DOUBLE SYNCHRONOUS SPEED ALTERNATORS.

By K. P. Roy.

SYNOPSIS.

A description is given of an alternator arranged for a rotor speed of twice that corresponding to synchronism in which power is delivered from both the rotor and the stator. Some of the peculiarities of this type of machine are considered and the similarity of its excitation requirements to those of the induction generator examined. Test results are given comparing an experimental double-speed alternator and an induction generator. Attention is drawn to the possibility of using this type of generator for coupling to high speed turbines in the case of 25–cycle systems and 3,000 RPM turbines; its use as a phase-converter of low weight; and its relation to cascade generators.

INTRODUCTION.

It has long been known that an ordinary induction motor having a wound rotor can be operated as a synchronous generator, without direct current excitation, when both stator and rotor windings are connected to the line and the rotor is driven at *exactly* double synchronous speed.

Machines of this type have been described by E. Ziehl (*Electrotechn. Z.*, 1905, **26**, 617; 1909, **30**, 473) and discussed briefly by E. Arnold and La Cour (*Die Wechselstromtechnik*, **5**, 575), but little importance appears to have been attached to the machine, and in the literature relating to it very meagre details are given.

As this type of generator bears a resemblance to the induction generator for which there are useful applications, the writer has carried out experiments with the object of obtaining comparative data relating to the two types of generator. The conclusions reached as a result of these experiments are that the double-speed generator possesses features sufficiently novel to warrant consideration, in certain circumstances, as an alternative form of generator.

Further, the double-speed alternator may be classed with cascade generators (Hunt, *Elect. Review*, 1925, **46**, 766) and, as these machines are being developed to a considerable extent, data relating to the action of the double-speed alternator may not be without interest to those considering such problems.

THE WORKING CONDITIONS.

The double-speed alternator consists essentially of a stator and a rotor provided with a slip-ring winding, the windings of both being connected to the alternating current mains. The rotor is driven in the same direction as the rotating magnetic flux set up by the stator windings, but at twice the speed, in order that frequency of the slip-ring voltage will be exactly the same as that of the stator supply. If the rotor is wound for the same voltage as the stator it may be connected directly to the line by the usual process of synchronisation using circuits such as are shown in Fig. 1.

Under these conditions any increase in driving torque will cause the phase of the stator and rotor electromotive-forces to advance sufficiently for an output to be delivered from both windings to the line, the machine behaving as a synchronous generator.

The output of power from both the stator and the rotor windings should result in a saving of weight and space, i.e., lower D^2l for a given output, together with the possible advantage of double the speed, for a given frequency and number of poles, that is necessary for an ordinary alternator. This in certain cases might prove such an important matter as to become the real cause for attention to be given to the type. At the same time it is apparent that certain objectionable features are inherent to the machine, the most important being the supply of magnetising current, from the line, which is necessary. The machine is like the induction generator in that it is incapable of magnetising itself and is therefore *not a self-exciting alternator*. If the connections are as shown in Fig. 1, the magnetic flux in the machine is provided by the magnetising ampere turns due to the magnetising current drawn from the bus-bars. Consequently other synchronous machines having direct current excitation must be connected, or parallel condenser circuits may be employed. Such arrangements for the excitation of induction generators have been considered in the past (A. S. McAllister, *Alternating Current Motors*, 1907, second edn.) but have not yet proved successful on account of general and well recognised difficulties. Some experiments are in progress in this department on the use of series-connected low-voltage electrolytic condensers. Any means which may be developed for the provision of the excitation of induction generators should be applicable to the excitation of the double-speed alternator. A further disadvantage of the machine is the need for slip-rings of sufficient current-carrying capacity to withstand continuous use and adequately insulated for the line voltage.

Synchronisation does not appear to present any unusual difficulties: in fact, the small machine tested was found to be capable of self-synchronising in the same manner as some cascade generators.

On account of the novel features alluded to, and in spite of the difficulties of introducing a new type of generator, the manufacture of the double-speed machine was undertaken to some extent in Germany (Messrs. Berliner Maschinenbau A. G., *Vorm.* L. Schwartzkopff), where it has been termed a 'double-field' alternator because the magnetising current to generate the field is drawn by both the stator and rotor windings from the bus-bars.

Self-synchronising Methods of Paralleling.

In carrying out the tests described below the following methods of starting and synchronising were found to be quite satisfactory. The rotor was driven at approximately twice synchronous speed with the stator connected to the line. After ensuring correct phasing, the machine pulls into step on closing the switches connecting the rotor to the line. The current rush, under these conditions, was limited by additional series reactance in the rotor circuit as shown in Fig. 1.

Load-test on a Double-speed Alternator.

For the purpose of the laboratory experiments a small four-pole induction motor, having a wound rotor and slip-rings, coupled to a direct-current motor, was employed and driven at twice its normal speed for the trials. The induction motor rating is 7½ B. H. P. at 100 volts 50 cycles; the transformation ratio between stator and rotor being approximately 1 : 1. The tests carried out included the load characteristics of the double-speed alternator, and the characteristics of the same machine when operating as an ordinary induction generator. The connections used for these trials are shown in Fig. 2.

In both cases the frequency was 25 cycles per second, and the speed of the two types of generator in consequence differed by approximately 100 per cent. Throughout the tests the excitation of the synchronous generator connected to the bus-bars was maintained constant; this latter alternator has a rated capacity of 20 kW and its purpose was to supply the magnetising current and at the same time to absorb the output from the machine on test.

Tables I and II, and the graphs in Figs. 6 and 7, give the information derived from these tests, from which it will be seen that the output of the double-speed alternator is about double that of the induction generator, as should be the case with such a speed ratio.

TABLE I (Fig. 6)

Observed output of small 25-cycle Induction Generator (asynchronous) at 750 × (1 + s) RPM.

D. C. Motor Input		Induction Generator Output		
Volts (V_1)*	Amps (A_1)	Output† Watts	Line Amps. (A_2) and (A_3)	Line Volts (V_2)
99	4·3	114	18·5	58·3
99·5	0·9	455	20	58·3
100	3	840	22·3	59
100	6	1140	25	58·5
100	9	1440	28·5	57·7
100·5	8·5	1394	34	54·7
100·5	8·5	1394	37	52·5
99·5	8·25	1360	41	48·8
99	6·0	...	45	43·5

TABLE II (Fig. 7)

Observed output of small 25-cycle Double-speed Synchronous Alternator at 1,500 RPM.

D. C. Motor Input		Double Speed Alternator Output				
Volts (V_1)	Amps. (A_1)	Output Watts	Line Amps. (A_2)	Stator Amps. (A_3)	Rotor Amps. (A_4)	Line Volts (V_2)
103	3·95	276	18·5	21·8	3·9	58·9
103	·5	724	20·5	21·3	4·8	60
103·5	4·75	1162	23	21·2	6·75	59·7
104	7·5	1452	26	21·6	8·5	59·8
104	11·5	1867	31	21·7	12·0	59·4
105	15·5	2302	38	23	16·6	55·9
105	16·0	2352	46·2	24·6	20·8	49·0
105	17·5	...	49	...	...	44

* V_1, A_1, A_2 etc., refer to circuit diagram, Fig. 2.
† Output = $V_1 \times (\pm A_1)$ + losses in synchronous motor set.

It is interesting to note that the line current is the vectorial sum of the rotor and stator currents in the case of the double-speed alternator, whereas it is the stator current only in the case of the induction generator.

These results indicate that theoretically the double-speed machine requires only 50 per cent. of the D^2l of the induction generator, or of an ordinary alternator, because full advantage is taken of the increased speed for the delivery of power from both rotor and stator.

The copper-loss should be one quarter that occurring in the induction generator at the same load, but on account of the additional line frequency iron-loss, when the rotor runs at double-speed, the overall efficiency of the alternator is not increased to the extent which might at first be anticipated. Another point of interest disclosed by the tests relates to 'pulling out'. The synchronous speed of the induction generator being 750 RPM, it was found to 'pull out' at a speed of 920 RPM, i.e., at a negative slip of 23 per cent. for the particular excitation kVA, whereas the double-speed alternator was entirely free from 'pull out' difficulties, and delivered its output at the constant speed of 1,500 RPM with a drop in terminal P.D. on overloads.

Attention may be drawn again to one of the most important features of the double-speed alternator, viz., its adaptability for high speeds; for instance, the maximum speed which can be employed for a 25-cycle alternator is 1,500 RPM on account of the limitation to two poles. On the other hand, the double-speed alternator with two poles would require to be driven at 3,000 RPM for twenty-five cycles, and hence would suit high steam-turbine speeds. Further, in connection with certain types of single-phase traction plant, it is important that the weight and cost of the phase-converter placed in a locomotive should be reduced as much as possible. Some experiments on the behaviour of the double-speed alternator when arranged for use as phase-converter indicated that serious distortion of the voltage wave-form takes place. The machine was run at twice synchronous speed as a motor connected to a single-phase supply. It was found that both the line voltage and the voltage across the phase unconnected with the line were distorted as shown in Figs. 4(*a*) and 4(*b*).

Voltage Regulation.

The results of tests on the two types of generator are shown in Fig. 7 where the variation of terminal voltage of the double-speed alternator is seen to be in no way greater than that of the induction generator under the actual test conditions, and on the whole it is not to be expected that this type of machine would be inferior as regards voltage regulation.

Wave-form of Line P.D.

The magnetic flux in both the induction generator and the double-speed alternator is produced by the ampere turns which are distributed in approximately a sine-wave form as the resultant, or difference, of the stator and rotor ampere turns. The latter two waves of magnetising ampere turns are nearly equal and opposite but they differ in phase and magnitude by an amount sufficient to magnetise the machine. A practically pure sine-wave of flux results and the wave-form is a constant sine-wave as is borne out by the oscillograph records shown in Fig. 3.

Short-circuit Conditions.

It has been suggested (Spooner and Barnes, *Elect. World.*, 1910, **55**, 464) that the current rush on short-circuit would be much less with induction generators than is the case with ordinary alternators. This has, however, been shown to be far from true (Doherty and Williamson, *J. Amer. Inst. Elec. Eng.*, 1921, **40**, 1), because the initial current rush is of the same order for both types although they differ in this respect, that the final current becomes zero in the case of the induction generator. Whilst no experiments have been carried out on this it is to be expected that a double-speed alternator would be similar to an induction generator in behaviour.

Cascade Combinations.

In cases where it is considered desirable to avoid the use of slip-rings, some form of cascade connection of the windings is necessary so that the output may be drawn from stator windings only. Such combinations involve the use of two polyphase windings in both the stator and rotor, but avoid slip-rings, as is shown in Fig. 5 below. In order to be effective, the two sets of windings must be wound for different numbers of poles and the speed of the rotor adjusted to give the required frequency in the second stator winding.

Let the stator and rotor have P_1 pairs of poles in the first set of windings and P_2 pairs of poles in the second set of windings. Let the supply frequency to the stator be f_1, the frequency of the rotor currents f_2 and the frequency of the current in the second stator winding be f_3. The speed of the rotor, N_r revolutions per second is,

$$N_r = \frac{f_3 + f_1}{P_2 + P_1}.$$

In cases where the secondary stator windings are to be used in parallel, e. g., when connected to the same bus-bars, the conditions are that f_3 must equal f_1 which reduces the above expression to

$$N_r = \frac{2f_1}{P_2 + P_1} \text{ revs. per sec.}$$

Thus the elimination of slip-rings is attended by considerable restrictions in the choice of rotor speed, and as far as the higher speeds are concerned the elimination of slip-rings is accompanied by the total loss of the advantage of small D^2l, because the whole output is delivered by the two stator windings in parallel.

A Modified Double-speed Alternator.

It is possible to use an alternator of the double-speed type provided with additional direct-current excitation in order to generate power without other synchronous machines being connected to the line; such arrangements are already in use for self-synchronising cascade alternators. Two alternatives may be considered, viz., a double-speed alternator with a direct coupled exciter-alternator of sufficient size to supply the kVA representing the magnetising input of the double-speed machine; or the exciter-alternator may be combined with the double-speed windings in the form of a direct current field winding on the stator and a three-phase winding on the rotor in addition to the output windings. In the latter case, for example, a stator wound to deliver power at 25 cycles when the rotor is driven at 1,500 RPM (double-speed) would be provided with a two-pole direct current field winding, the rotor being provided with an additional two-pole winding connected by slip-rings to a four-pole stator winding. The rotor three-phase winding, having four poles, would then generate at 25 cycles and deliver its output in parallel with the four-pole stator winding.

Note on the Self-excitation of Alternators.

A double-field alternator was recently described by Contell (*Elect. Review*, 1924, **94**, 204) who claimed for it self-excitation properties, i.e., capability of delivering output without a synchronous supply line being connected to it; that this is impossible has been conclusively proved by the writer who tried the arrangement experimentally and found that *output ceased* immediately on cutting off the synchronous machine circuit which supplies the magnetising current.

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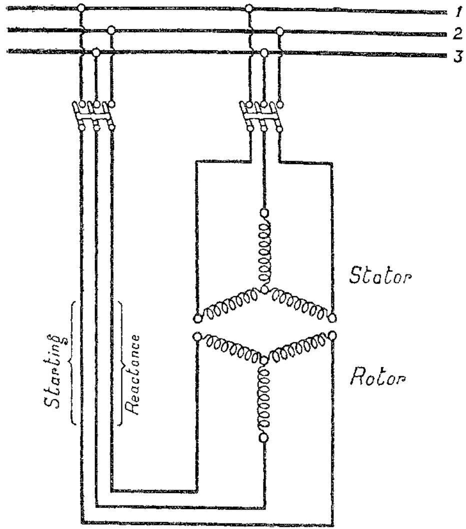

Fig 1. *Double speed alternator circuits.*

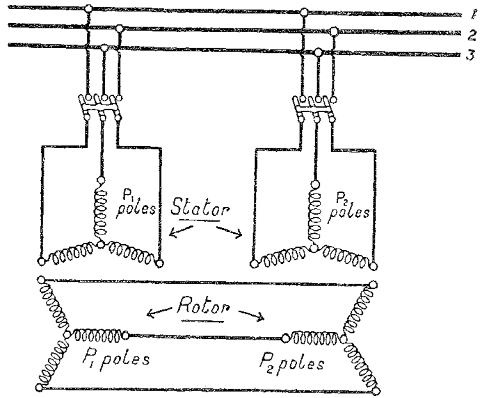

Fig 5. *Cascade Connection.*

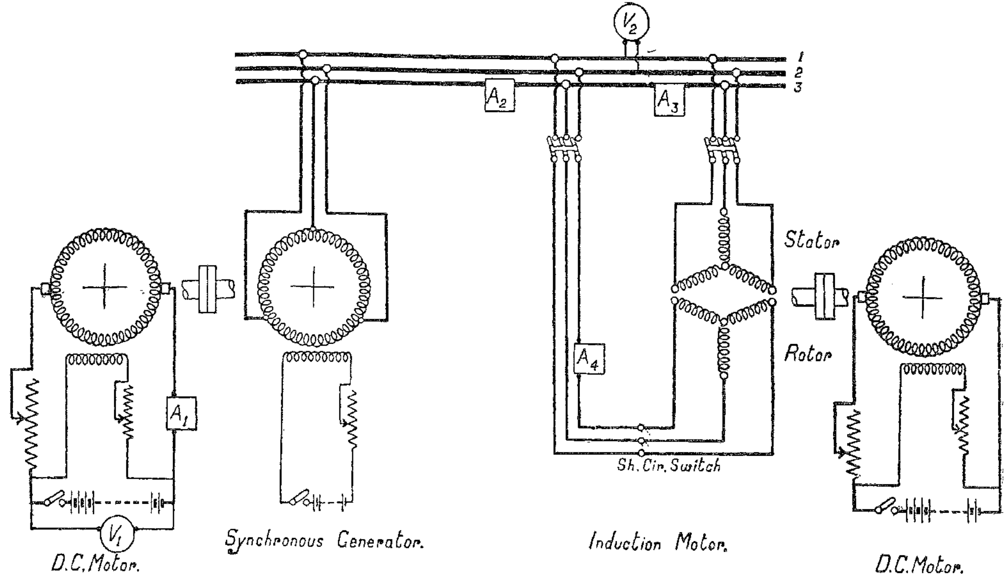

Fig 2. *Circuit used for testing generators.*

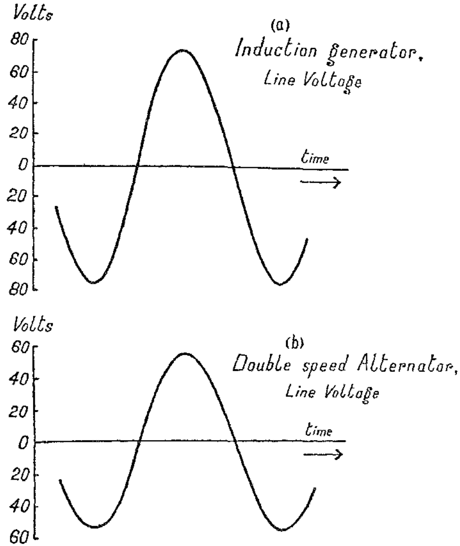

Fig 3. Terminal Voltage.

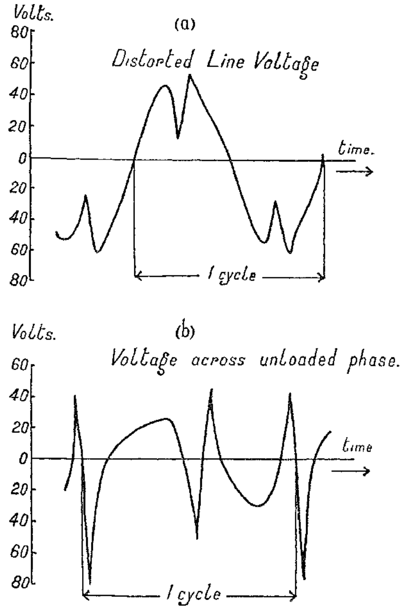

Fig 4. Double speed single phase alternator.

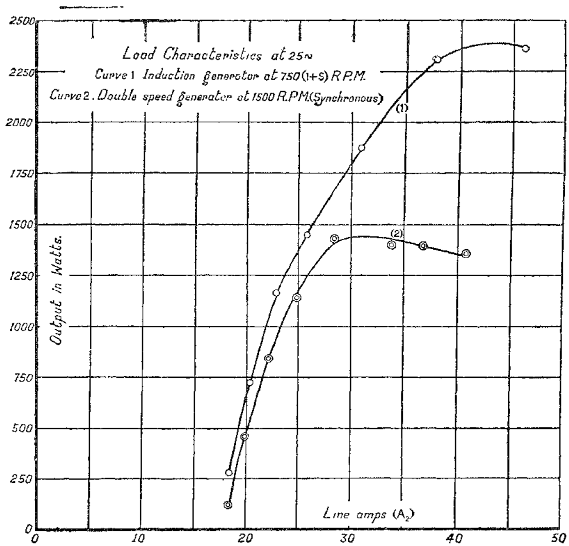

Fig 6. *Induction generator and Double speed generator; Load Characteristics.*

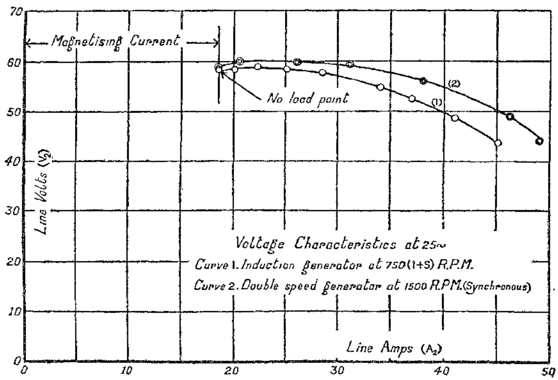

Fig 7. *Terminal Voltage Characteristics*