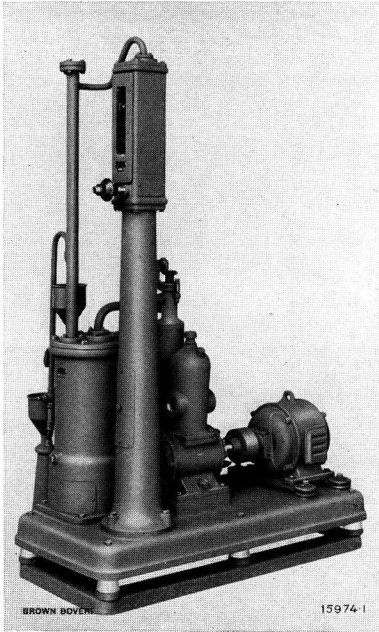


Fig. 6. — Air-pump set Type GRLW.

is actuated by the oil flowing back under atmospheric pressure, and therefore prevents a further advance of the oil along the suction pipes. In the second stage the vacuum is increased to 0.001—0.0001 mm of mercury, by a mercury vapour pump which works on the diffusion principle. The mercury is vaporised by a hot plate, which consumes

about 500 watts. In all high-voltage installations the hot-plate is connected either to the two outside conductors of the excitation transformer, or supplied from a special transformer. The cold water consumption of the pump amounts to about 0.7 litres per minute at an initial temperature of 15° C. A compression vacuum gauge is used for the determination of the vacuum.

Fig. 7 shows one of the sixteen rectifier sets, as supplied in 1922 by Brown, Boveri & Co., to the Midi Railway, Paris. The illustration shows the screen of expanded metal, which surrounds the whole set to protect the attendants from the parts under tension.

The provision of remote control with insulated couplings renders the regulation of the rectifier and vacuum pumps possible from outside the expanded metal screen. In comparison with arrangements requiring an insulated floor, the above method of erection effects a great saving of space.

For high-tension plants of over 2000 V in which the negative pole is earthed, a closed-circuit cooling system must be used in order to prevent the possibility of a short circuit to earth through either the inlet or outlet cooling-water pipes. The whole of the cooling plant is insulated as shown in Fig. 8. The cooler is so proportioned that it is capable of dissipating, at room temperature and full load, the

heat given to the water as a result of the various losses, i.e., the cylinder is kept at an allowable temperature. As shown in Fig. 9, the cooling system is surrounded by a sheet-iron casing and arranged so as to take full advantage of natural ventilation.

In power rectifiers the arc is generally formed by indirect contact ignition, which method has proved to be the most reliable in operation. For this purpose a movable silver-steel rod, 4 mm in diameter, passes from the solenoid fitted to the top cover of the cooling chamber and through the whole rectifier as far as the ignition anode, the normal position of which is approximately 4 mm above the surface of the mercury cathode as in Fig. 10. On exciting the solenoid referred to, the steel rod carrying the ignition anode, is pulled downwards, against the force of a spring, and makes contact with the cathode surface. The connections are such that immediately after contact separation of the electrodes takes place, thus striking an arc, which is transferred to the excitation anodes almost instantaneously. To put the rectifier into service only a few seconds, and about 5 A at 110 V are needed. This energy is supplied by a small separate motor-generator set, consisting of an induction motor coupled to a direct-current generator, which is insulated from the bed plate and the driving motor. A push-button fitted on the switchboard makes it possible to close the ignition circuit momentarily, when the solenoid takes a current of 3 A and the ignition

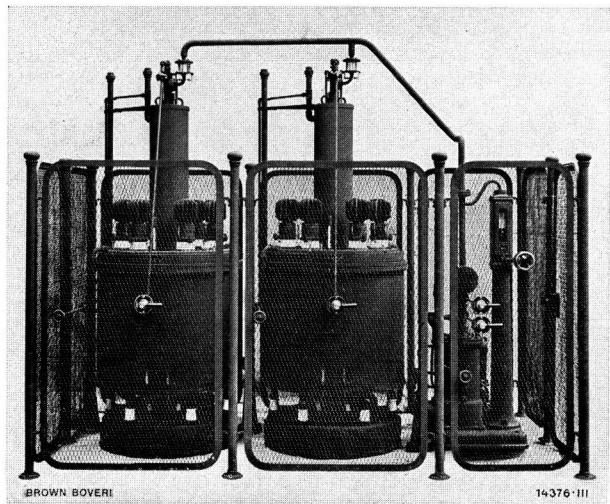


Fig. 7. — Rectifier plant consisting of two rectifiers Type GRZ 156, air-pump set Type GRLW, and vacuum piping with remote control and expanded metal screen.

anode itself 5 A approximately. A suitable resistance, fixed behind the switchboard, serves to limit the above current, measurement of which is made by an ammeter. Up to the present, ignition by means of a movable auxiliary electrode supplied with direct current has proved to be the most satisfactory method of starting power rectifiers.

In plants where the work is intermittent, such as traction substations, the demand for current sometimes falls to zero, with the result that the main arc becomes extinguished, so that on a fresh demand for current it has to be re-ignited. Two auxiliary anodes are provided in every power rectifier, to maintain an arc independent of the main current. This arc, between the auxiliary anodes and the cathode keeps the main anodes always ready for service. As shown in Fig. 11, alternating current is used for this purpose. The excitation transformer which should be dimensioned for an output of about 1.4 kVA, gives a no-load pressure of 2×116 V on the secondary side. To

decrease the fluctuations of the excitation current and to limit its value, a choke coil and a resistance respectively are installed behind the switchboard, together with the excitation transformer. Generally both outer leads of the excitation transformer are also connected to the hot plate of the high vacuum pump, as in Fig. 12, which shows the simplicity of the connections for a rectifier plant.

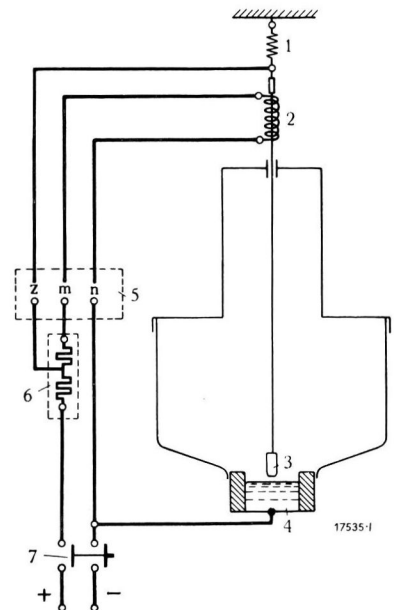


Fig. 10. — Diagram of connections for the ignition apparatus.

- 1. Spring.
- 2. Ignition solenoid.
- 3. Ignition anode.
- 4. Cathode.
- 5. Terminal board.
- 6. Resistance.
- 7. Push-button.

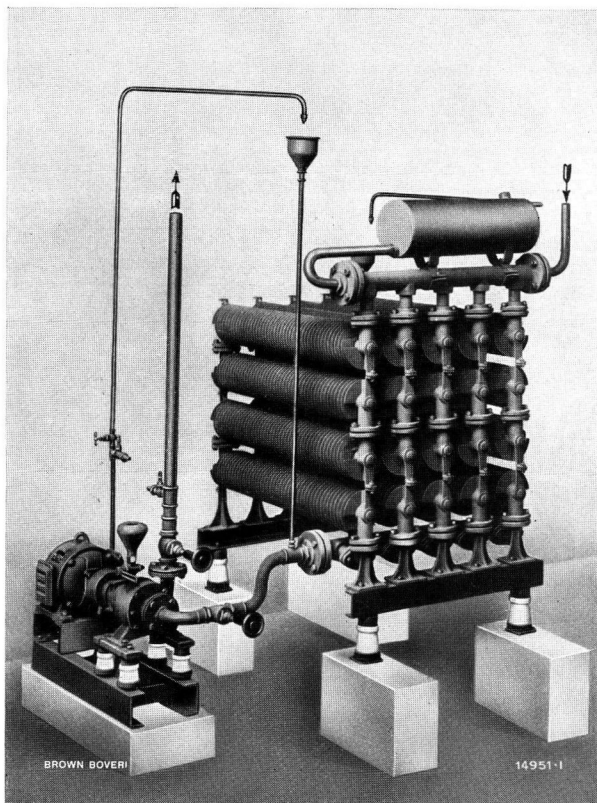


Fig. 8. — Circulating cooling set with casing removed.

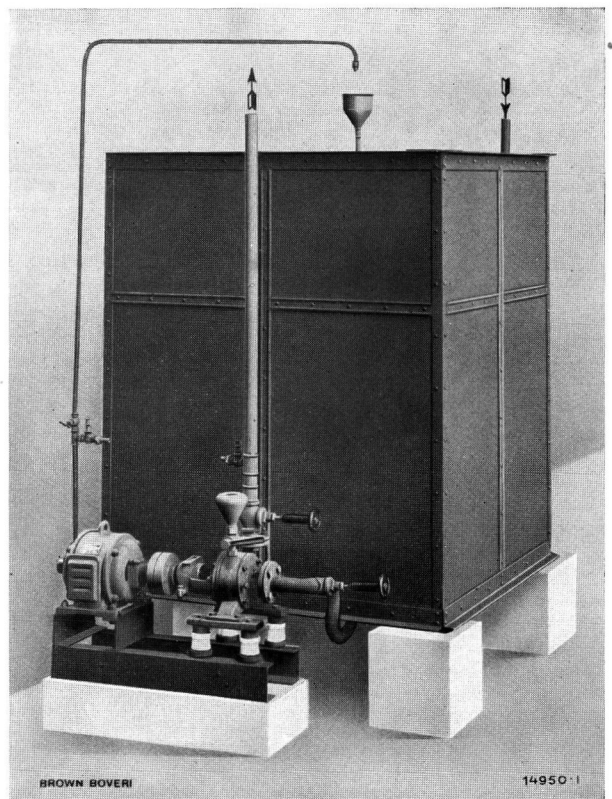


Fig. 9. — Circulating cooling set complete with casing.

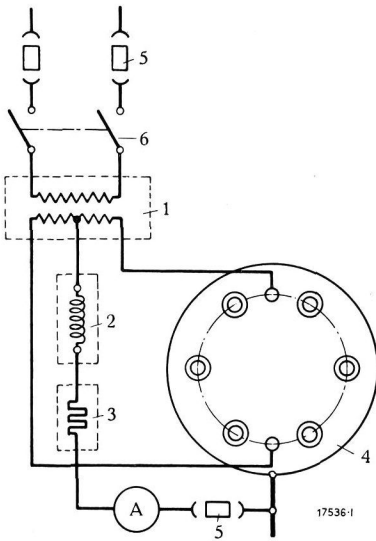


Fig. 11. — Diagram showing connections of auxiliary anodes.

1. Excitation transformer.
2. Excitation choke coil.
3. Excitation resistance.
4. Rectifier.
5. Fuses.
6. Switch.

The current from the busbars passes through isolating switches, and an oil switch provided with direct built-on relays, to the primary terminals of the main transformer. This transformer is generally provided with a six-phase secondary winding, the neutral points of which are connected to the absorption choke coil, the mid-point of the choke coil winding constituting the negative pole of the direct-current system. The six phases of the secondary windings of the transformer are connected to the six main anodes of the rectifier. The lead from the cathode (the positive pole of the direct-current system) is connected to the direct-current busbars, through an ammeter, automatic switch (quick-acting circuit breaker) and an isolating switch. All auxiliary circuits are supplied with current by a small auxiliary transformer connected to the high-tension busbars. This is provided with fuses on both primary and secondary sides. A three-pole knife switch is provided for disconnecting the auxiliary busbars. A fuse and a knife switch must be connected between the auxiliary busbars and the excitation transformer. The excitation anodes of the rectifier are connected to the outer leads of the excitation transformer. The cathode of the rectifier is connected, through the excitation choke coil and excitation resistance, an ammeter, and a fuse, to the neutral point of the secondary winding of the excitation transformer. The driving motors of the circulating pump, of the vacuum pump, and of the ignition motor-generator are also each connected to the auxiliary busbars through fuses and a knife switch. The leads from

the ignition generator pass through fuses, a push-button switch, and the ignition resistance to the ignition apparatus. The hot plate of the vacuum pump is supplied from the outer leads of the excitation transformer. Voltmeters are provided to enable the ignition voltage and the direct-current voltage of the rectifier to be measured.

The starting of rectifiers is particularly simple, and is carried out as follows:—

The switch is closed putting into action the circulating pump, vacuum pump, and ignition motor-generator. The vacuum cocks on the cylinder and

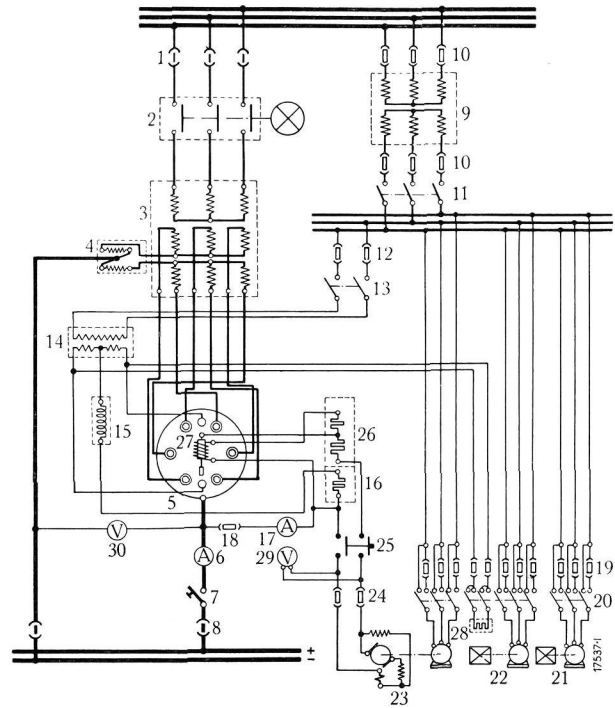


Fig. 12. — Diagrams of connections for mercury arc rectifier installation.

- | | |
|----------------------------------|-------------------------------------|
| 1. Isolating switches. | 17. Ammeter. |
| 2. Oil switch. | 18. Fuse. |
| 3. Main transformer. | 19. Fuse. |
| 4. Absorption choke coil. | 20. Knife switch. |
| 5. Rectifier. | 21. Circulating pump. |
| 6. Ammeter. | 22. Vacuum pump. |
| 7. Quick-acting circuit breaker. | 23. Ignition motor-generator set. |
| 8. Isolating switch. | 24. Fuses. |
| 9. Auxiliary transformer. | 25. Push-button. |
| 10. Fuses. | 26. Ignition resistance. |
| 11. Three-pole knife switch. | 27. Ignition apparatus. |
| 12. Fuses. | 28. Hot plate, mercury vacuum pump. |
| 13. Knife switch. | 29. Voltmeter. |
| 14. Excitation transformer. | 30. Voltmeter. |
| 15. Excitation choke coil. | |
| 16. Excitation resistance. | |

TABLE I.

Installation	Number of rectifiers	Direct current		Primary current		Application	In operation since
		total kW	voltage	system	voltage		
Ekeberg Railway, Christiania	2	500	1200	3-phase	17,500	suburban line	April 1921
Midi Railway Co., Paris:							
Lourdes Substation	6	3600	1575	3-phase	60,000	main line	March 1923
Tarbes Substation	6	3600	1575	3-phase	60,000	"	June 1923
Lannemezan Substation	8	4800	1575	3-phase	60,000	"	Dec. 1923
Montréjeau Substation	6	3600	1575	3-phase	60,000	"	Oct. 1923
Guadarrama Railway, Spain	1	350	1350	3-phase	15,000	suburban line	July 1923
Aigle-Sépey-Diablerets, Switzerland	1	320	1350	3-phase	20,000	interurban line	May 1923
Delft Electricity Supply Co.	1	250	1200	3-phase	2,880	suburban line	May 1923
Staatl. Bergwerkdir. Dresden, Hirschfeld, Saxony	1	550	1100	3-phase	6,500	mining	Dec. 1922
Bernese Oberland Railway, Zweilutschinen, Switzerland	1	650	1550	3-phase	7,000	interurban line	Oct. 1921
Hague Electricity Supply Co.	1	400	1200	3-phase	10,000	main line	Feb. 1924
N. S. W. Government Railways and Tramways, Sydney, Australia	1	650	1500	3-phase	10,500	main line	May 1924
Zurich-Forch Tramway, Zurich	1	250	1200	3-phase	8,000	suburban line	June 1924
Gran Metropolitano Barcelona, Spain	2	1500	1300	3-phase	6,200	underground railway	Oct. 1924
Soc. Ferrovia Torino-Lanzo-Ceres, Italy	1	800	4000	3-phase	21,000	main line	Oct. 1924

TABLE II.

Installation	Number of rectifiers	Direct current		Primary current		Application	Year of order	Remarks
		total kW	voltage	system	voltage			
Midi Railway, Paris, for Pau Substation	6	3600	1575	3-phase	60,000	main line	1924	{ In course of erection
London Midland & Scottish Railway Co., St. Pancras, London	2	1000	2300	3-phase	11,000	power supply	1923	
Japanese Government Railways	6	4800	1500	3-phase	10,500	main line	1924	{ In course of erection
Yoshino Railway, Japan	1	610	1425	3-phase	15,000	suburban line	1924	
Dutch State Railways	6	4500	1470	3-phase	5,150	main line	1924	
Aichi Denki Nagoya, Japan	2	1000	1500	3-phase	30,000	suburban line	1924	
F.C.deZumarraga à Zumaya-Urola, Spain	2	700	1650	3-phase	30,000	main line	1924	

vacuum pump are opened and the vacuum in the rectifier measured. The switch of the excitation transformer is then closed, and, on pressing the push-button, the rectifier is ignited and energised. The oil switch and automatic circuit breaker are then closed, and the rectifier is ready for service, the whole of the starting operation occupying only a few seconds.

While the rectifier is working it is necessary to check the vacuum in the cylinder occasionally. The normal vacuum is from 0.005 to 0.001 mm of mercury.

The rectifier plant is put out of operation in the reverse order to that described above viz., release of the oil switch, automatic switch, and all switches for the auxiliary apparatus.

In Table I some of the high-tension rectifier plants supplied by Brown, Boveri & Co., and already in service are enumerated.

Table II shows the high-tension rectifier plants at present either under construction or on order.

(MS 300)

C. Brynhildsen. (J. R. L.)

THE BROWN BOVERI SCHERBIUS SYSTEM OF SPEED REGULATION FOR INDUCTION MOTORS¹.

Decimal index 621. 317. 4:621. 313. 64.

- I. *The principle of sub and super-synchronous speed regulation for operation as a motor.*
- II. *Regulation for operation as a generator.*
- III. *The Scherbius machine and frequency converter.*
- IV. *The excitation of the Scherbius machine.*
 1. *For speed regulation.*
 2. *For power-factor compensation.*
 3. *For compounding.*
- V. *Characteristics and field of application of the system.*

I. THE PRINCIPLE OF SUB AND SUPER-SYNCHRONOUS SPEED REGULATION FOR OPERATION AS A MOTOR.

WHEN a polyphase commutator machine is connected in cascade with an induction motor, it exerts an influence on the speed of the main motor, (i. e. the induction motor) by introducing an additional voltage in its rotor circuit. The rotating field of the induction motor revolves at synchronous speed, which is determined by the frequency of supply and the number of poles, and it is well known that, for a given supply voltage, its value remains practically constant, being influenced only slightly by the load and not at all by the speed. The torque exerted by the motor is equal to the product of the constant field and the rotor current; the latter is given by the quotient of the resultant effective voltage in the rotor circuit and the resistance of the circuit. Then, if the resistance is constant, the torque of the motor is proportional to the voltage in the rotor circuit. This consists of the slip voltage, which is induced in the rotor of the main motor by its rotating field and is proportional to the slip, together with the voltage induced in the rotor of the commutator machine. If the latter is zero, the torque of the main motor is proportional to the slip, and except for the effect of the additional resistance due to connecting the commutator motor in its rotor circuit, the induction motor runs on all loads at the same speed as if it were working independently. If a pressure opposing the slip voltage of the main motor is generated in the rotor circuit by means of the commutator machine, the resultant voltage in the rotor circuit and the torque of the main motor are less than when the commutator machine is inactive. If the motor is to

¹ See The Brown Boveri Review, 1924, No. 7, p. 139.

exert its original torque, it must revolve at a slower speed than before, its slip voltage increasing by an amount equal to the counter pressure of the commutator machine. On no load also, the motor will run at that speed which gives a slip pressure equal and opposite to the pressure of the commutator machine. It is naturally assumed that the frequency of the latter is always the same as the slip frequency, as it would otherwise be impossible for the two machines to work together. When running on load, the speed of the main motor depends upon the manner in which the pressure of the commutator machine varies with the load, and, according to the influence of this machine, the main motor exhibits either a shunt, compound, or series characteristic¹.

The voltage of the commutator machine is determined by the strength of its field, so that, by suitably varying the excitation, the speed of the main motor can be adjusted as desired, whether on load or running light. This constitutes the whole difficulty of the problem, and the manner in which it is solved by the Brown Boveri Scherbius system of control is dealt with in section IV.

To begin with, it is assumed that the voltage of the commutator machine, regulated for no-load, remains constant as the load is applied to the main motor². The speed of the main motor on load must differ from that when running light by an amount giving a resultant pressure in the rotor circuit equal to the pressure drop due to the rotor load current. As the pressure of the commutator machine is constant, this variation can only be realised by a corresponding change in the slip voltage. The speed drop on load is thus independent of the speed when running light, and is the same as with an independent induction motor; that is to say, the main motor has shunt characteristic. In the practical application described later, certain secondary influences arise, which cannot be entered into more fully here, but which have the result that under certain circumstances the speed drop with a shunt characteristic may be

¹ See The Brown Boveri Review, 1924, No. 7, p. 139.

² See section IV. 3 with regard to the influence of a variation of this voltage.

somewhat smaller than that of a motor working independently, in spite of the increased resistance in the rotor circuit due to the commutator machine.

It has been assumed so far that the voltage of the commutator machine acts in opposition to the slip voltage; this is not always the case, however, and it can also act in the same sense as the slip voltage¹. The resultant pressure in the rotor circuit is then no longer equal to the difference, but to the sum of the two pressures, and, in order that it may have the value corresponding to the motor torque, the slip voltage must be smaller and the speed of the main motor consequently higher than with the commutator machine unexcited. If the voltage of the commutator machine is adjusted on any particular load so as to equal the slip voltage which would be generated by the main motor running independently on that load,—i.e., the pressure drop resulting from the rotor current,—the slip voltage is reduced to zero, and on the given load, the main motor runs synchronously. The independent induction motor only attains synchronous speed on no load; torque and rotor current being zero, and it is impossible to raise the speed above synchronism without employing an outside source of power. If synchronous running on load is attained by means of the voltage generated by the commutator machine, the three phases of the

¹ The influence of phase displacement between these two voltages is dealt with in section IV 2.

rotor are traversed, not by alternating current, but by a system of direct currents, the values of which are constant although they vary among themselves in value and direction. The voltages induced in the commutator machine must also be constant in value and direction and must always correspond to the instantaneous value of the voltage due to the slip of the induction motor running independently. Under these conditions, the main motor operates no longer as an asynchronous motor, but as a synchronous machine, the rotor of which is excited by three different direct currents. It differs from ordinary synchronous machines in that it is not permanently confined to synchronous speed, because, whereas the exciter of the synchronous motor is only capable of supplying direct current to the rotor, the excitation due to the commutator machine immediately changes to an alternating current at slip frequency upon the slightest departure from synchronism, as described in greater detail later.

Should the load decrease, for example, so that the voltage of the commutator machine is greater than the ohmic pressure drop of the rotor current required, the current and torque at synchronous speed exceed the required values. The main motor will consequently speed up to some super-synchronous speed, and run with negative slip, three-phase current again flowing in the rotor circuit. As with sub-synchronous speeds, the slip voltage induced in the rotor is proportional to the extent of the slip. However, as the rotor rotates at a greater speed than the field, the latter moves relative to the rotor in the opposite sense to that for sub-synchronous running, and, for given positions of field and rotor, the direction of the voltage induced in the rotor is opposite in the two cases. To enable super-synchronous speed to be attained, the commutator machine must be excited so that on passing through synchronism, its voltage maintains both magnitude and direction. In order to reach synchronous speed on load, this voltage must act in the same sense as the sub-synchronous slip voltage, and, consequently, it is opposed to that due to the super-synchronous slip voltage, as when it operates at greatly reduced speeds. The resultant rotor pressure is again given by the difference of these two components.

The higher the speed of the main motor, the greater becomes the super-

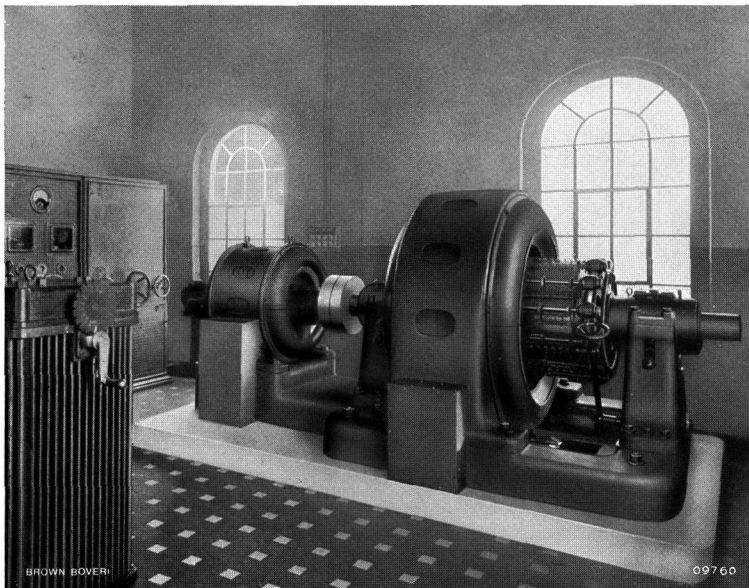


Fig. 1 — Drive of a mine fan by three-phase induction motor, 600 H.P., 2000 V, 50 cycles, 500 r. p. m., adjustable by Brown Boveri Scherbius regulating set between 330 and 485 r. p. m.

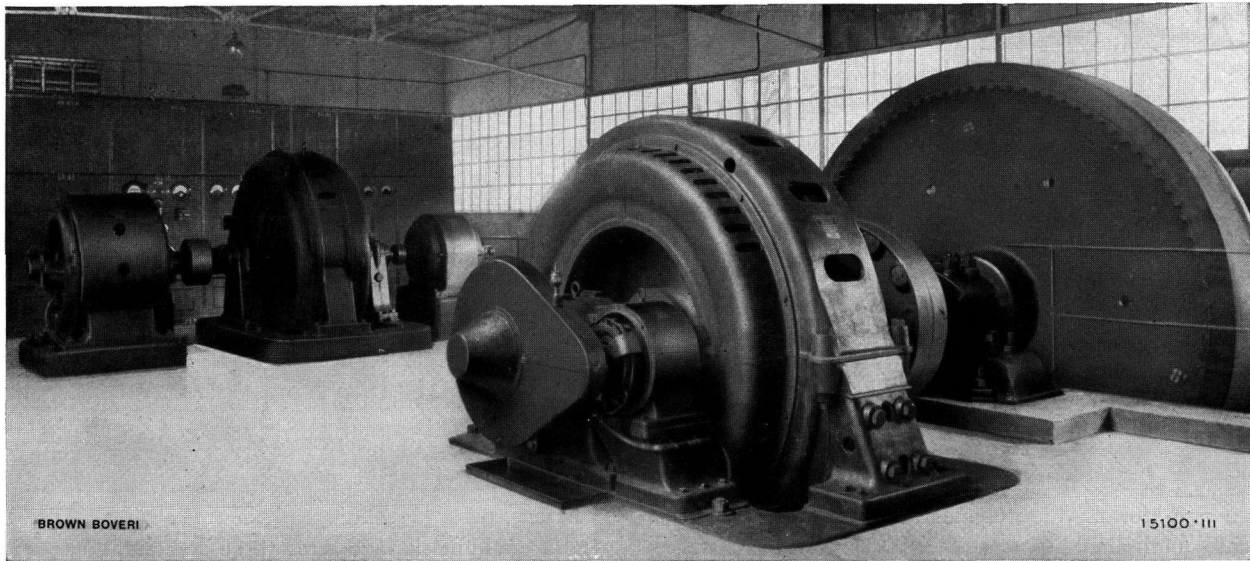


Fig. 2. — Drive of a rolling mill by three-phase induction motor, 1200 H.P., 5000 V, 50 cycles, 250 r. p. m., adjustable by Brown Boveri Scherbius regulating set between 180 and 312 r. p. m.

synchronous slip voltage, and the smaller the resultant voltage and the current in the rotor circuit. Thus above synchronism the torque falls off with increasing speed and increases when the speed drops, as below synchronism also. For a given torque, the speed is higher, the higher the voltage of the commutator machine.

The conditions on no-load are the most simple to understand:—

If the voltage of the commutator machine is zero, the main motor runs synchronously.

If the commutator machine applies a pressure in opposition to the sub-synchronous slip voltage, the speed of the main motor decreases to such an extent that its slip voltage is equal to the voltage of the commutator machine.

If the voltage of the commutator machine acts in the same direction as the sub-synchronous slip voltage, the speed increases by the corresponding amount.

In order that the rotor current may give rise to a motor torque at speeds above synchronism, the current in the rotor circuit must have the same direction with regard to the field of the main motor as below synchronism. When the main motor runs super-synchronously, the slip voltage and the voltage of the commutator machine act in a direction opposite to that for sub-synchronous running, so that the rotor current, which below synchronism had the direction of the slip voltage, has the same direction, as the voltage of the commutator machine above synchronism. The latter consequently operates as a generator and

mechanical power must be supplied to its shaft to the extent of the slip power of the main motor, with the addition of the losses occurring in the rotor circuit.

II. REGULATION FOR OPERATION AS A GENERATOR.

It is well known that an independent induction motor driven at a speed above synchronism acts as a generator. The same rule applies when a commutator motor is connected in cascade, with the difference that the no-load speed for which the set is adjusted takes the place of the synchronous speed in this respect. On no-load, the voltage of the commutator machine both above and below synchronism is equal and opposite to the slip voltage of the main motor. If the speed is now raised by the application of external power, so that the slip voltage increases above synchronism and decreases below synchronism, when the voltage of the commutator machine has become constant, the resultant pressure in the rotor circuit acts in the direction opposite to that when the speed falls, as for the main motor loaded mechanically (i.e., when it actually works as a motor). For a given position of the rotating field, the rotor and starter currents of the main motor flow in the opposite direction to that for operation as a motor; consequently, the torque and stator power change their direction, the main motor gives electrical energy to the mains and works as a generator.

Instead of raising the speed of the induction motor above the no-load speed for which it is adjusted,

it is naturally also possible for a given speed to re-set the regulation to give a lower no-load speed, so that the main motor is obliged to operate as a generator at the speed in question. This property is also very desirable for working as a motor, as it enables the speed of the main motor to be rapidly reduced, the energy stored in the rotating masses being converted into the electrical form and returned to the mains.

When the main motor operates as a generator, the commutator machine works as a generator below synchronism and as a motor above synchronism. When the main motor is regulated by means of resistances, which are naturally only capable of absorbing energy and not of giving any out, super-synchronous operation of the main motor as a motor and sub-synchronous operation as a generator, such as is possible with a commutator machine connected in cascade, is in this case unobtainable.

III. THE SCHERBIUS MACHINE AND FREQUENCY CONVERTER.

The Scherbius machine connected to the slip rings of the main motor according to the Brown Boveri Scherbius system is a three-phase commutator machine with commutation poles. The stator iron is not uniformly distributed as with the three-phase induction motor but consists of salient poles three, or a multiple of three in number (Fig. 3). Each phase of the field winding surrounds one pole; there is no overlapping of the windings as with polyphase induction motors. Thus the arrangement of the poles corresponds to the construction usual for direct-current

machines, except that every third pole is of the same polarity, three neighbouring poles being considered as a pole group. The armature is also similar to the armature of a direct-current machine, but the winding is spaced at 120° (electrical) instead of 180° . The rows of brushes *c*, separated by 120° rest on the commutator *b*. Further, in Fig. 3, three turns of the armature winding short-circuited by the brushes are indicated. Each brush short-circuits one turn; on account of the pitch being decreased, the two armature conductors constituting a turn are situated 120° (electrical) from each other. As the groups of brushes are also separated by 120° , two armature conductors, each short-circuited by different brushes, are situated at the same point on the periphery of the armature. There are consequently only three commutation zones, whereas, with a winding pitch of 180° (electrical), there would be six, and these three commutation zones lie in the gaps between the main poles, as with direct-current machines. Then, as the three phases of the field winding do not overlap, they are practically independent of the main field and can be influenced by the commutation poles *d*.

By moving the turns short-circuited by the brushes in the field of these commutating poles, a voltage is induced in them of such magnitude that the resultant voltage of these coils is zero; in this way, entirely sparkless commutation is attained, as good as that of the best direct-current machines.

The special construction of the Scherbius machine, which differs completely from that usual for polyphase machines, is intended particularly to save a considerable proportion of the copper otherwise necessary for the excitation of the commutation poles. The field of the commutation poles must differ from the field of the neighbouring main poles, and must act in opposition to it under certain circumstances. If the winding of the main poles had a pitch of 180° (electrical), they would also exert an influence on the commutation poles, and with them give rise to a field which would have to be counterbalanced entirely or in part by the excitation winding on the commutation poles, and, in addition, a field of the required value would have to be established. Compared with the Scherbius machine, in which the commutation poles are not influenced by the excitation winding of the main field, this represents a waste of copper. The decrease in the number of commutation zones and the shortening of the end connections are further advantages of the Scherbius machine, which represents the most favourable form for a polyphase commutator machine with commutation poles.

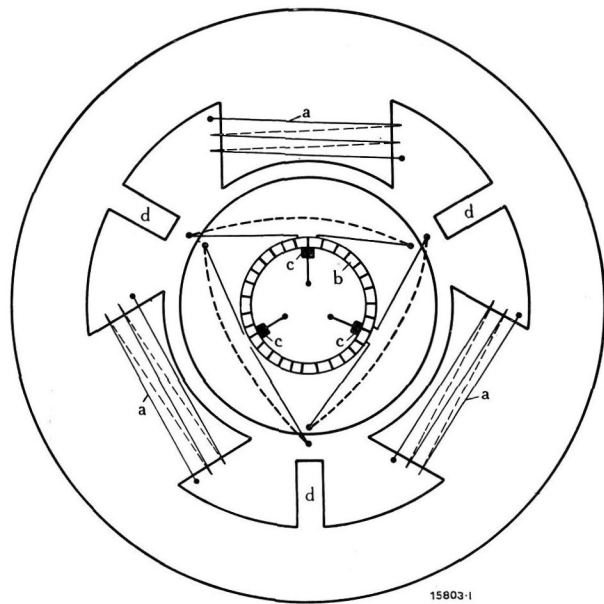


Fig. 3. — Diagram of Scherbius machine.

The Scherbius machine operates as a true three-phase machine in that every event takes place under any pole $\frac{1}{3}$ of a period later than under the preceding pole. Its operation, however, is most easily understood if it is considered as three single-phase motors combined, each of which works in the same manner as a direct-current machine. The rotation voltage of one phase, i.e., the voltage between one brush and the neutral point, is only proportional to the speed of the armature and the strength of the magnetic field under which the brushes lie, and thus, neglecting the effect of saturation, to the excitation current. The frequency of the voltage is equal to that of the excitation current. The difference between this and a direct-current machine lies in the fact that the magnetic fields and armature voltages are not constant but together form a three-phase system. This has the result that a pressure is induced in the armature, not only on account of the rotation of the field, but also owing to its oscillation. As this voltage is not desired, it is counteracted by connecting in series with the brushes a compensating winding, arranged on the stator (not shown in Fig. 3). This compensating winding is electrically identical with the armature winding, but wound in the opposite sense. Thus, as the field alternates, equal and opposite voltages are induced in the armature and the compensating winding, of which the sum is zero, so that in the whole armature circuit only the rotation voltage, i.e., the voltage induced by the rotation of the armature in the magnetic field is effective, this being proportional to the field strength and the speed.

Further, for the Brown Boveri Scherbius system of regulation, a frequency converter is employed. This is a machine similar to a rotary converter, having a rotating armature provided with a normal direct-current winding. This winding is connected to a commutator, and also three points 120° (electrical) apart to three slip rings. In this case, however, the commutator is provided with three sets of brushes 120° apart instead of the two sets at 180° , as with the usual form of converter. The stator is not fitted with salient poles, but has uniformly distributed field iron, which, in the simplest designs is not provided with any winding. A voltage from the mains is applied to the slip rings, and a magnetic field is set up, which rotates with regard to the armature at a definite synchronous speed determined by the number of poles and the supply frequency. If the rotor is rotated at the same speed but in the opposite sense, the field remains stationary in space. As a result of the rotation of the winding, the field induces voltages of con-

stant magnitude and direction between the brushes, as with a rotary converter. If the speed of the frequency converter is increased or decreased at all, however, the field slowly rotates in space in one direction or the other. The voltages induced between the brushes, previously constant in direction, now change their value according to the position of the field in space, and thus change to alternating voltages, which together constitute a three-phase system. Their frequency corresponds to the departure of the converter from synchronous speed. They have the same effective value as the supply voltages applied to the slip rings, as the number of turns between any two commutator brushes is always the same as between any two slip rings. The value of the voltages between the brushes on the commutator is thus independent of the frequency on the commutator side.

If the frequency converter is constructed with the same number of poles as the main motor, rigidly coupled to it, and excited through its slip rings by current from the mains, the frequency of its commutator voltage will be equal to the slip frequency of the main motor, as both frequencies correspond to the difference between the actual speed and synchronous speed. Whereas the voltage of the main motor is proportional to the slip, however, the commutator voltage of the converter remains constant and independent of the slip so long as the voltage applied to the slip rings remains unchanged. By changing either the position of the commutator brushes, or the phase displacement of the voltage applied to the slip rings of the converter, the phase displacement between the slip voltage of the main motor and the commutator voltage of the converter can be adjusted to any desired value. Should the frequency converter have a different number of poles to the main motor, it must be coupled to the latter by toothed gearing, so that the speeds of the machines are inversely as their number of poles. Belt drive cannot be employed for this purpose, as it does not constitute a rigid coupling.

IV. THE EXCITATION OF THE SCHERBIUS MACHINE.

1. *Excitation for speed regulation.*

According to section I, the rotation voltage induced in the Scherbius machine for the speed regulation of the main motor must be equal and opposite to the slip voltage required at each regulation step. It must remain constant in magnitude and direction on variable load and always have the slip frequency. With the Scherbius machine running at constant speed, which is assumed in all that follows,

motor being transformed to the required value either by a static excitation transformer or by an excitation machine.

The connections when an excitation transformer is employed are shown diagrammatically in Fig. 4. 1 indicates the supply to which the main motor 2 is connected; its slip rings 3 are connected to the armature circuit 5 of the Scherbius machine 4. As the Scherbius machine may only be employed for regulating the speed of the main motor and not for starting purposes, the change-over switch 6 is provided for connecting the rotor of the main motor to the starting resistances 7 during the starting period, and for switching over to the Scherbius machine when the motor has been started. The excitation winding 9 of the Scherbius machine is connected in series with the excitation transformer 8 which transforms the slip-ring voltage of the main motor, and with the commutator side of the frequency converter 10 which is rigidly coupled to the main motor. The slip rings 11 of the frequency converter are connected to the mains through a variable auxiliary transformer 12. The change-over switch 13 enables the ends of the excitation winding 9 to be interchanged. The speed of the Scherbius machine is kept constant by the induction machine 14.

The no-load speed can be set by changing the voltage ratio of the transformers 8 and 12. The secondary voltage of the excitation transformer 8 must always be equal to the inductive pressure drop in the excitation winding 9, which is equal to the product of slip frequency and the flux of the Scherbius machine. As the flux itself must be proportional to the slip voltage of the main motor, the inductive pressure drop is proportional to the square of the slip frequency; it is represented as the parabola a in Fig. 5. The slip-ring voltage of the main motor, which is directly proportional to the slip, varies as indicated by the straight line b in the same diagram. As the slip-ring voltage, after transformation by the excitation transformer, is to be equal to the pressure drop represented by the parabola a, the setting of the voltage ratio of the transformer necessary for obtaining a desired slip OA is given by the ratio of the ordinates AC:AB. The greater the slip required the higher the secondary pressure of the transformer must be. Fig. 5 applies to both sub-synchronous and super-synchronous running, so that, by a certain setting of the excitation-transformer ratio, either positive or negative slip can be obtained. The range in which the main motor operates depends solely upon the position of the change-over switch 13. On account

of the change which takes place in the order of the rotor phases when passing through synchronism, the sense in which the excitation winding of the Scherbius machine acts must be reversed for super-synchronous operation¹, which is effected by putting over the switch 13 as synchronous speed is reached.

The excitation ohmic pressure drop of the Scherbius machine is covered by the commutator voltage of the frequency converter 10, and therefore the pressure applied to the slip rings 11 must also have this value. In this way, the

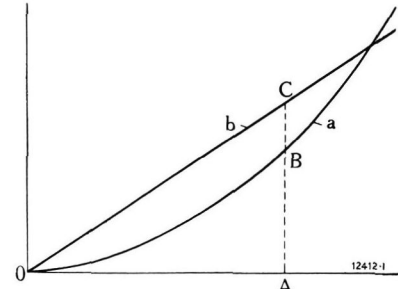


Fig. 5. — Voltages in the excitation circuit of the Scherbius machine as functions of the slip, with connections as shown in Fig. 4.

- a. Excitation inductive pressure drop.
- b. Slip-ring voltage of the main motor.

the auxiliary transformer 12 is fixed for each value of the slip; if the resistance of the excitation circuit is constant, the secondary transformer pressure must be proportional to the slip. This secondary pressure is also frequently kept constant and the resistance of the excitation circuit varied by a regulating resistance inversely as the slip of the main motor, so that the ohmic pressure drop in the excitation circuit remains constant, although the current varies with the slip.

When an excitation machine is employed, the slip-ring pressure is transformed to equal the value of the inductive pressure drop by connecting in series with the slip rings a special excitation machine, the voltage due to rotation of which is added to or subtracted from the slip-ring voltage. The connections are shown in Fig. 6, in which the references 1—7 have the same meaning as in Fig. 4. 9 is the excitation machine, which is usually also constructed as a Scherbius machine, but for about 2—4% of the kVA rating of the main Scherbius machine 4, with which it is directly coupled. Its armature circuit 10 is in series with the slip rings 3 of the main motor, and the excitation winding 8 of the main Scherbius machine. It is provided with two excitation windings 11 and 12. The voltage induced in the armature depends upon the sum of the currents in the two excitation circuits. The winding 11 is connected to the slip rings of the main motor through a variable resistance 13. The winding 12 is connected to the commutator brushes 15 of the frequency converter 14. Thus, the

¹ See *Elektrotechnik und Maschinenbau*, 1924, p. 131.

frequency converter does not supply the excitation circuit of the Scherbius machine 4 directly, but indirectly through the excitation machine. As both excitation windings 11 and 12 are supplied at slip frequency, the armature current induced will also have slip frequency. The slip rings 16 of the frequency converter are supplied through the regulating resistance 17 at the constant secondary pressure of the auxiliary transformer 18, the primary of which is connected to the mains. The ends of the excitation winding 8 of the main Scherbius machine can be interchanged as before by means of the change-over switch 19, a similar switch 20 being provided for the field winding 11 of the excitation machine. 21 is the induction motor for driving the Scherbius machine.

The current in the field winding 11 of the excitation machine is adjusted by the resistances 13 to such a value that the corresponding armature voltage increases the slip-ring voltage of the main motor to the value required for feeding the excitation winding of the Scherbius machine. In Fig. 7, as in Fig. 5, the parabola a represents the excitation inductive pressure drop of the Scherbius machine, and the straight line b, the slip-ring voltage of the main motor as functions of the slip. The voltage required from the excitation machine for every value of the slip is thus the difference between the ordinates of the two curves at the point considered, and is represented separately by the curve c. Below the slip S_1 , it is opposed to the slip voltage, and above this slip it

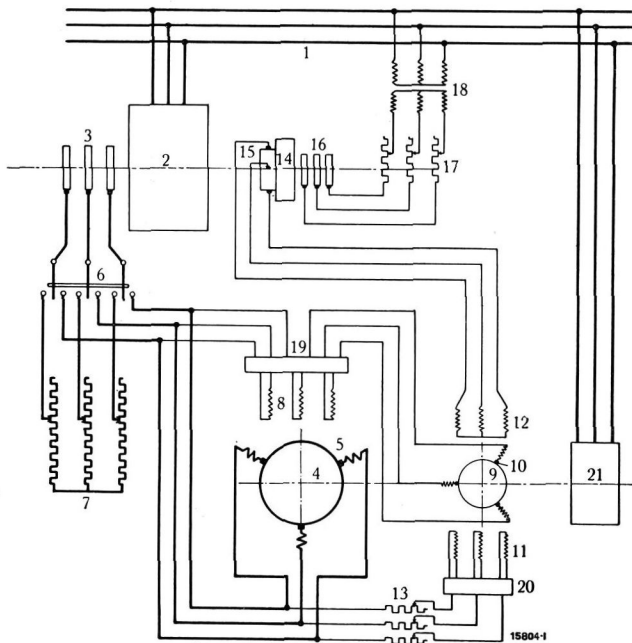


Fig. 6. — Diagram of connections of Brown Boveri Scherbius set for double-range regulation. Excitation-machine type.

acts in the same direction. As the armature voltage is proportional to the excitation, the excitation current flowing in the winding 11 varies as indicated by the curve c. It is equal to the quotient of the slip-ring voltage (straight line b) divided by the resistance of the excitation circuit. The resistance of the excitation circuit 11, Fig. 6, which is adjusted by means of the series resistance 13, consequently varies with the slip as shown by curve a in Fig. 8. It is smallest at synchronism, becomes infinitely great when the slip is S_1 , at which the slip-ring voltage of the main motor is equal to the inductive excitation

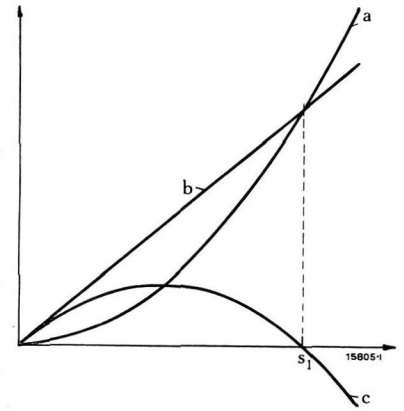


Fig. 7. — Voltages in the excitation circuit of the Scherbius machine as functions of the slip, with connections as shown in Fig. 6.

- a. Excitation inductive pressure drop.
- b. Slip voltage of the main motor.
- c. Voltage of the exciting machine.

voltage of the Scherbius machine, and then falls off as the slip increases further. As the sense of the voltage of the excitation machine has to be reversed when the slip S_1 is exceeded, the direction of current flow in the winding 11 must be reversed by putting over the switch 20 as the slip attains this value. The value of the slip S_1 is determined by the dimensions of the Scherbius machine. If the maximum amount of slip desired does not exceed this value, the switch 20 is unnecessary. The switch 19 serves the same purpose as the switch 13 in Fig. 4; according to its position, sub or super-synchronous slip is obtained by means of the resistance 13.

Upon the armature voltage of the excitation machine so far considered is superposed the voltage corresponding to the current in the excitation winding 12, which should cover the ohmic pressure drop in the excitation circuit of the Scherbius machine; thus, the resistance of this circuit remaining constant, the current flowing in the excitation winding 12 should be proportional to the slip. The magnetising current being neglected, the current on the commutator side of the frequency converter 14 (Fig. 6) is equal to the current supplied to the slip rings. Thus the latter must always be proportional to the slip, which can be ensured if the regulating resistances 17 are set to suit each value of the slip. This is the case when

the resultant resistance in the circuit of the frequency converter varies with the slip as indicated by curve b in Fig. 8, i.e. hyperbolically, the secondary voltage of the auxiliary transformer 18 being constant. As when an excitation transformer is employed, however,

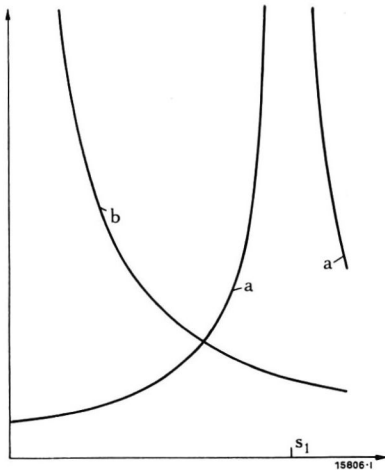


Fig. 8. — (a) Excitation resistance of the exciting machine, and (b) resistance in the frequency-converter circuit, both as functions of the slip.

it is also possible to keep this resistance constant, varying the resistance in the excitation circuit 8 of the Scherbius machine instead.

The results obtained are equally good whether an excitation transformer or an excitation machine is employed. The latter method involves an additional rotating machine but enables a transformer with

a variable ratio to be dispensed with; this may be the better course under certain circumstances, as a large number of tappings and heavy currents in the excitation circuit can give rise to certain difficulties of construction. Thus, the greater the range of regulation and the number of steps required, the greater are the advantages of the excitation machine. Quite a small number of steps may furnish all the running speeds required, but nevertheless, should the range of speed be great, it will be necessary to provide a large number of steps; otherwise changing over from one step to the next would cause the main motor to develop a sudden power peak, either as a motor or as a generator, before attaining the new speed. This peak can certainly be reduced with a small number of steps if a resistance is connected in the rotor circuit of the main motor between one step and the next.

2. Excitation of the Scherbius machine for power-factor compensation.

So far, it has been assumed that the voltage of the Scherbius machine acts directly in opposition to, or in the same direction as the slip voltage of the main motor. In this case, the resultant voltage in the rotor circuit has the same direction as that of the independent induction motor, so that neglecting the slight influence of the rotor reactance, the rotor

current has also the same direction as for an induction motor working independently, i.e., it is opposed to the watt current of the stator and has no influence on the magnetising current displaced by 90° .

If the voltage of the Scherbius machine is out of phase with the slip voltage of the main motor, however, the resultant voltage in the rotor circuit and the rotor current are no longer in phase with the slip voltage. The rotor current has a component either supporting or opposing the stator magnetising current, the effect of which it augments or weakens. Now, the magnetic field and the resultant magnetising current necessary for exciting it are fixed by the supply voltage. If the rotor current has a magnetising component, the magnetising current flowing in the stator is smaller by the corresponding amount, the power factor of the main motor increases, and it is said to be "compensated". On closer consideration it becomes evident that, for power-factor compensation, the Scherbius machine must introduce a voltage in the rotor circuit approximately equal to the ohmic pressure drop corresponding to the magnetising current in the rotor. Both above and below synchronism, the compensating voltage must lag 90° with regard to the voltage necessary for regulating the speed. If it is so large that the magnetising current flowing in the rotor of the main motor is itself sufficient to provide the necessary field, the magnetising current in the stator becomes zero and the main motor runs with unity power-factor. If the compensating voltage of the Scherbius machine is still greater, the magnetising current flowing in the rotor is greater than required and the main motor consequently gives up a lagging current to the mains, which can serve as magnetising current for other motors connected to the system. In this case, the main motor is said to be over-compensated. Any degree of compensation naturally involves an increased rotor current, with a correspondingly larger heat loss in the rotor. As this heating may not exceed a certain limit, the extent of the compensation possible is limited. Compensation has hardly any influence in the overall losses of the main motor, at least as long as it is not over-compensation, as the increase in rotor losses results in a corresponding decrease in the stator losses.

As compensation should usually result in a reduction of the stator magnetising current by the same amount throughout the range of regulation, the compensating voltage of the Scherbius machine, which is approximately equal to the ohmic pressure drop of the magnetising current flowing in the rotor, must

also be constant and independent of the value to which the speed is regulated. Hence, in addition to the speed-regulation component so far dealt with, the excitation current of the Scherbius machine must have both above and below synchronism a constant component lagging 90° for power-factor compensation. In order to obtain this additional excitation current, additional voltages must be introduced in the excitation circuit of the Scherbius machine to cover the inductive and ohmic pressure drops due to this current. The latter being constant, its inductive pressure drop is proportional to the slip and displaced 90° with regard to the slip-ring voltage, which covers the inductive pressure drop of the speed-regulating current. It is covered by the secondary voltage of a transformer with fixed ratio, the primary of which is connected to the slip-rings of the main motor. The 90° phase displacement between the primary and secondary voltages is obtained by suitably constructing the transformer. When an excitation transformer is employed, the two are combined, but with an excitation machine, it is constructed separately as a special "compensating transformer". The resistance of the excitation circuit being constant, the ohmic pressure drop resulting from the additional excitation current is also constant, and independent of the speed; it is covered indirectly from the mains through the frequency converter. For this purpose, when an excitation transformer is employed, a voltage which is constant and displaced 90° with respect to the speed-regulating voltage is applied to the slip rings of the frequency converter in addition to the latter. When an excitation machine is used, a constant additional current is supplied to the slip rings, which traverses the second field winding of the excitation machine, and thus introduces a voltage independent of the speed in the excitation circuit of the Scherbius machine.

When the slip is small, the voltage of the Scherbius machine necessary for power-factor compensation exceeds the speed-regulating voltage, and with increasing slip, it becomes smaller and smaller compared with the latter. Thus, with large slip, a voltage component affecting the degree of phase compensation can also be obtained from the Scherbius machine by slight phase displacement of the speed-regulating voltage, without any great alteration in its magnitude. This is most simply effected if the voltage applied through the frequency converter to cover the

ohmic pressure drop of the speed-regulating excitation current is adjusted somewhat in excess of the pressure drop itself. The same result to that obtained by increasing the pressure applied can also be achieved by decreasing the resistance of the excitation circuit; this also causes the rotation voltage of the Scherbius machine to be displaced in a lagging sense, and thus gives rise to a phase-compensating voltage component. In the immediate neighbourhood of synchronism, the phase compensation obtained depends solely upon the voltage applied through the frequency converter. When the slip is great, it is determined by the secondary voltage of the compensating transformer and by the voltage of the frequency converter.

3. Excitation of the Scherbius machine for compounding.

Compounding the main motor (i.e., imparting to it a falling characteristic, so that, as the load increases, the speed falls off from the value for which it is adjusted on no-load, by an amount proportional to the load) is often required, in order to make use of the power stored in the flywheel masses coupled to the main motor, and thus to relieve the system of sudden variations of current. This is effected by suitable excitation of the Scherbius machine, its field not remaining constant with fluctuating load (see page 29), but becoming smaller above and greater below synchronism. Thus, for the difference between the slip-ring voltage and the voltage of the Scherbius machine, which determines the rotor current and the torque of the main motor, to reach a certain value, a greater change of speed will be necessary, than if the voltage of the Scherbius machine remained constant. The speed of the main motor must consequently fall more rapidly to exert a certain torque, than if the voltage of the Scherbius machine were constant.

The desired variation of the field of the Scherbius machine with fluctuating load can be secured in two different ways, according to whether the field is excited from one or from two separate windings. In the former case, the excitation winding of the Scherbius machine is energised from the same source of current as in the arrangement dealt with up to this point; besides this, however, additional voltages are applied which cover the ohmic and inductive pressure drops of the extra excitation current necessary for compounding. As the change of speed is to be proportional

to the load, this additional excitation current must similarly be proportional to the load, and therefore also to the watt current in the rotor circuit; the influence of the wattless current will not be discussed here. The inductive pressure drop of the additional excitation current is thus proportional to the product of the rotor current and the slip frequency, and the ohmic pressure drop to the rotor current.

The inductive voltage component is supplied by the "secondary compounding transformer", the primary of which is energised by the rotor current of the main motor and the secondary connected in series with the excitation winding of the Scherbius machine. The voltage induced in the secondary of the transformer by the current in the primary winding is proportional to the slip frequency and the rotor current, and consequently to the load of the main motor. In order that saturation shall have no disturbing influence, the magnetic circuit of the transformer is interrupted by numerous air gaps.

The additional ohmic voltage component is supplied through the frequency converter. If this supplies the excitation circuit of the Scherbius machine directly (the method of connection when an excitation transformer is used, Fig. 4), the voltage applied to its slip rings must be varied, when the load increases, by an amount proportional to the load, being increased below synchronism and decreased above. If, instead of this, the frequency converter supplies the field circuit of the excitation machine (Fig. 6), the same applies with regard to the current supplied to the slip rings of the latter. In both cases, the primary compounding transformer is employed, the primary winding of which is energised by the stator current of the main motor, its secondary winding being connected to the slip rings of the frequency converter.

With the second possible method of connection for compounding the main motor, with which the Scherbius machine is provided with two excitation windings, one of these (the shunt winding) is again connected as shown in Fig. 4 or 6, and the second (the compound excitation winding) is energised by the rotor current of the main motor. Thus, the rotor current is employed for exciting the field of the Scherbius machine. As the Scherbius machine operates below synchronism as a motor, and above synchronism as a generator, the rotor current has the opposite direction below synchronism compared with the field

to that above synchronism; consequently, if the current in the compound winding acts so as to strengthen the field below synchronism, it will weaken it above synchronism, without any necessity for switching over at synchronous speed. As with a direct-current compound-wound machine, this system would ensure the provision of the necessary additional field component if it were not choked by the shunt winding arranged on the same poles. A voltage is applied from the slip rings to the shunt winding; if the inductive reactance of the latter is of much greater importance than the ohmic resistance, as is the case when the slip frequency is high, the field set up by this winding is determined solely by this voltage. The current in the compounding winding, which acts upon the same field, cannot influence the field strength; the current in the shunt winding varies by such an amount that the field retains the value determined by the voltage applied to this winding. The shunt field winding and the compounding winding may be considered as the primary and secondary windings of a transformer. It is well known that, in such a case, the field is fixed by the magnitude of the primary voltage, whereas the secondary current influences the magnitude of the primary current only.

The choking of the compounding field current can be prevented by connecting in series with the shunt field winding the secondary winding of a "secondary compounding transformer", as for the first case discussed, where only the shunt winding was provided; in this way, the resultant voltage applied to the shunt winding changes according to the required variation of field, and this change is no longer hindered by the shunt winding.

The secondary compounding transformer is thus necessary with both methods of connection; the difference between the two lies in the fact that, in the second case, the additional magnetic flux is provided by a separate winding, so that the current in the shunt winding remains constant as the load varies, and no source of current is necessary for covering its additional ohmic pressure drop. In the first case, in which the current in the shunt winding must vary according to the change of field, an additional source of current (the primary compounding transformer) is necessary. If this were omitted, the compounding would be inadequate in the neighbourhood of synchronism, as here it is the ohmic resistance, not the inductive

reactance, which determines the excitation current; furthermore, if the voltage necessary to cover its ohmic pressure drop were neglected, the direction of the additional excitation current would be incorrect throughout the range of regulation which would influence the phase displacement of the main motor (see page 37).

Both the methods of compounding the main motor referred to are employed in practice, as sometimes one and sometimes the other works more satisfactorily, according to the special conditions in each individual case.

The complete connections of an installation for speed regulation on the Brown Boveri Scherbius system providing for a compound characteristic and power-factor compensation of the main motor are shown in Fig. 9. The speed on no-load is regulated by an excitation machine, and compounding effected by means of a compound winding and secondary compounding transformer. The reference numbers are the same as for Fig. 6; in addition, 22 is a resistance through which the frequency converter is supplied with a current, the phase of which is displaced with regard to that of the current flowing in the resistance 17, so that the power-factor of the main motor is compensated at synchronous speed; 23 is the compound-

ing winding of the Scherbius machine, 24 the compensating transformer, and 25 the compounding transformer. The secondary windings of both transformers are connected in series with the excitation winding 8 of the Scherbius machine. By means of the switch 26, the necessary switching over of the resistance 22 can be effected as synchronous speed is passed.

When the main motor is required to have a series characteristic, synchronous speed is chosen as its no-load speed and the whole shunt excitation circuit of the Scherbius machine can be dispensed with, including the frequency converter. The speed drop is obtained only by the compound winding of the Scherbius machine, the magnetic influence of which is now no longer choked. A series characteristic thus involves a particularly simple method of connection. The compounding winding is as a rule so connected that, on load, it gives rise to a component of the magnetic field by which the power factor of the main motor is improved. Compensation of the power factor on no-load is usually dispensed with.

The step switches of the regulating resistances and tapping transformers, by which the no-load speed is adjusted with shunt and compound characteristics, are always coupled together and operated by a common handwheel. Thus for regulating the speed, it is only necessary to bring this handwheel into the corresponding position. Although the theoretical considerations upon which the Brown Boveri Scherbius system of regulation is based are somewhat complicated, the operation of a plant working on this system is particularly simple—simpler in fact than that of the other well-known regulation systems—so that it can well be controlled by personnel with but little training. The perfect running of the main motor and all auxiliary machines, and the reliability of the method of connection as a whole have been proved by a number of installations of this kind which have been in operation for a considerable time.

V. CHARACTERISTICS AND FIELD OF APPLICATION OF THE SYSTEM.

As with the independent induction motor, a circle diagram can also be employed to represent the conditions under which an induction motor with a Scherbius machine connected in cascade operates. The circle diagrams corresponding to the various regulation steps, i.e. the diagrams for different no-load speeds,

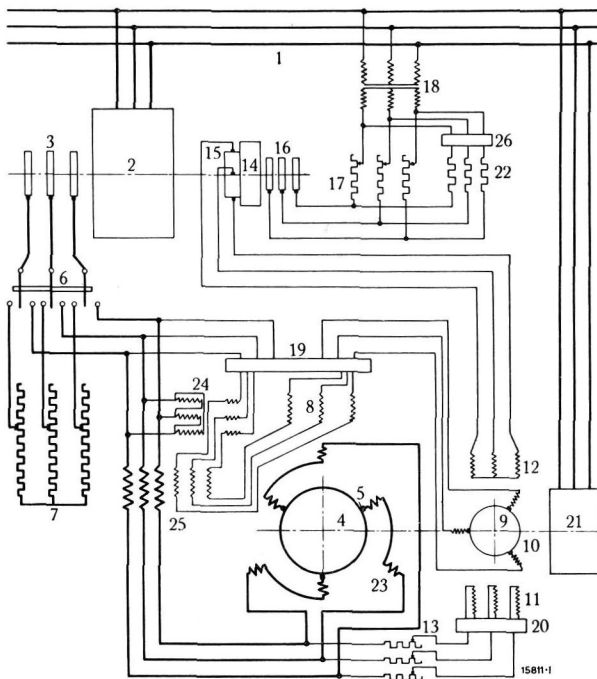


Fig. 9. — Diagram of connections of Brown Boveri Scherbius set for double-range regulation, compounding, and power-factor compensation of the main motor. Excitation-machine type.

usually coincide, so that each point of the circle so obtained corresponds to a number of different speeds. In general, this circle will be situated as circle a in Fig. 10. It differs from the circle diagram of the independent induction motor, which is indicated by a dotted circle,

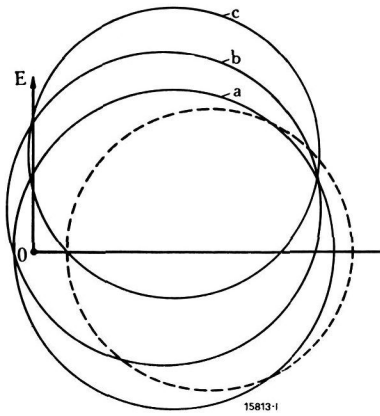


Fig. 10. - Circle diagrams of compensated induction motor fitted with regulation set.

a dotted circle, particularly in that the no-load point is displaced outside the point O. This means that the magnetising current of the main motor has become negative, i.e. leading¹. Under certain circumstances, the no-load point becomes displaced only near to, but not beyond the

point O. In any case, however, the no-load current of the main motor will be considerably less than it was before a regulating set was provided. The power factor is much higher throughout the working range. The circle a applies whether compounding is employed or not. If the set is compounded, a circle diagram can also be obtained corresponding to the circle b in Fig. 10. Under these circumstances, the power factor and overload capacity, when operating as a motor, are greatly improved compared with those given by the circle a, but they are not so good when operating as a generator. A diagram according to the circle a or b can also be obtained with installations in which the speed of the main motor remains unchanged on no-load, but falls rapidly upon the application of the load (series characteristic). The plant necessary can be made particularly simple if a diagram according to the circle c is sufficient, power-factor correction being effected only on load and not when running light (see page 40).

Induction motors provided with a regulating set imparting a shunt characteristic are chiefly employed for driving fans, pumps, blowers, etc., and often also for rolling mills. Whereas the first drives mentioned only require speed regulation on load, with rolling-mill drives, regulation of the no-load speed is also necessary; usually, however, not a shunt but a compound characteristic is required for this purpose,

¹ To describe a machine as taking up leading current is equivalent to saying that it gives out lagging current.

providing an adjustable no-load speed and a falling off of the speed as the load is applied; a characteristic of this kind is sometimes also necessary for the drive of pumps etc.

A further application of the Brown Boveri Scherbius system is for the speed regulation of frequency changers, such as are employed for connecting two distribution systems of different frequency. If the frequency-changing set consists of a synchronous machine and an induction machine and it is desired to transfer a definite adjustable quantity of electric energy from one system to the other, even with variable supply frequencies, the no-load speed of the induction machine must be adjustable between certain limits. This can be effected by connecting a regulating set to its slip rings. If the frequency of the system to which the synchronous machine is connected remains constant, its speed, and thus the speed of the induction machine coupled to it also remain constant. If the speed at which the induction machine would run on no-load be now adjusted by means of the regulating set to a value higher than the speed at which it is forced to run by the synchronous machine coupled to it, the induction machine takes power from its supply system and operates as a motor, driving the synchronous machine, which gives up energy to its mains. If the no-load speed of the induction machine is set at a value less than the actual speed, the flow of energy takes place in the reverse direction. The greater the difference between the no-load speed adjusted and the actual running speed, the greater will be the power transmitted. Thus, at a given speed, the induction machine operates sometimes as a motor and sometimes as a generator. An induction machine controlled by resistances in its rotor circuit could not fulfill these conditions, as below synchronism it would only be capable of operating as a motor and above synchronism only as a generator.

Another important application of the Brown Boveri Scherbius system of regulation is for load-equalising sets. It is well known that the fluctuations in the power taken from the mains by an induction motor can be diminished if a flywheel is fitted and the speed of the motor is reduced by automatic devices when peak loads occur, so that the flywheel is able to give up its stored energy, the flywheel being recharged when the load is small. The best known example of this kind is the Ilgner motor-generator set, which consists of an induction motor coupled to a generator and a flywheel. The speed of this set can be regulated by switching resistances into the rotor circuit, but this results in very con-

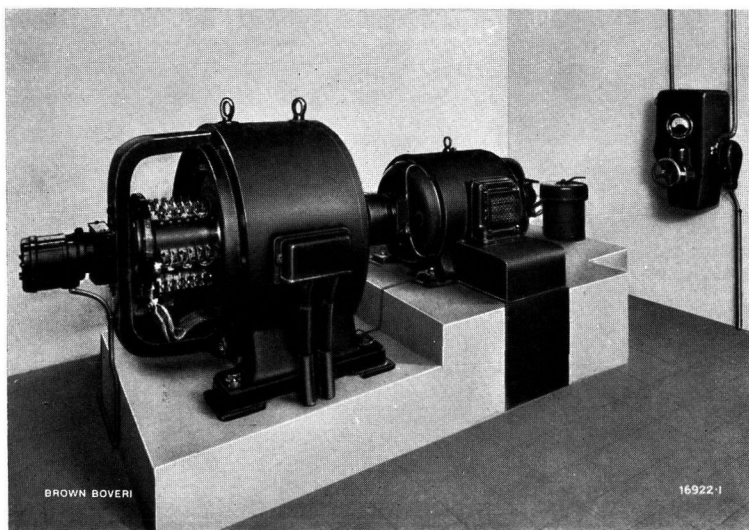


Fig. 11. — Scherbius machine for 110 kVA at 1500 r. p. m. coupled to an induction generator.

siderable amounts of energy being dissipated as heat, and it is much more satisfactory to control the speed of the induction motor by means of a regulating set connected in the rotor circuit.

therefore, the regulation set with an exciting machine is suitable. The necessary number of steps can be somewhat reduced by slight compounding.

(MS 309)

Dr. W. Seiz. (G. T. S.).

NOTES.

Shutting down pumping stations automatically without the use of pilot wires.

Decimal index 621. 317. 4: 621. 67.

IN water-supply systems where the reservoir and the pumping station are situated a considerable distance apart, the installation of pilot wires connected to a float gear is a very costly matter. In municipal systems where electrically driven pumps are used, most of the pumping is carried out at night in order to obtain power at a cheaper rate, and, in these circumstances, pilot wires are usually avoided by fitting a clock switch to stop the pump motor at a certain time for which the clock is set. This method is necessarily very inaccurate, as it depends neither upon the water level in the reservoir, nor upon the demand for water during pumping, and it very often happens that too much water is pumped and escapes unused at the overflow, or else the pump is stopped too soon, before the reservoir is full. In May, 1921, Brown, Boveri & Co., together with Messrs. W. & J. Rapp of Basle, — a firm of civil engineers who have installed a number of such pumping plants, — employed an automatic shutting-down device in the Aesch pumping station near Basle. This plant was ordered by the "Elektra Birseck" company and was put into operation in the beginning of the year 1922. The method adopted was to use a mechanical float gear fitted in the inlet to the reservoir, which it closed completely when the reservoir

became full. This has the same effect on a centrifugal pump as closing the main stop valve in the delivery pipe, i.e., the pump being unable to deliver any more water, the power necessary to drive it is less, so that the output of the motor decreases. By fitting a suitable relay, this decrease in output causes the main switch of the motor to be tripped. Many forms of relay are suitable for this purpose, for instance, a current relay, or better still, a power relay — a device recently installed by Brown, Boveri & Co. in Reinach pumping station and found to be most reliable. The switch can also be tripped by means of a contact wattmeter with an adjustable contact pointer. Alternatively, a non-return valve, which closes when the quantity of water delivered decreases to a certain minimum value, can be incorporated in the delivery pipe line. To this non-return valve, a suitable contact is fitted, which may interrupt the no-volt circuit, or actuate a magnet on the motor switch, which is thus released.

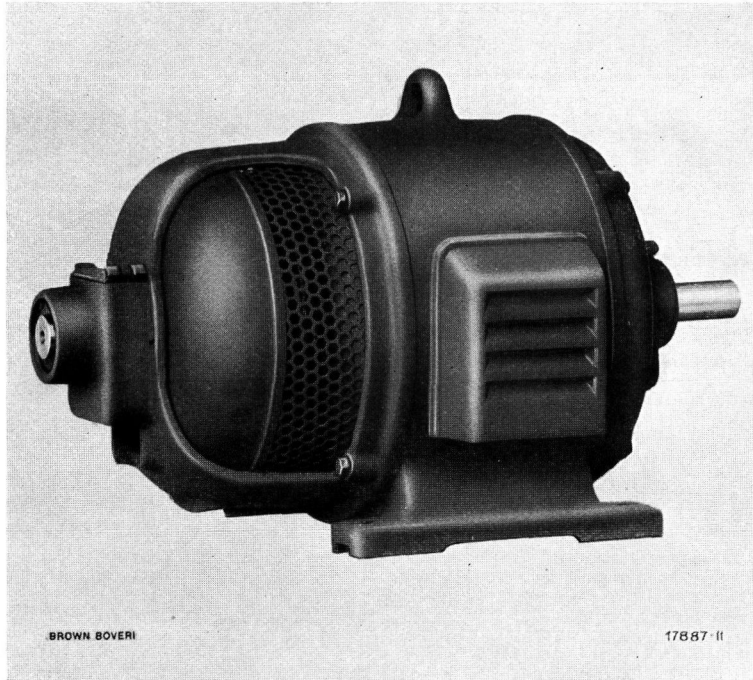
The important point in this system of automatic control is that it enables all electrical connections to be dispensed with between the pumping station and the float gear in the reservoir. A suitable float valve at the upper end of the delivery pipe, capable of influencing the output of the motor as described and thus actuating a circuit breaker and stopping the plant, would often prove of great advantage, and has already been made use of by Brown, Boveri & Co. in a number of cases.

(MS 315)

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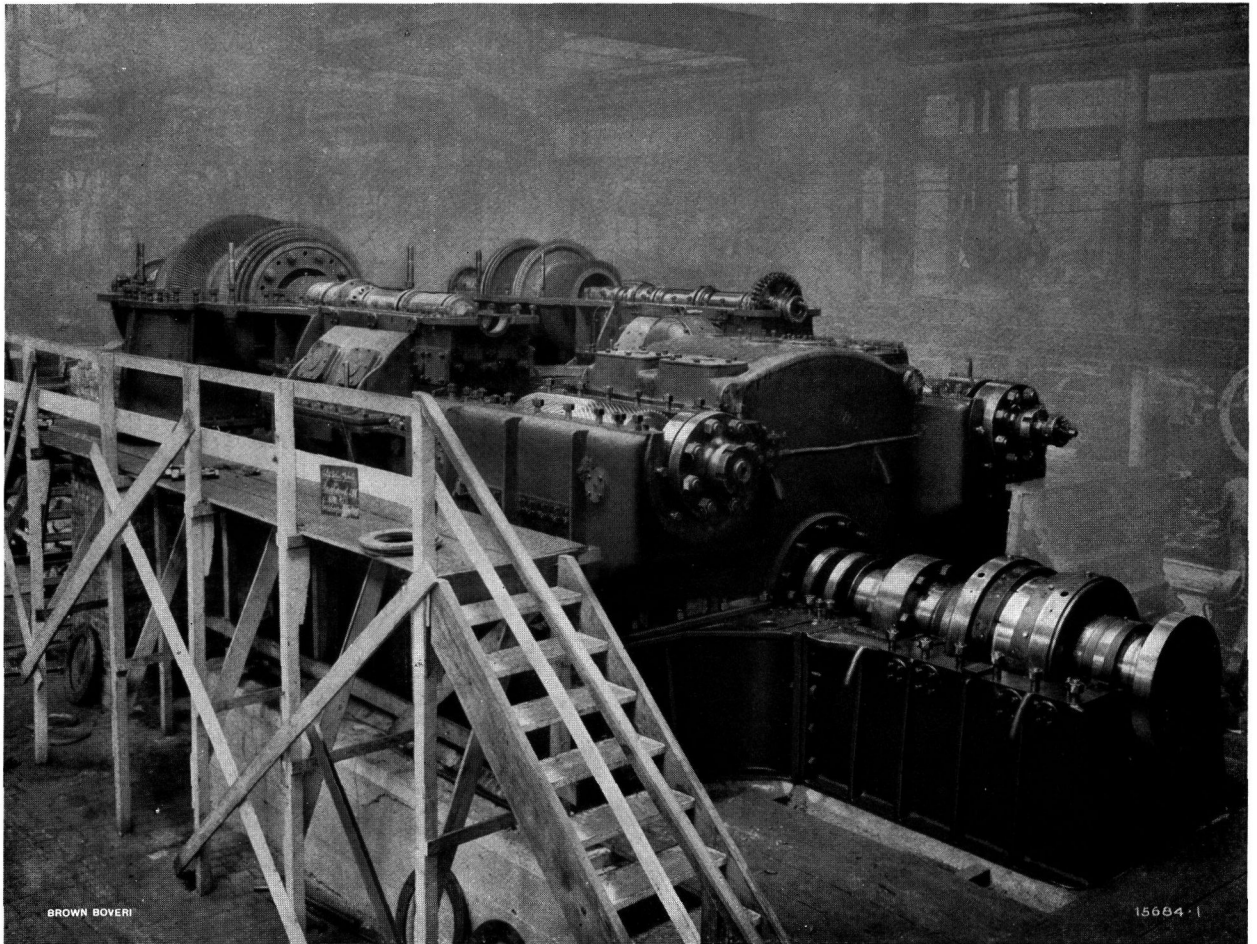
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