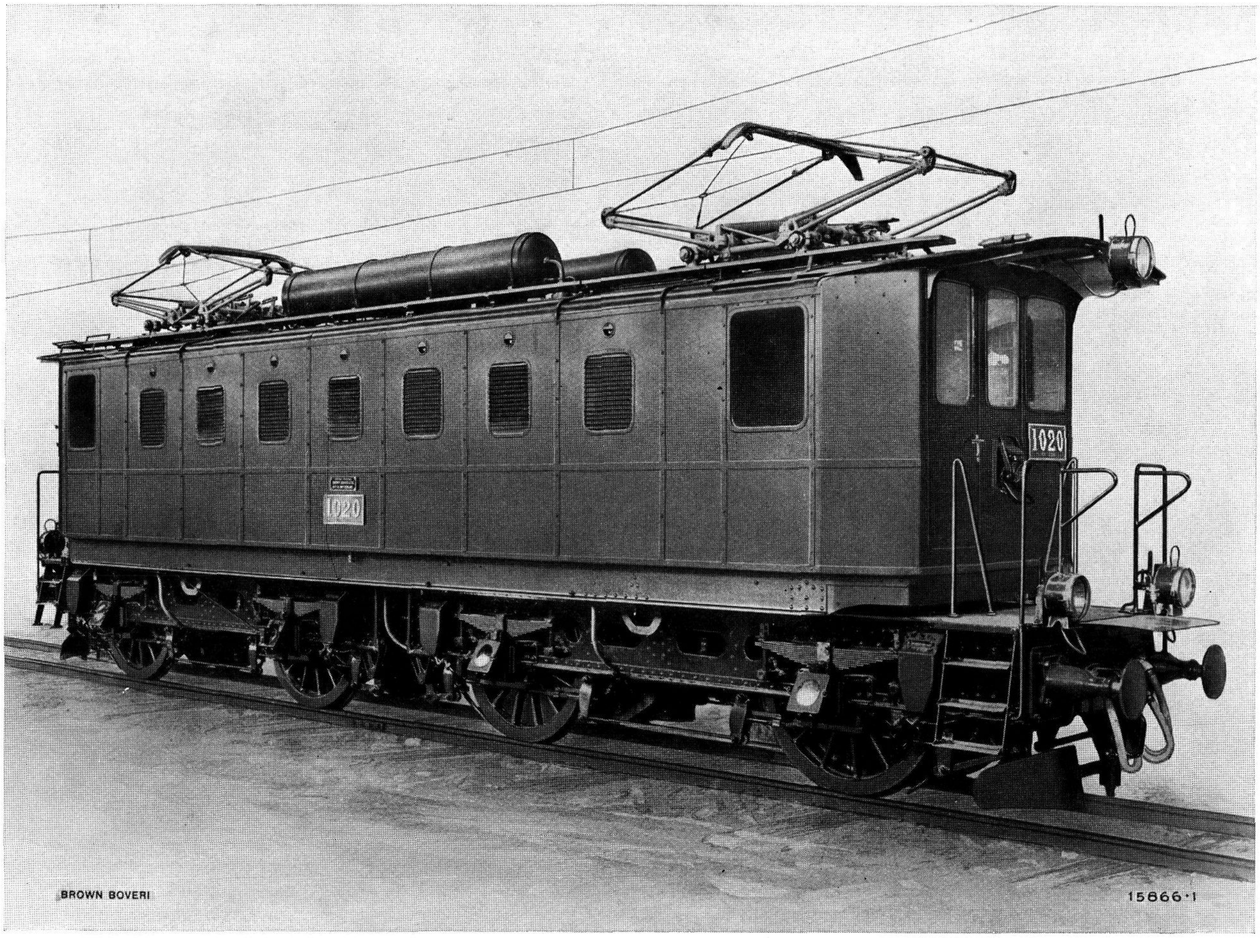
VOL. X DECEMBER, 1923 No. 12

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)



B-B GOODS LOCOMOTIVE ON THE JAPANESE GOVERNMENT RAILWAYS.
1380 H. P. (one-hour rating), 1500 V direct current, 1067 mm gauge.

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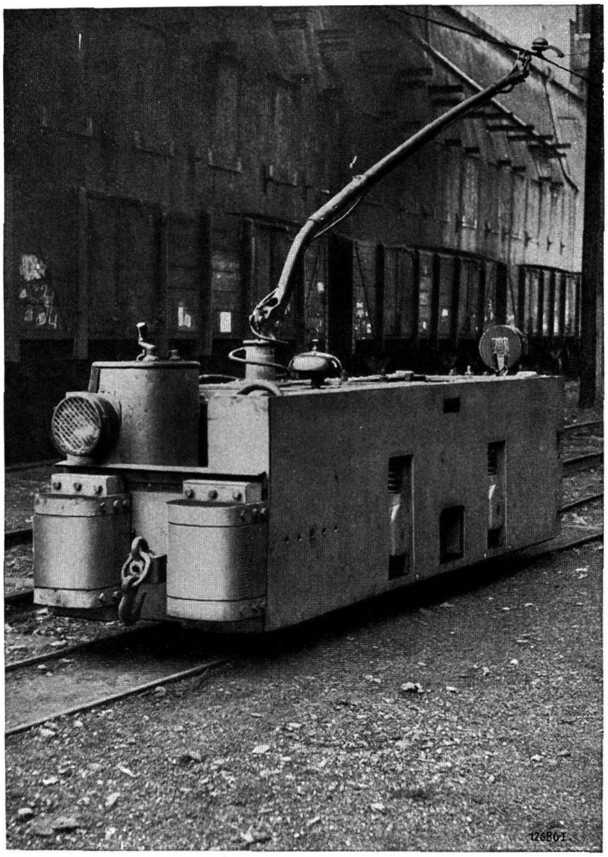
COMPLETE EQUIPMENT
OF INDUSTRIAL RAILWAYS
FOR ELECTRIC TRACTION



ELECTRIC MINE LOCOMOTIVE SUPPLIED TO THE SOCIÉTÉ DE MOUTIERS
(France).

MINE LOCOMOTIVES - BATTERY LOCOMOTIVES
BATTERY TRUCKS - RAILWAY MATERIAL

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. X DECEMBER, 1923 No. 12

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RAANAASFOSS POWER STATION.

Decimal index 621.312.134 (48.1).

THE Raanaasfoss power station is a co-operative undertaking on the part of the Akershus-Amts-Elektrizitetsverke, Norway. It is situated on the River Glommen — the largest river in the country — at a point about 40 km east of Christiania. The concession rights of two further falls, Bingsfoss and Sundfoss, in the immediate neighbourhood of the first, have been acquired with a view to their subsequent development.

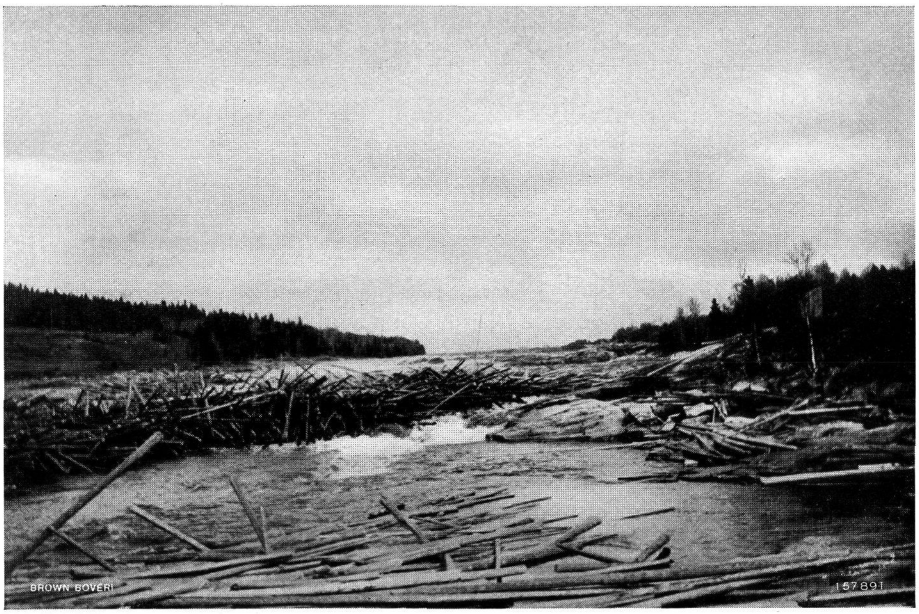

Fig. 1. — Raanaasfoss rapids before the construction of the power station.

Norway is well known as the European country possessing the greatest water-power resources. The United States Geological Survey has estimated the available water power of the whole world at 325'000'000 kW: about 4'000'000 kW of this occurs in Norway, although only 15 % has so far been exploited. In the west, installations working with high heads are principally to be found, while in the east, smaller falls with greater volumes of water offer opportunities for development and are already utilised to some extent. At the present time, however, development of these resources is practically at a standstill, as there is yet no great demand for electric power.

In such countries as Switzerland, difficulties arise in planning low-head installations owing to the increasing consideration it is necessary to give to river navigation. Similarly in Norway, considerable trouble is experienced on account of the drift-wood rights, according to which the way must remain open for timber to be floated down stream. These rights are of very old standing, and full advantage is still taken of them, particularly on the River Glommen, down which many million tree trunks are annually floated to supply the wood grinders of the great paper mills.

The portion of the rapids utilised at Raanaasfoss is situated between 118·25 and 105·25 metres above the sea, giving a fall of 13 metres, which can be increased to 14 metres by extending the tail race.

The River Glommen has an exceptionally variable discharge. It can be as great as 3000 m^3 per second when the water is highest, which occurs each year upon the melting of the snows, and for six or seven months of the year it exceeds 500 m^3 per second. It is calculated that, upon the completion of the work

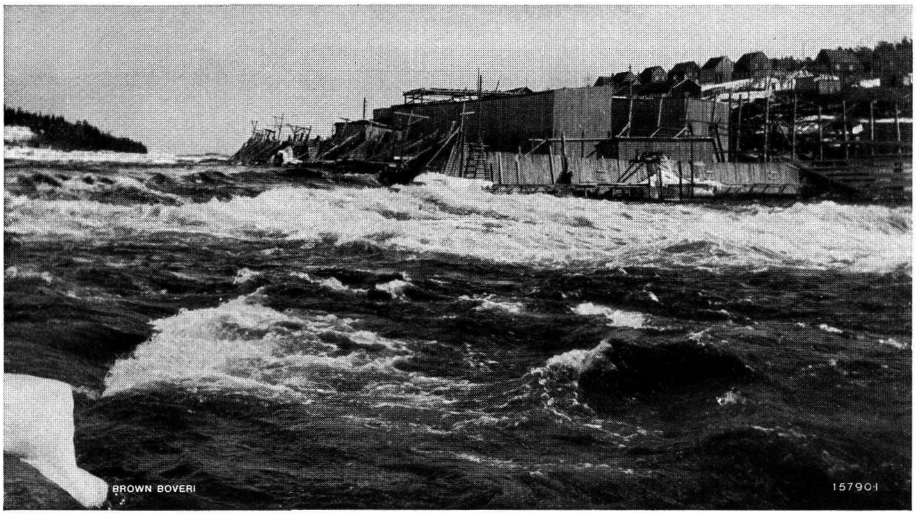

Fig. 2. — Condition of the work on March 3, 1919.

necessary to enable the outflow of Lake Mjösen to be controlled, the minimum will be 220 m^3. When the dam near Svanfoss is finished, the water level of this lake will be raised 2·2 m, providing a reservoir containing about 800×10^6 m^3. Further, storage of water from day to day is also possible on account of the large reservoir above Raanaasfoss and the smaller rapids Bingsfoss and Sundfoss.

The output of the machines in the Raanaasfoss power station has been fixed at 75'000 H. P., i.e., six sets each of 12'500 H. P. With a flow of 220 m^3 per second and a head of 13—14 metres, the minimum output amounts to about 30'000—32'000 kW.

In addition to the city of Christiania, the most important *field of application* of this electric energy is the Akershus district, where most towns and villages are connected to the system. Distribution is carried out at 50'000 V, a pressure of 17'000 V being employed only in the immediate neighbourhood of the centres of consumption. The transformation of the energy from 50'000 to 17'000 V is carried out partly in the power station itself, but to a larger extent in substations near Nerdrum, Dal, Minnesund, and Tonsen.

Building operations were commenced on the Raanaasfoss power station in the year 1919. That part of the country being entirely uninhabited, it was of primary importance to provide adequate shelter for the workmen and engineers. Progress was greatly assisted owing to the near proximity of the Christiania-Kongsvinger railway line, and a railway station was built at Raanaasfoss, with a special track connecting it with the power station.

Fig. 2 shows the condition of the work on March 3, 1919, and Fig. 3 the progress made up to March 1921. On December 24, 1921, two of the machines were ready to deliver power.

The complete station may be considered as consisting of three main parts: the drift way, the weir, and the power house.

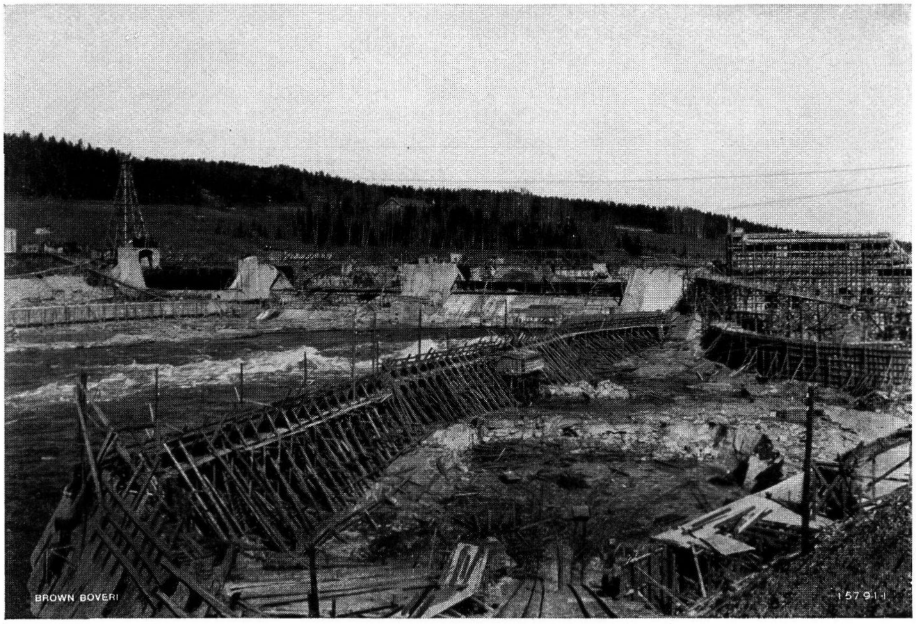

Fig. 3. — Condition of the work on March 26, 1921.

THE DRIFT WAY.

The drift way was constructed as specified by the experts who were appointed in conformity with the water-flow regulations. It is intended to allow wood being floated down the river to pass the power station when the water is low and not overflowing the weir. The channel is sufficiently large for the passage of 180'000 tree trunks a day, the necessary flow of water being 15—30 m^3 per second. The complete drift way has a length of 800 m, including a tunnel 200 m long, where it passes the weir. The remainder is an open channel faced with concrete throughout the whole of its length.

The entrance to the drift way is just above the mouth of the tunnel, and is provided with an inlet sluice, into which the water flows from an iron funnel which is used to regulate the water flow when logs are being passed through. Above the funnel, a pin weir is built, by which the channel and its entrance may be kept dry in winter. When wood is being floated down, it is led to the channel by substantial framework guides.

Fig. 4. — The weir.

THE WEIR.

The weir is provided with an ice chute, emptying gear, two main sluices, and a roller sluice.

The ice chute. An outlet is necessary for ice collecting in the forebay during the winter, and for this purpose an ice chute is provided. It is three metres wide and is built directly on to the turbine house. By means of an easily operated sluice, the ice can be allowed to flow away from the turbine intakes.

The emptying gear. Six sluices at the bottom of the weir, each two metres wide and about four in height, enable the water level to be lowered as far as possible for inspecting and repairing the foot of the weir and the sill of the turbine intakes.

The sluice machinery can be actuated either electrically or by hand and is so strongly constructed that, however high the water may be at the weir,

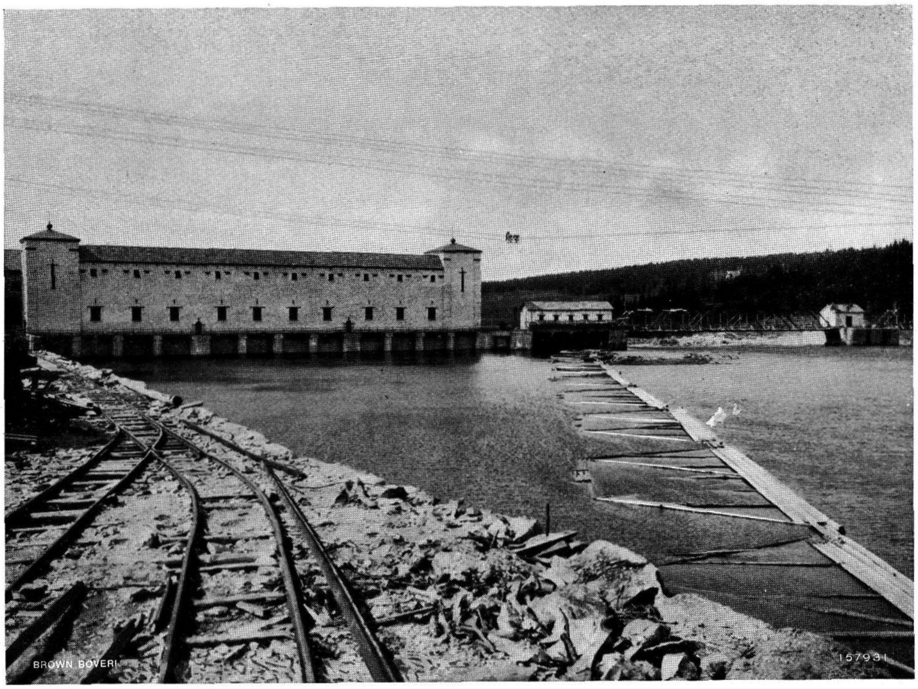

Fig. 5. — The forebay and turbine intakes.

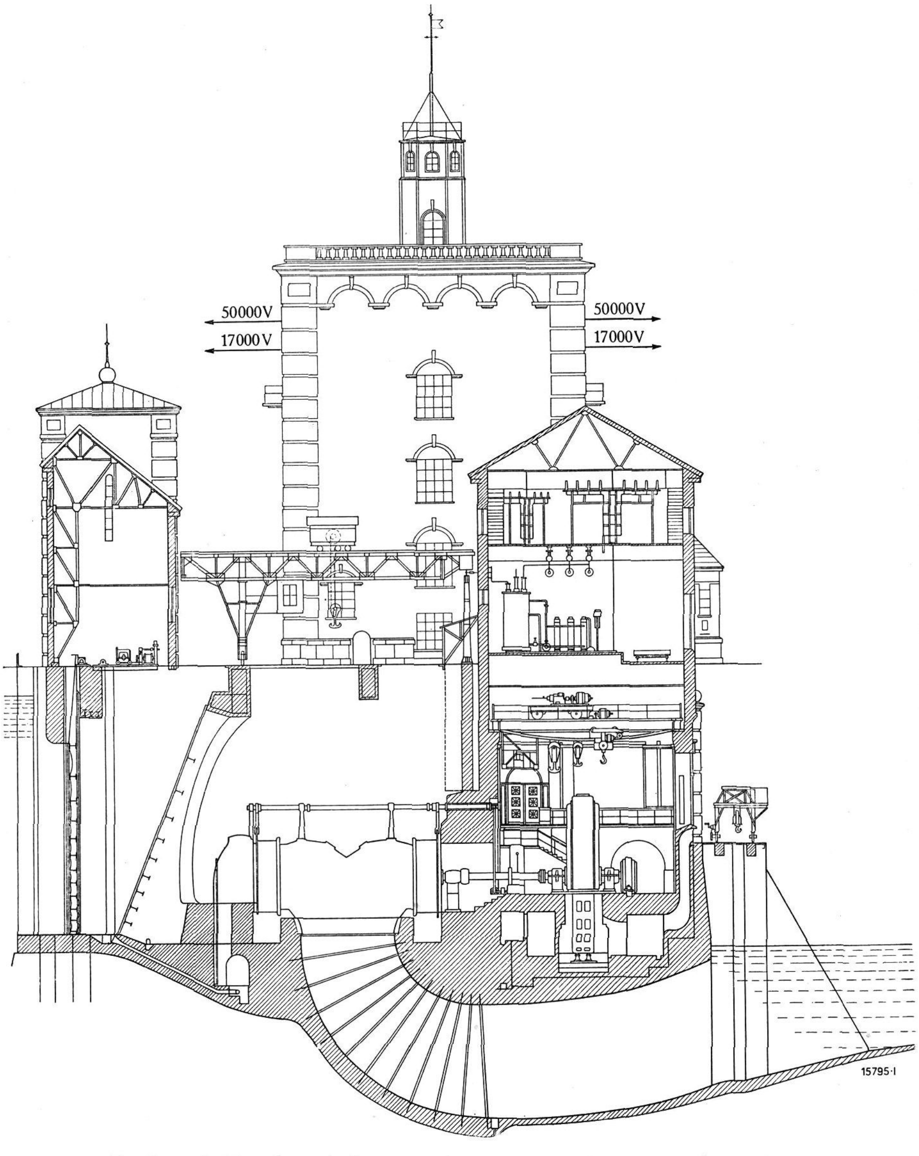

Fig. 6. — Section through the power house, turbine chambers, and gate house.

it is possible to operate the sluices. The latter are only intended for the purposes mentioned above.

The main sluices. On account of the large amount of drift wood handled on the River Glommen, and the irregularity with which these operations occur at Raanaasfoss—depending upon the flow of the water and the melting of the snow—two main sluices, 50 m broad and adjustable over a height of 3·75 m, were built in the spillway of the weir. They are so arranged that, by simple means, they can be lowered below the surface of the water, permitting drift wood to pass over absolutely freely.

The control gear is accommodated in the masonry structure dividing the two spillways. For dealing with ice at the sluices and carrying out any necessary repair work, an air compressor and a small steam boiler are also installed.

Movable pin weirs provided above these sluices enable the water to be completely shut off for inspection and repairs. In winter they also serve to shut down the two spillways completely so that the sluices may not be damaged by the formation of ice.

A roller sluice 45 m long is situated next to the right bank and completes the equipment of the weir. It is arranged for six different height adjustments. The packing at the sides is provided with electric heaters so that the sluice can be adjusted at any time during the most severe cold periods. Both the main sluices and the roller sluice are products of the *M. A. N. works at Gustavsburg.*

The three spillways are crossed by bridges two metres in width built by the *Vulcan company, Christiania.*

THE POWER HOUSE.

The building forms a continuation of the weir and constitutes the abutment against the left bank of the river. The greater portion stands directly on the rock of the river bed.

The plant consists of three sections: the turbines with their control gear, the alternators, and the switchgear.

The turbine installation. This comprises six units with their strainer racks and head gates.

On account of their size, the turbine sluices, which are of the roll-screen type, are divided by a central support; the necessary machinery is contained in the gate house immediately above them. They can be operated by hand or by motor, and closing can be effected from the control room by a push-button.

The sluices and their hoisting gear were delivered by the firm of Kværner, Brug (Norway).

Behind the head gates are the strainer racks for protecting the turbines from drift wood and other material. They are constructed so that they can be electrically warmed to prevent ice forming. In addition, the warm air from the generators can be led out immediately above the water surface in the gate house.

The turbines run in open chambers which are fitted with removable wooden covers.

Under a head of 13 m each turbine develops 12'500 H.P., and, with a 14-m head, about 14'000 H.P. They are of the double Francis type and run in horizontal bearings.

The shafts pass through the wall into the generator room, a water-tight gland being employed. The turbine governors, and the couplings between the turbines and generators are situated in the generator room, as is also the entrance to the inspection tunnels giving access to the turbine bearings.

Of the six turbines installed, three where supplied by the A/B Karlstad mek. Verkstaden, Christinehamn (Sweden) and three by the firm of J. M. Voith, Heidenheim (Germany).

The water from the turbines flows from the draught tubes beneath the generators into the tail race. By the use of stank boards, both the turbine chambers and draught tubes can be rendred quite dry. A 25-ton travelling crane is installed above the open turbine chambers to assist in erection and inspection, and is so arranged that machine parts can be unloaded direct from the railway trucks.

The machine room. This is situated immediately beyond the turbine chambers on the ground floor.

The complete scheme includes six 12'000-kVA alternators, the first four of which are in operation. These were supplied by the A/S Norsk Elektrisk & Brown Boveri, Christiania, and were manufactured in Baden. Later on in this article, an account is given of

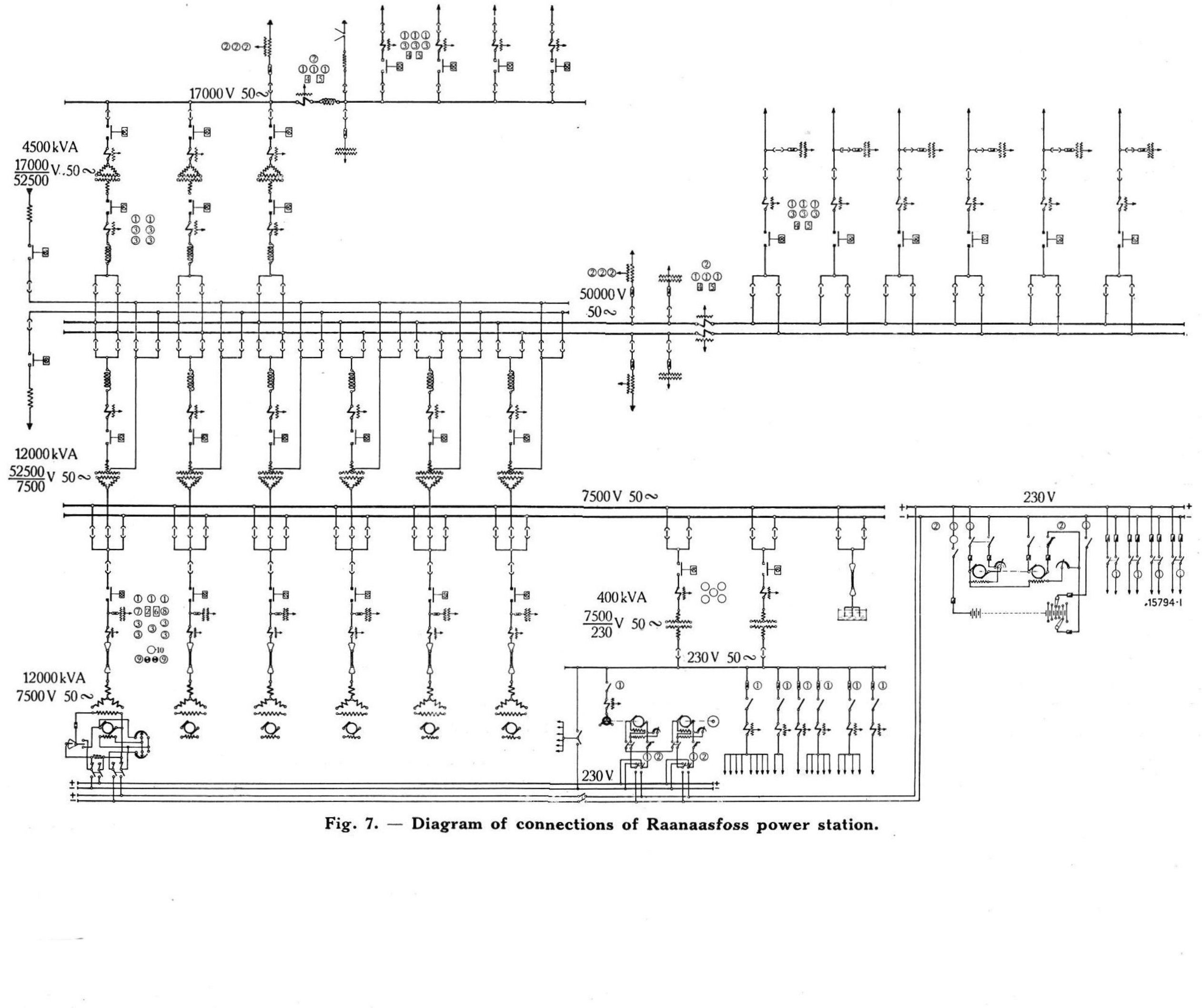

Fig. 7. — Diagram of connections of Raanaasfoss power station.

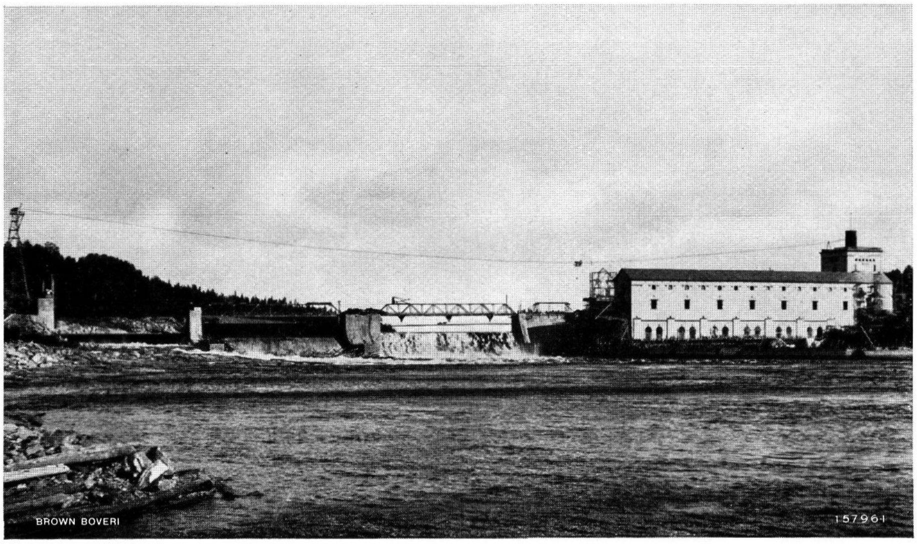

Fig. 8. — General view of the power station from the tail race.

these machines, their erection and putting into operation, and of the guarantee tests subsequently carried out.

The switchgear. On the first floor of the power house, above the machine room, the transformers are installed. Six of these, each with an output of 12′000 kVA, transform the generator pressure of 7500 V to 50′000 V, at which the transmission system works. The general diagram of connections is given in Fig. 6. Two 4500-kVA transformers for 50′000/17′000 V and two for 7500/220 V are provided, the latter being for the use of the station itself. On the same floor, the generator switches and the 50-kV transformer switches are also arranged.

On the second floor, above the transformer room, are the busbars and the horn lightning arresters of the 17-kV feeder. A dissonance extinguishing coil is provided for the 50-kV distribution system.

Adjoining the power house is a distribution tower, which carries the outgoing 50-kV mains, and contains the offices, and the control room for the whole of the apparatus.

The alternators. The order for the first four three-phase alternators was placed with the A/S Norsk Elektrisk & Brown Boveri, Christiania, in the autumn of 1919. They were built according to the following data:—

Output	12′000 kVA at 0·7 power factor
Terminal pressure	6400—7850 V, normally 7500 V
Speed	107 r. p. m.
Frequency . . .	50 cycles
Overload capacity	1120 A at 7850 V and 0·6 power factor.

The machines were designed and constructed in the Baden works. The sectional and outside views in Fig. 9 show the type of machine employed. The shaft is mounted in horizontal bearings, the coupling flange being at one end and the armature of the built-on exciter at the other. Each alternator is completely enclosed and draws its cooling air through a separate channel, discharging it through two outlet channels, one on each side of the turbine. Throttle valves, which are adjustable from the machine room, are arranged in the outlets.

The stator is divided into four parts with horizontal and vertical joints. It rests upon two removable feet and also upon four adjustable supports. The feet stand upon soleplates which are embedded in the concrete foundation, to which they are also fixed by strong bolts.

The winding is laid in open slots, in which it is kept in place and secured against short-circuit by wedges and clamps. The individual coils are former wound and are insulated from the iron by moulded sleeves of mica capable of withstanding at least 30′000 V under test. Each turn is also insulated with mica to withstand pressures up to at least 9000 V without puncture. In addition, the coils are carefully compounded to exclude all air and to improve the heat conducting qualities. The conductors are proportioned to carry half the current and are divided into two parallel circuits. To prevent exchange currents flowing, the coils constituting these two circuits were distributed symmetrically round the complete circumference, and for the same reason, the arrangement of the individual conductors in the slots required special attention.

The rotor consists of the spider, the rim, and fifty-six poles, the first being in two, and the second in four parts. Each of the poles is attached to the rim by four bolts which pass through the latter from the inside. The complete rotor is 7200 mm in diameter and has a flywheel effect of 1700 tm^2. It is firmly fixed to the shaft by keys and shrink rings. Before dispatch, each rotor was completely assembled in the workshops, statically and dynamically balanced, and subjected to an overspeed test up to 200 r. p. m.

The bearings are water cooled and ring lubricated. They stand upon separate soleplates and are firmly held down by strong foundation bolts. The bearing pedestals carry the end covers of the machine.

The four soleplates of the bearings and stator are connected to a frame which forms the edge of the pit, and to which the floor plating covering the latter is attached.

The exciter frame is mounted on a separate soleplate and fitted with end shields. Its ten field magnets are of the so-called regulation-pole type, which obviates the necessity for a series rheostat.

With regard to the excitation connections, it should be noted that both the exciters themselves and the alternator rotors can be separately excited. Separate excitation of the exciting machines has the advantage that the pressure of all the alternators can be increased from zero simultaneously, so that the paralleling operation is avoided, and much time saved; any liklihood of applying full pressure with a short circuit already on the system is also prevented. The independent excitation of the alternators, on the other hand, is only provided in case it should be impossible to stop a set by any other means, on account of the turbine control gear or the sluices becoming jammed.

Erection. It was specified in the contract that the first two generators were to be ready for putting into operation on January 1, 1921, but, owing to delay in the structural work, the first generator had to be stored in Christiania, and the commencement of erection operations was postponed till August 1, 1921. To have two machines ready by December 1, 1921, in accordance with the revised requirements of the clients, it was necessary to work to the strenuous erection programme given in Fig. 10. Five erectors with their assistants were consequently employed in two shifts, in such a way that there was always one group working on the assembly of the rotors, while a second group was occupied in setting up the bearings and the stators. It was possible to carry out the work successfully on this system of groups and shifts, because, in the first place, the work of erecting the turbines was already well forward, and secondly, owing to the fact that the crane was used exclusively for the erection of the generators, the turbines being situated outside the power house itself.

Figs. 11 and 12 show the progress made in erection up to August 23, 1921. The bearing pedestals

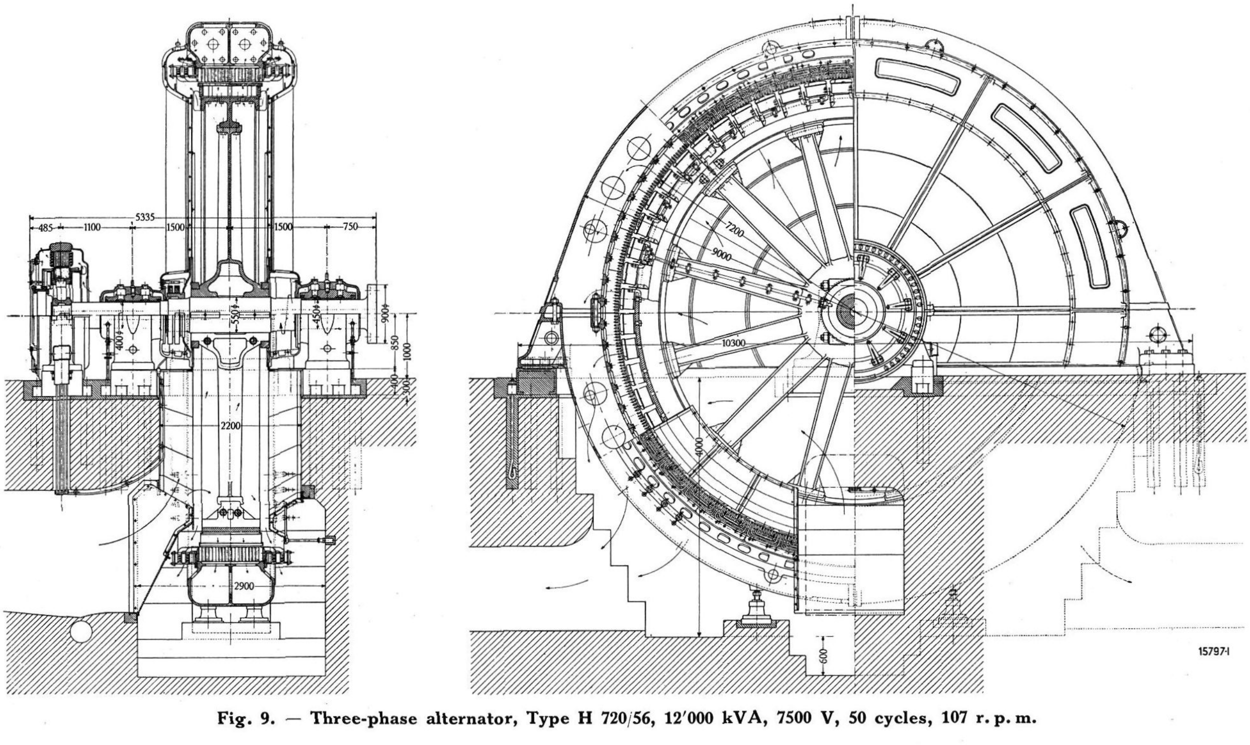

Fig. 9. — Three-phase alternator, Type H 720/56, 12'000 kVA, 7500 V, 50 cycles, 107 r. p. m.

of the first generator are already embedded in the foundation, a spare shaft being used for obtaining correct alignment. The lower half of the stator is also in place, ready for the soleplate to be cemented in, and the assembly of the rotor has progressed sufficiently far for the shrink rings to be fitted. Fig. 13 shows the rotor of the first machine being definitely placed in position on October 14, 1921. This rotor has the considerable outside diameter of 7·2 m, and, to enable it to be handled by the crane, it was necessary to omit the poles at the top and bottom. After the upper portion of the stator had been added, these gaps in the rotor proved very convenient when completing the stator winding at the points of division. The remaining poles were subsequently put into place from the pit, and bolted to the rotor.

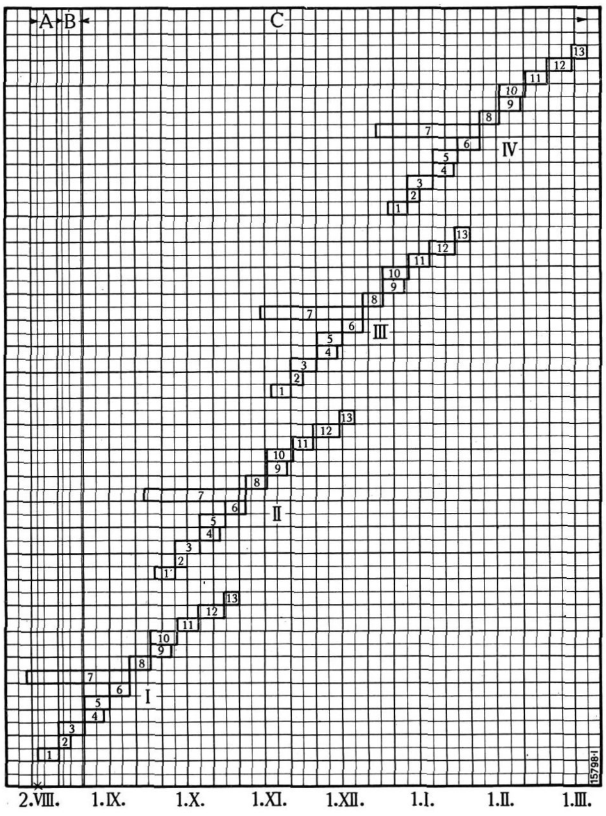

Fig. 10. — **Erection programme for four three-phase alternators, each 12'000 kVA, 7500 V, 50 cycles, 107 r. p. m.**

1. Setting up bearing pedestals and soleplates.
2. Embedding in concrete.
3. Assembly of lower half of stator.
4. Completion of windings at the joint.
5. Assembly of upper half of stator.
6. Completion of windings at the joint.
7. Assembly of rotor.
8. Placing stator and rotor in position.
9. Completion of windings at the joints.
10. Rendering air channels airtight, and fitting floor plates.
11. Fitting exciter and coupling.
12. Fitting end covers.
13. Miscellaneous work.

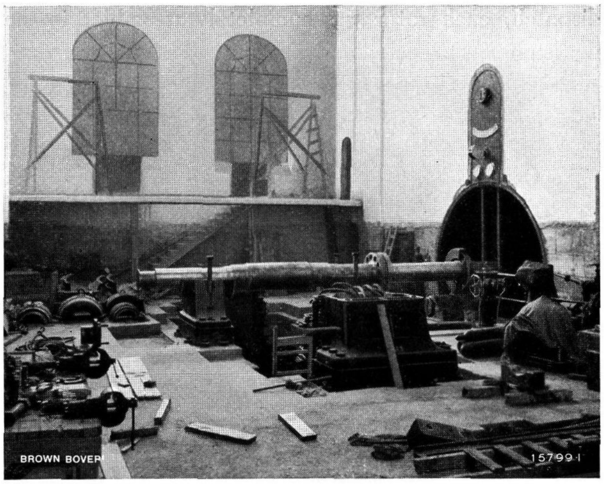

Fig. 11. — **Progress made in erection up to August 23, 1921.**

Altogether, the weight of material assembled was 640 tons, the erectors' working time being 4900 hours, in round figures, i. e., a mean rate of 130 kg per hour for each erector, which must be considered a highly satisfactory result. In addition to the actual work of erection, 3250 working hours were expended as shown by the following summary:—

Winding	1080	working hours
Finishing work . .	674	„ „
Waiting	496	„ „
Running and tests .	1000	„ „
Erection	4900	„ „
Total	8150	working hours.

Thanks to the excellent organisation and the good understanding which existed with the constructional engineers, it was possible to adhere perfectly to the programme. In fact, a considerable reduction would have been possible if the delivery of the last rotor had not been delayed owing to faulty casting and to the fact that a strike on the German State Railways occurred during transit. The erection of the generators was always well in advance of the other work in the completion of the station, and in no case occasioned any delay in putting the sets into service. The two first (Nos. 1 and 4), one coupled to a turbine of Swedish manufacture, and the other to a German turbine, were handed over ready to deliver power on December 22, 1921. Set No. 2 followed on January 12, 1922, and No. 3 on March 4, without the slightest hitch or difficulty.

One particularly noticeable feature is the extremely silent running of the generators. This is due to their being of the totally-enclosed type, which is the only way to obtain really quiet working. Any reduction in noise is greatly appreciated by the power-station staff, and more attention on the part of turbine builders to the silent operation of their products would be very welcome, particularly in the case of auxiliary machinery, such as the oil pumps and their drives, which can frequently be heard above every other sound.

Guarantee tests. These tests on the alternators were carried out by Nissen & von Krongh, consulting engineers of Christiania, who acted for the clients. They took place between June 22 and 25, 1922, and included the following:—

(a) Determination of the no-load and short circuit characteristics.
(b) Regulation test.
(c) Heating test.
(d) Determination of pressure variation.
(e) Efficiency test.
(f) Test on direct short circuit at 9000 V.
(g) Insulation tests.

No-load and short circuit characteristics. The tests and measurements (a)—(f) were only carried out on machine No. 4, with which the other three generators are identical. The air gap is 7·7 mm, and the no-load characteristic is correct for this value with regard to the pressure variation and maximum excitation. On prolonged short circuit, the current amounted to 1·25 times normal with excitation corresponding to no-load, and 2·2 times normal with full-load excitation.

The regulation of each alternator by its shunt-field rheostat from no load to full load, and between the limits of 6400—7850 V, fulfils all requirements. The exciters themselves can be separately excited as shown in Fig. 6, the change from self-excitation being effected by a two-pole change-over switch. Each of these two circuits has a separate field rheostat, both of which are, however, operated by a common control. The employment of two rheostats in this manner was considered necessary as, in the case of the separate excitation at 220 V, it was impossible to obtain sufficiently fine regulation with one rheostat only. With the rheostats in their zero position, the field is short-circuited.

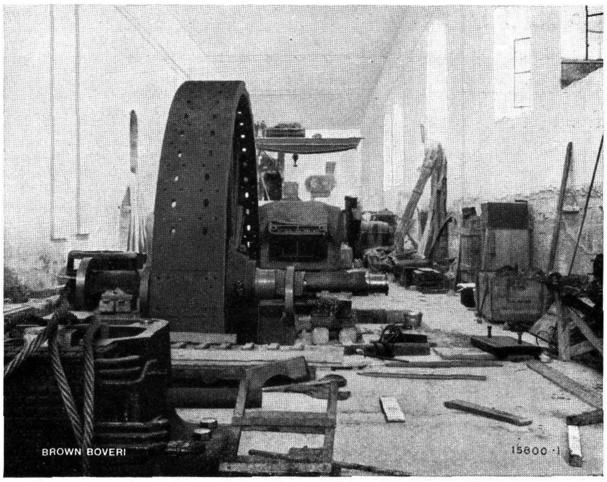

Fig. 12. — Progress made in erection up to August 23, 1921.

The no-load losses include bearing friction, ventilation, and iron losses. Together with the power required by the turbine running light, these amount to 238 kW. The alternator was not uncoupled from the turbine during these tests, in the first place, to avoid the considerable waste of time involved, and secondly because it would not have influenced the overall efficiency of the alternator to any appreciable extent. Generator No. 4 was run synchronously as a

Fig. 13. — Progress made in erection up to October 14, 1921.

motor. For this purpose, its rotor was connected in series with that of the generator supplying the current, and the two machines were excited together from a common source and run up to speed from rest. The connection of the two rotors in series has the great advantage that, when readings are being taken for the curve of the losses as a function of the pressure, the phase displacement remains practically constant and the measuring instruments are not subjected to risk of damage. The separate losses were as follows:—

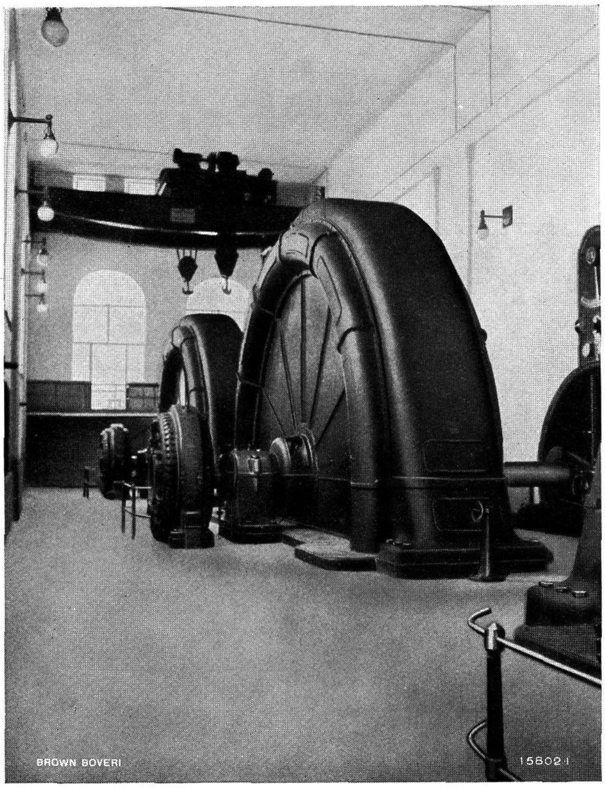

Fig. 14. — Completed generators.

Ventilation losses and bearing friction .	133 kW,
Iron losses	105 kW.

The heating test was run on a load of 12'000 kVA, —930 A, 7500 V, 0·7 power factor, 50 cycles,— which was provided partly by a water resistance, and partly by an under-excited alternator running in parallel.

The mean increases in temperature of the stator and rotor windings were determined by the change in their resistance, while thermometers were employed to measure the temperature rise of the coil ends, stator iron, rotor copper, pole shoes, slip rings, and bearings. The following results were obtained:—

I. Determined by resistance measurements:

Rotor:

Resistance cold (17° C) = 0·241 ohms.
Resistance warm with cooling air at 13·2° C. . = 0·288 ohms.
Temperature rise with an exciting current of 465A = 47·8 + 3·8 = 51·6° C.

Stator per phase:

Resistance cold (17° C) = 0·0243 ohms.
Resistance warm with cooling air at 13·2° C. . = 0·0289 ohms.
Temperature rise . . . = 47·3 + 3·8 = 51·1° C.

II. Thermometer measurements:

Temperature rises above cooling-air temperature

Air outlet.	18·0° C
Coil ends.	39·1° C
Stator iron	34·8° C
Rotor copper . . .	42.8° C
Pole shoes	27·8° C

Temperature rise of slip rings above room temperature . . . . = 37° C.
Temperature rise of bearings above cooling-water temperature . . . . . . = 18° C.
Temperature rise of all parts of the exciter. . . . . < 20° C.

Concerning the ventilation, it should be mentioned that the air valves fitted at the inlet were completely open, while the outlet was partially closed. Under these conditions, the volume of cooling air passing through the machine only amounted to approximately 50 °/o of normal, which explains the relatively high temperature rise of 18° C recorded at the air outlet. Naturally, with normal ventilation, all other temperature rises which depend upon the flow of cooling air would have been several degrees lower, but even with the supply reduced to half, they were within the values guaranteed, and in accordance with the regulations of the Verein Deutscher Elektrotechniker— a proof that the machines are very liberally proportioned.

The pressure variation was measured during the heating test, with the machine running at a power factor of 0·7, and found to be 25·5 %. This value agrees exactly with that obtained from the no-load characteristic. Fixing the pressure variation at such a low figure is important for an installation in Norway, as hand regulation is still almost exclusively employed there. It is curious that such little use should be made of automatic regulating apparatus in that country, whereas in Switzerland, for example, such equipment has given the most favourable results in the largest stations, from the point of view of labour saving and reliability, and for parallel working on the most extensive systems.

The efficiency is guaranteed on a basis of the separate measurable losses, which comprise the no-load, stator-copper and excitation losses. An allowance of 20 % of the power delivered by the exciter was made to cover the losses in that machine and at the brushes.

The results of the measurements were as follows:—

	Power factor 1		**Power factor 0·7**	
	12'000 kVA	6000 kVA	12'000 kVA	6000 kVA
	kW	kW	kW	kW
No-load losses . . .	238	238	238	238
Excitation: I^2R (warm) + 20 %	37	30	75	49
Stator copper: $3 \times I^2R$ (warm) . .	74	19	74	19
Total	349	287	387	306
	%	%	%	%
Losses	2·83	4·6	3·12	4·78
Measured efficiency .	97·17	95·40	96·88	95·22
Guaranteed efficiency	95·8	92·6	94·7	92·1

The efficiency as measured is thus considerably better than the guaranteed figures.

The direct short-circuiting of the alternator terminals was also a condition of the contract. The 7500-V busbars were metallically connected, and the main switch of each machine in turn was closed on the short circuit. A preliminary test was first carried out at a pressure of 7500 V, during which the machines behaved entirely normally, the effects of the short circuit being barely noticeable. On the other hand, at 9000 V with full-load excitation, short-circuiting resulted in a report like that of a cannon, and one felt that all parts of the machine must have been subject to great mechanical stresses. In spite of such a short circuit, which is much heavier than any that can occur at 7500 V whatever the excitation, all four generators remained entirely undamaged. At the instant of short circuit the exciting current rose to many times its normal value, but in spite of this only the slightest sparking at the brushes was observed.

Insulation tests were carried out on the four portions of each stator in the works at Baden before dispatch. As required by the clients, these tests were repeated at Raanaasfoss upon the completed machines, the following pressures being employed:—

22'000 V for 1 minute,
15'000 V for 5 minutes,
12'000 V for 15 minutes.

The alternate use of the machines up to May 22, 1922, was quite sufficient to ensure that all windings were well dried out. Thus the above tests were carried through without the slightest breakdown or flashover. The pressure was measured in the usual manner by a sphere spark gap. At 22 kV the power absorbed by the capacity of one complete stator winding amounted to about 70 kVA.

In conclusion, emphasis should be laid on the fact that Raanaasfoss power station was built and installed with four machines in a period of barely three years and is, in every respect, a credit to those in charge of the work. With regard to the generators themselves, it must be acknowledged that in their design, manufacture, and erection, as well as their general performance, a very high standard indeed has been attained.

W. Holliger. (G. T. S.)

TESTS ON THE VIBRATION OF DISCS.

Decimal index 531. 32 : 621. 165. 14.

ON account of the number of turbine failures which have occurred during the last few years,[1] as a result of disc vibration, the investigation of the nature and the cause of these vibrations would appear to be a matter of the greatest importance. Dangerous vibrations of a turbine disc can only take place when the periodic action on the disc of a constant force such as a steam jet is in resonance with one of the natural frequencies. The first step in eliminating this danger, therefore, is the determination of these natural frequencies. The present article deals with certain tests conducted for this purpose by Brown, Boveri & Co. upon turbine discs complete with blading. Some of these tests were carried out with stationary discs (static tests), and some with rotating discs mounted on a shaft as in a turbine (dynamic tests).

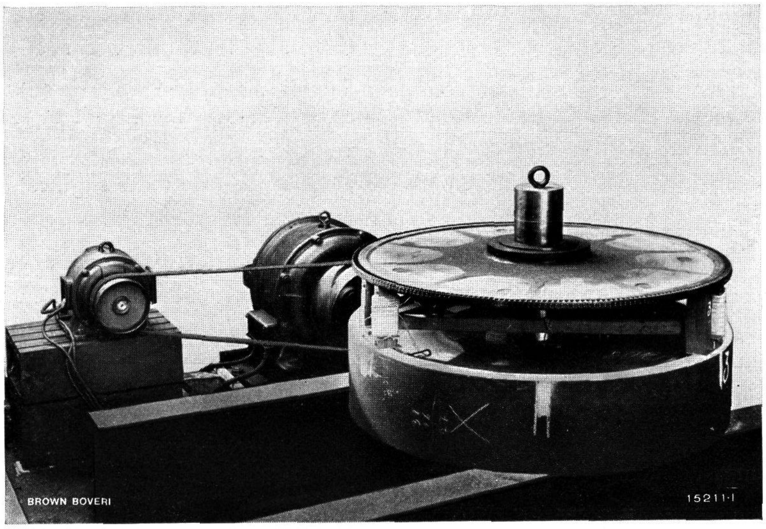

Fig. 1. — Apparatus for performing static tests on the vibration of turbine discs.

Static tests.

The discs to be tested statically were shrunk on to a vertical shaft and subjected to the action of an alternating-current magnet (Fig. 1). Variation of the periodicity of the alternating current from 0 to 150 cycles per second by means of a frequency converter enabled the discs to be vibrated at various natural frequencies, the frequency of vibration being determined by the periodicity of the current. The manner of disc vibration was indicated by the patterns in

Fig. 2. Turbine disc with whole circumference vibrating without nodes.

Fig. 3. — Vibration with one nodal diameter.

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[1] See, for instance, "Turbine troubles", Power, Vol. 47, No. 12, and Engineering, March 20, 1921, p. 631.

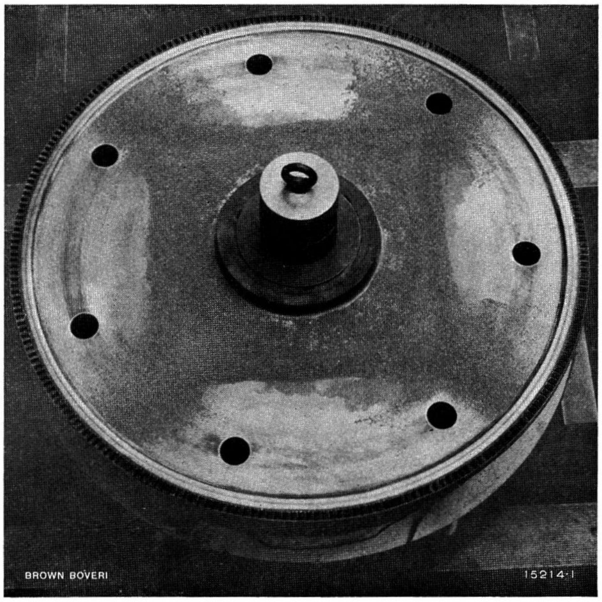


Fig. 4. — **Vibration with two nodal diameters.**

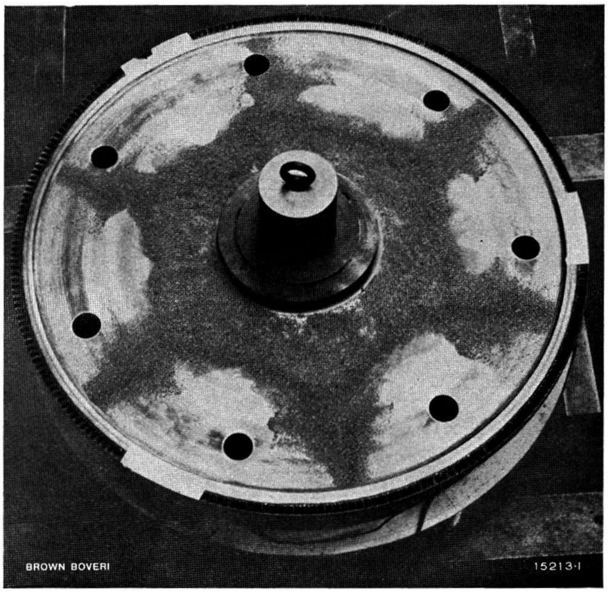


Fig. 5. — **Vibration with three nodal diameters.**

which sand arranged itself when sprinkled over the surface.

Each of the various natural frequencies of a disc corresponds to a certain number of nodal diameters, i. e., lines along which the disc remains perfectly at rest. In the case illustrated in Fig. 2, the whole circumference is vibrating without any nodes.

In Fig. 3, the conditions are such that vibrations are taking place about one diameter, which remains at rest while the remainder of the disc oscillates.

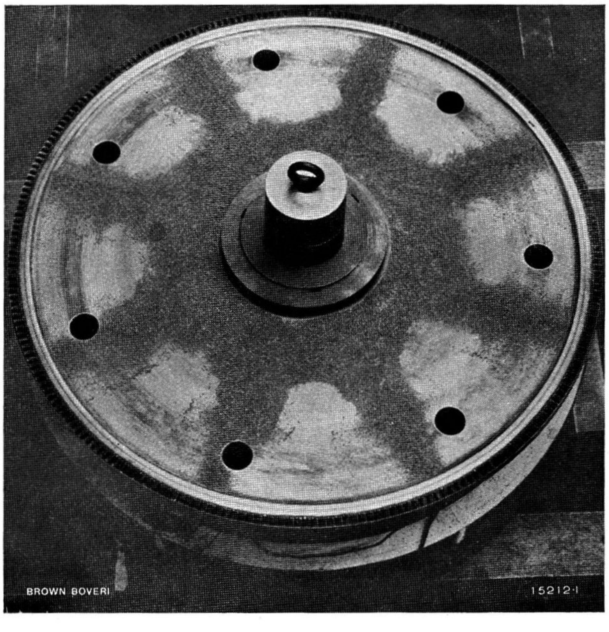


Fig. 6. — **Vibration with four nodal diameters.**

Fig. 4 shows vibration about two, Fig. 5 about three, and Fig. 6 about four nodal diameters.

Fig. 7 illustrates a combination of the cases shown in Figs. 2 and 4; this only occurs with thin discs, however, and cannot be produced with those usually employed in turbines.

Heat conditions have a considerable influence on the behaviour of the disc, in which, if the

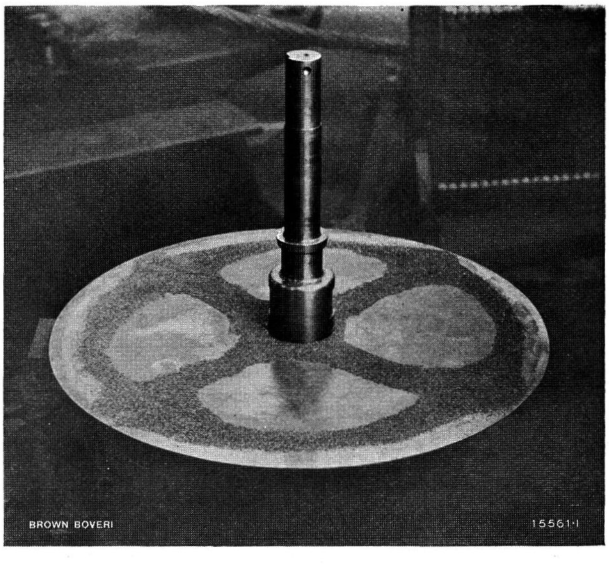


Fig. 7. — **Combined vibration with circular nodes and two nodal diameters.**

temperature is not uniform, a change in the stresses is caused, with a corresponding change in the frequency of vibration.

Curve 1 in Fig. 12 shows the results of static tests on a cold disc, the frequency being plotted as a function of the number of nodal diameters from 0 to 6. Curve 2 in the same figure is the corresponding curve for a disc of which the rim is warmer than the remainder, as in the case of discs working under high-pressure steam. It indicates that the result of the uneven heating is to raise the natural frequency of vibration without any nodal diameters, or with only one, whereas the frequency for 2—6 nodal diameters is lower than before.

The natural frequencies determined from experiments on fixed discs do not correspond to those which occur in practice, as a rotating disc is subjected to centrifugal force, giving rise to stresses which influence the frequency to a considerable extent. The effect of the tension resulting from this force is to stiffen the disc, so that it has a higher frequency of vibration than with static tests and behaves as though it were thicker than it actually is.

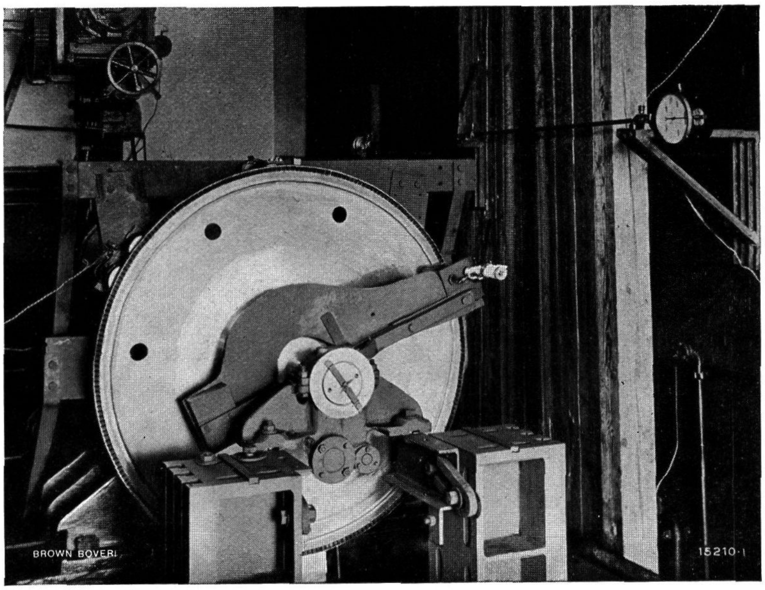


Fig. 8. — Apparatus for determining the manner in which rotating turbine discs vibrate, and the amplitude.

Curve 3 in Fig. 12 illustrates the results of a vibration test on a rotating disc, the rim of which was warmer than the remainder. A comparison of this curve with curve 2 shows that, for a dynamic test, the frequency is greater throughout than for a static test under similar conditions.

Dynamic tests.

Brown, Boveri & Co. were the first to conduct these dynamic tests on discs. The apparatus employed is illustrated in Fig. 8 and was set up in the overspeed testing department, where the disc could be rotated at any desired speed from 0 to 4600 r. p. m. To produce a periodic force on the rotating disc, such as exerted by the partial admission of steam to the turbine, a direct-current magnet was employed. The vibrations occur at various speeds according to the number of nodal diameters. The positions of the diameters and the apparent form of the disc were determined by an indicator mounted on a movable arm. It is possible to carry out observations in this way owing to the fact that, although the disc rotates, its apparent form and the nodal diameters about which the vibration takes place remain stationary relative to the magnet, i. e., in space. Fig. 9 gives to a reduced scale several diagrams taken by this means, for various numbers of nodal diameters. The speeds at which these vibrations take place at first appear to obey no definite law, but, if the frequency of vibration—which is given by the product of the speed of rotation and the number of nodal diameters—is plotted as a function of the latter, a smooth continuous curve results, as shown by curve 3 in Fig. 12. Curves 5 and 6 in Fig. 13 are similar results obtained with another disc.

The effect of switching the magnet on and off, with the disc rotating at the speed corresponding to a natural frequency of vibration, is illustrated in Fig. 10, which shows clearly the sudden commencement and damping out of the disc oscillations measured relative to a stationary point at the circumference.

In Fig. 11 are plotted the results of observations on a disc vibrating about four nodal diameters. The top curve shows the vibration beginning at 2490 r. p. m., that in the centre, the deformation at its maximum amplitude, which occurred at 2550 r. p. m., and the bottom curve, the vibration at 2650 r. p. m., when

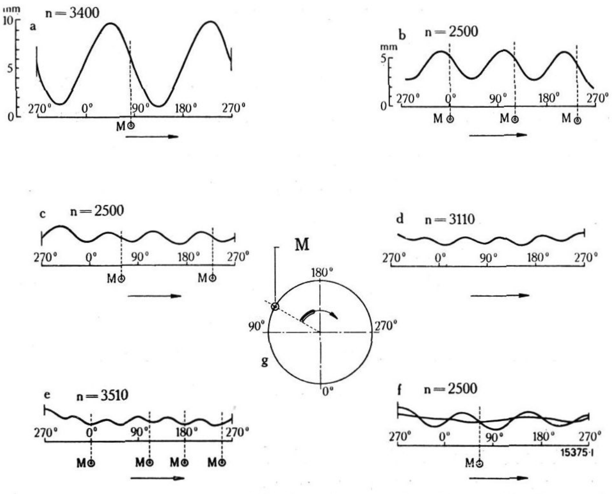


Fig. 9. — Various ways in which the rotating disc vibrated during test.
a. 2 nodal diameters, 3400 r. p. m. e. 6 nodal diameters, 3510 r. p. m.
b. 3 „ „ 2500 „ f. 3 „ „ 2500 „
c. 4 „ „ 2500 „ M. direct-current magnets.
d. 5 „ „ 3110 „
In the last diagram. curves are given for vibrations with and without the magnet in action.

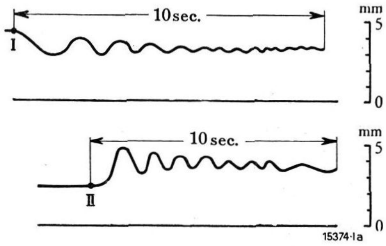


Fig. 10. — Effect of switching the direct-current magnet on and off.
I. Switching on the magnet.
II. Switching off the magnet.

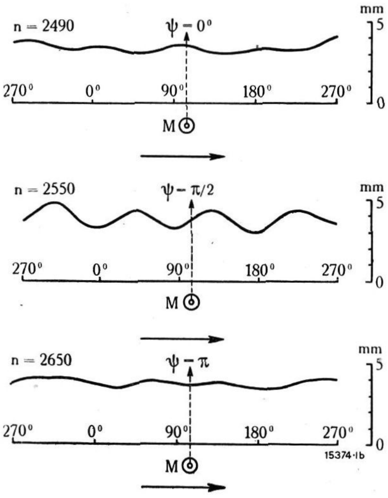


Fig. 11. — Influence of speed on the vibration.
a. Commencement of the vibration at 2490 r. p. m.
b. Maximum vibration at the speed of resonance, 2550 r. p. m.
c. Vibration dying away at 2650 r. p. m.
M. Direct-current magnet.

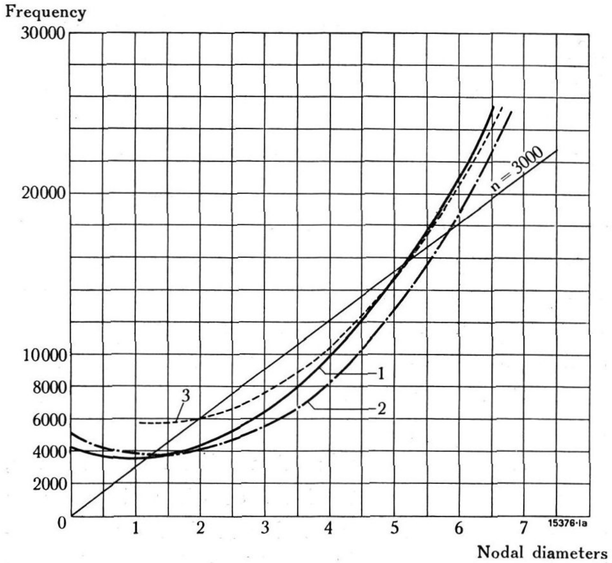


Fig. 12. — Vibration curves and line of inducing frequency for a turbine disc.
Curve 1. Static test on cold disc.
Curve 2. Static test, rim of disc heated.
Curve 3. Dynamic test, rim of disc heated.

it is dying away again and is once more weak and irregular. It is thus evident that 2550 r.p.m. is the exact speed of resonance for four nodal diameters.

The possibility of dangerous vibrations being set up in a turbine depends not only upon the natural frequencies of the discs, but also upon the frequency of the inducing periodic force to which they may be subjected. Only when these two frequencies are in agreement, is there any risk of vibration, or of a disc becoming fractured. The critical frequencies of the inducing force are equal to the products of the various numbers of nodal diameters and the speed: for 3000 r. p. m. with two nodal diameters, the critical frequency of the inducing force would be 6000; for three nodal diameters, 9000; for six nodal diameters, 18′000; and so on. Thus the critical frequencies for a certain speed must lie on a straight line drawn through the origin of the curves given in Figs. 12 and 13.

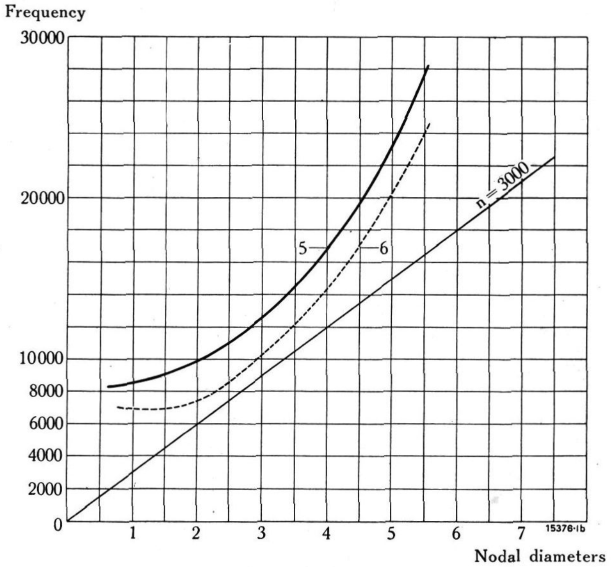
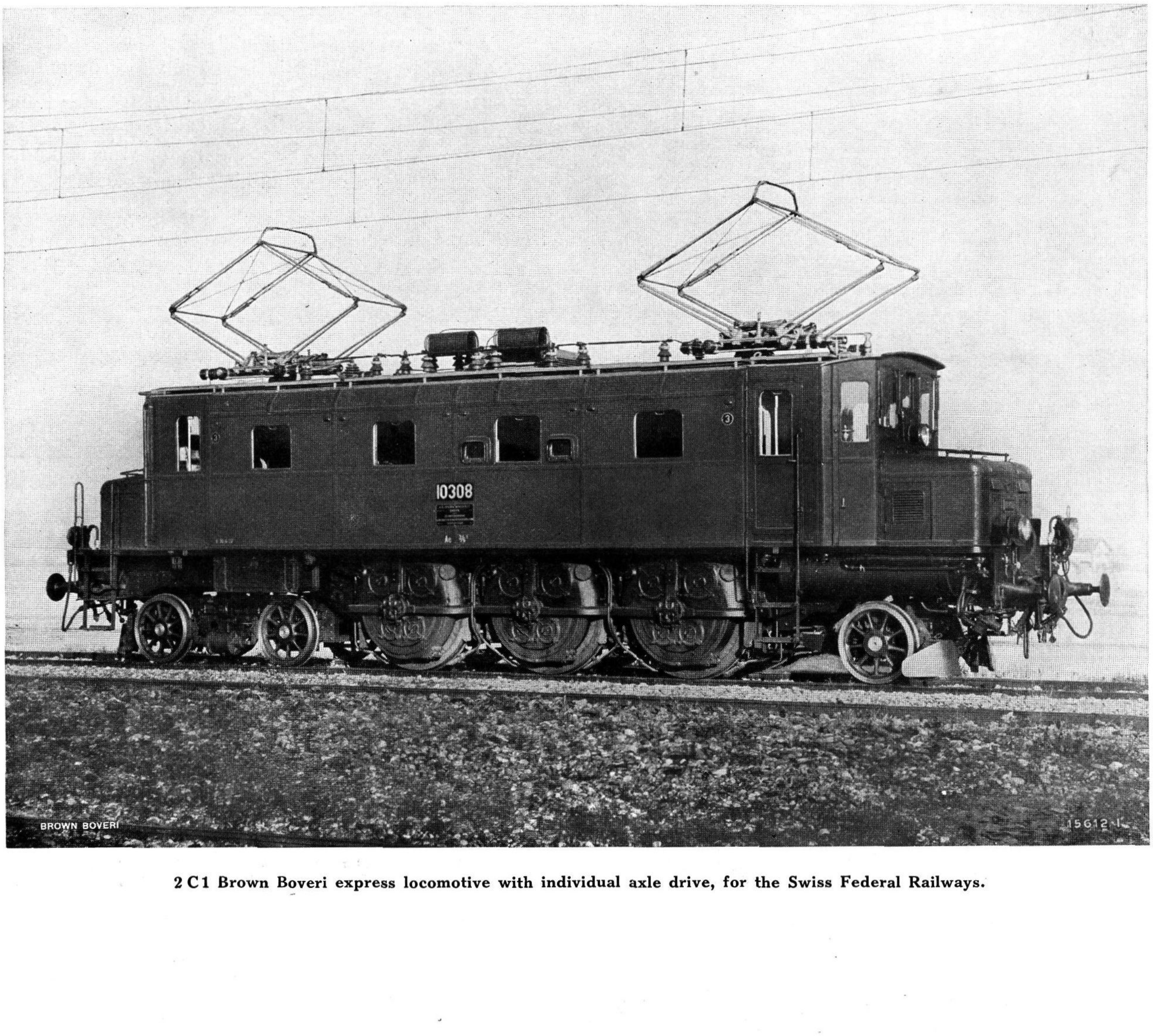


Fig. 13. — Vibration curves and line of inducing frequency for a strengthened disc.
Curve 5. Dynamic test on cold disc.
Curve 6. Dynamic test, rim of disc heated.

Vibrations can only occur with a whole number of nodal diameters (vibration with 2·3 nodal diameters, for example, being impossible), and, therefore, only when the straight line of the inducing frequency cuts the vibration curve at a point corresponding to a whole number of nodal diameters, as shown for two nodal diameters on curve 3 in Fig. 12. It will be readily understood that the point of intersection of the line of inducing frequency with the vibration curve may vary over a considerable range according to the heat conditions of the disc, so that, between two extreme values, a condition may be possible for which the point of intersection coincides with a nodal point. This is the explanation of the phenomenon, occurring with some turbines, of discs vibrating on one definite load, because this load happens to correspond to certain heat conditions. Hence, the possibility of vibration can only be eliminated if the line of inducing frequency lies outside the vibration curve and does not cut it at all. This condition is satisfied by both the curves in Fig. 13. Curve 6 is drawn for a disc tested with the rim heated to about 150° C above the temperature of the centre, which is a condition that can never occur at any turbine load in practice.

The two methods of testing described—static and dynamic—furnish a means by which the danger of vibration of turbine discs can be entirely avoided at all loads. At the same time, they make it possible to verify by experiment the values obtained theoretically for the natural frequencies of discs. From the most recent calculations of Professor Stodola, which are shortly to be published, it is possible to work out this frequency for any usual form of disc, and also to take the effects of temperature into account.

Ad. Meyer. (G. T. S.)



2 C 1 Brown Boveri express locomotive with individual axle drive, for the Swiss Federal Railways.

NOTES.

Brown Boveri electric locomotives with individual axle drive.

Decimal index 621. 334. 7.

SHORTLY following the conclusion of the first series of tests on a Brown Boveri individual axle drive fitted to a 2 B 1 locomotive[1] of the *Swiss Federal Railways*, Brown, Boveri & Co. received from the latter orders for 27 locomotives equipped with this drive. Although, in the first experimental design, the drive was arranged on both sides of the motor, the axles of subsequent locomotives were driven from one side only. As many of the locomotives fitted with the Brown Boveri individual axle drive have now run more than 90'000 km on various sections of the Swiss Federal Railways, much valuable data regarding their operation has been obtained, which confirms that they are as eminently suitable for the work required of them as was anticipated.

Other railway authorities have also evinced an interest in this individual axle drive. The *German State Railways* have placed an order for ten express locomotives for their Bavarian section with Brown, Boveri & Co., Mannheim, who are building them in their works at Mannheim-Käferthal.

The Cie. Electro-Mécanique, Paris, has in hand an order for two express locomotives with the Brown Boveri individual axle drive for the *Paris-Orleans Railway Company*. It is noteworthy that, in spite of the fact that they develop as much as about 4000 H. P. and are constructed for the high maximum speed of 130 km per hour, the weight of these locomotives is only about 116 tons.

Finally, two locomotives fitted with this drive have been ordered by the *Dutch East Indies State Railways* (Java).

The accompanying table is a summary of the more important data relative to individual-axle-drive locomotives in operation and under construction.

W. Luthi. (G. T. S.)

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[1] In operation since the end of July 1918. Cf. Revue BBC, March/April, 1919, p. 41.

Railway	Gauge mm	Current Supply	Type of locomotive	No. of locos. ordered	Output of the motors		Maximum speed km/h	Number of axles		Driving-wheel diameter mm	Weight of loco. tons
					1-hour rating H. P.	Continuous rating H. P.		Driving	Guiding		
Swiss Federal Railways	1435	Single-phase, 15'000 V, $16^{2}/_{3}$ cycles	2B1*	1	2×600 at 70 km/h	2×500 at 70 km/h	75	2	3	1610	74
Swiss Federal Railways	1435	ditto	1B1-1B1**	1	4×700 at 65 km/h	4×600 at 65 km/h	90	4	4	1610	127
Swiss Federal Railways	1435	ditto	2C1	26	3×700 at 65 km/h	3×600 at 65 km/h	90	3	3	1610	92
German State Railways (Bavarian section) . . .	1435	ditto	1D1	10	4×600 at 63 km/h	4×500 at 63 km/h	110	4	2	1600	102
Paris-Orleans Railway Company .	1450	Direct current, 1500 V	2D2	2	4×950 at 63 km/h	4×900 at 66·5 km/h	130	4	4	1750	116
Dutch East Indies State Railways (Java)	1067	Direct current, 1500 V	1D1	2	4×375 at 55 km/h	4×300 at 61 km/h	90	4	2	1500	70

* Test locomotive, one motor fitted with the Brown Boveri drive and the other with the Tschanz drive.
** Test locomotive, two motors fitted with the Brown Boveri drive and two with the Tschanz drive.

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