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THE DETERMINATION OF THE EFFICIENCY OF THE TURBO-ALTERNATOR.

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SUMMARY.

With the methods ordinarily employed of establishing efficiency of the turbo-alternator, the stray loss that is sent on load is either deduced by a substantially conventional method or is ignored altogether. As alternators for larger outputs are constructed, the stray loss becomes of greater importance and, indeed, may prove to be one of the factors that will limit the maximum size of unit that it is practicable to employ. A still more unsatisfactory feature of the existing methods is that it is becoming impracticable to apply them to the very large alternators now being constructed, on account of the difficulty of providing a driving motor of sufficient power. Further, with a driving motor, it is obviously impracticable to make any tests on site. It becomes increasingly important, therefore, to introduce a method of establishing the alternator efficiency which is based on the measurement of the actual losses on load. The object of this paper is to show that the actual losses on load can be deduced conveniently and accurately from measurements of the cooling air flowing through the alternator. It is further shown, however, that although such methods are sound in principle, misleading results may be obtained unless certain precautions are taken in applying them.

INTRODUCTION.

The efficiency of a turbo-alternator is usually expressed in terms of the rate of steam consumption in relation to the output of electrical energy, and therefore the purchaser has little direct economic interest in the accurate determination of the efficiency of the alternator. Nevertheless the matter is of considerable interest to the purchaser, since the efficiency of an alternator is an indication of the quality of the materials employed and of the degree of excellence of the design. The manufacturer is more vitally concerned in the matter, for the reason that the accurate determination of the alternator efficiency is the only means of ascertaining the magnitude of the actual

stray loss; for if the total loss on load can be found, the stray loss can be deduced when the other losses have been measured separately. With turbo-alternators of even moderate size the stray loss may be as high as five or six times the ohmic loss in the stator copper and, in the opinion of some authorities, this loss may prove to be one of the factors that will limit the output of electrical energy obtainable from a single unit. It will be seen, therefore, that if the efficiency on load can be determined accurately it will be one of the most important of the designer's informative tests.

The common practice in this country is to base the guarantees of the alternator efficiency on the summation of the various losses that can be measured separately, and either to ignore the stray loss altogether or to employ a substantially conventional method of determining it. Thus, some makers measure the windage and friction and the stator core loss (e.g. by driving the alternator with a calibrated motor) and calculate the copper losses (e.g. by deducing the full-load exciting current from open-circuit and short-circuit tests and taking the stator copper loss equal to the ohmic loss as for a direct current). The sum of the separate losses thus obtained is then assumed to represent the total losses in the alternator. The efficiency obtained in this way, however, is practically meaningless since the stray loss is entirely ignored. Other manufacturers make an allowance for the stray loss by assuming that it bears some definite relation to the stray loss present when the machine is run on short-circuit. In the conventional method adopted by the American Institute of Electrical Engineers, and used by some manufacturers in this country, the whole of the stray loss present on short-circuit is included when computing the conventional efficiency of polyphase machines (see Appendix II, Rule 458). That the nature and distri-

bution of the loss under the two conditions may be quite different, however, is shown by studying the heating in the two cases. When making short-circuit tests the authors have found in some cases great heating of the laminations at the ends of the stator core and considerable, although somewhat less, heating of the stator end-plates, whereas on full load the temperature of those parts was quite normal. For instance, in the case of a 5,000-kw. alternator at 3,000 r.p.m. embedded thermo-couples showed a temperature rise of 250 degrees F. at the ends of the stator core after running for an hour on short-circuit, although on full load the temperature rise of the same parts was only 60 degrees F. This phenomenon has not been fully investigated by the authors, but it is possibly due in part to a reverse flux between the stator core and the rotor steel end-bells which can only exist under short-circuit conditions. It will be seen, therefore, that when there is agreement between the value of the stray loss on load and on short-circuit it is partly accidental and is not to be expected in all cases. The investigations carried out by the authors confirm this reasoning, for although there is fairly close agreement between the two values in some cases, there is considerable disagreement in others, as is shown by the typical test results given in Table 7.

The efficiency can also be determined by running the alternator as an over-excited synchronous motor, but the kilovolt-amperes that have to be circulated limit the size of machine that can be dealt with in this way. Further, although the test can be made with full flux, a current lagging almost 90 degrees behind the electromotive force may give a value for the stray loss that is different from the actual loss on load. Also, the rotor copper loss with such a test is invariably too high, and to make the necessary correction entails a knowledge of the proper exciting current.

When two similar machines are available the Hopkinson test can be used, but the application of such a test to turbo-alternators is obviously very limited and is now rarely used.

It will be seen that at present there is not in common use any accurate method of determining the efficiency of the turbo-alternator, nor is there any standardized conventional method whatever in use in this country. It is an obvious and increasing necessity that a standardized method of establishing the efficiency should be adopted and, if possible, the method should not be one in which conventional values are assigned to one or more of the losses. Further, the method should preferably be one that can be applied at any time after the alternator has been erected on site.

For some time past the authors have been investigating the subject in conjunction with turbo-alternators made at the Sheffield works of Messrs. Vickers, Limited, and their investigations show that provided certain precautions are taken, the alternator efficiency can be conveniently and accurately determined under actual load conditions from measurements of the cooling air. From such measurements the separate losses can also be deduced—a matter of considerable importance when a driving motor is not available.

DETERMINATION OF THE LOSS IN TURBO-ALTERNATORS ON LOAD FROM MEASUREMENTS OF THE COOLING AIR.

Modern turbo-alternators invariably have forced ventilation and, with the exception of the relatively small amount of heat dissipated from the external surface of the stator, all the losses except the bearing losses are carried off by the cooling air. Consequently the most obvious method of finding the losses on load is to ascertain, with regard to time, the heat energy that is being carried away by the ventilating air; for if the volume of air flowing through the machine in unit time, and the average increase in temperature that the air undergoes in absorbing the losses in the machine, are known, then the total losses on load can be calculated without difficulty. This method will hereinafter be referred to as the "air-heating" method. The principle involved in this method formed the subject of a paper on "The Testing of Electric Generators by Air Calorimetry," read before the Institution * in 1903 by Professor R. Threlfall, the machines in this case being totally enclosed in a specially constructed housing.

An alternative method which does not involve measuring the air volume, is to ascertain the increase in temperature of the cooling air caused by a loss of known magnitude in the alternator, and from the observed temperature rise of the air on load to deduce the total losses. This method will hereinafter be referred to as the "calibrated air-temperature" method.

In the determination of the losses in the alternator from the cooling air, the bearing losses are not included. Such an arrangement is not altogether illogical, since, when the turbine builder sub-lets the contract for the alternator, it is the custom for him to supply the alternator bearings and it is a simple matter for him to make the allowance for the bearing losses. These losses may be determined fairly accurately by measuring the volume and temperature rise of the lubricating oil and by making a suitable allowance for the heat dissipated in other ways. Since the bearing losses constitute but a small percentage of the whole, a fairly big error in determining them would have only a small effect on the result.

MEASUREMENT OF AIR VOLUME AND TEMPERATURE.

Air velocity can be measured in a variety of ways, and any of the following methods could be considered for our present purpose:—

- (1) The Pitot tube.
- (2) The Venturi tube.
- (3) Electrical methods.
- (4) The anemometer.

(1) *Pitot tube*.—The Pitot tube consists essentially of a dynamic tube placed in the line of air flow and a static tube with the plane of its orifice set at right angles to the line of air flow. The shape and size of the orifice of the dynamic tube have been found by careful experiment to be unimportant, but the size and position of the orifice of the static tube are most

* *Journal I.E.E.*, 1904, vol. 33, p. 28.

important.* Tubes conveying the two pressures, i.e. the dynamic and static heads, are connected to a differential fluid gauge. The difference of pressure that the gauge shows has been found to be proportional to the square of the air velocity over a very wide range. For the present purpose the average gauge readings are of the order of one-fifth of an inch of water, and for accurate work with such low pressures it is necessary to employ a special form of manometer with the tube inclined at a large angle to the vertical. The micro-manometer designed by Mr. B. J. B. Roberts † is very exact and has been employed by the authors in their investigations with excellent results. Another very accurate type of manometer is a tilting tube operated with a micrometer screw that is adjusted until the index bubble assumes the central position, and the difference of dynamic and static pressures is given by the micrometer reading.‡ Such instruments are

FIG. 1.—Type of anemometer used in tests.

hardly suitable for the present purpose, on account of the skill required in using them and the time required to take the readings. For example, Sir J. I. Thornycroft found that with the Roberts micro-manometer it may take five minutes or more for the index bubble to reach its final position.

The principal objection to the Pitot tube, however, for this work is that when making absolute measurements it is dependent for its accuracy on the air flow being in line with the dynamic tube and at right angles to the static tube—conditions that cannot exist when the air flow is variable in direction. To facilitate the accurate measurement of the velocity of the air leaving the alternator it is desirable to fit a temporary discharge trunk, as described below; but no matter what precautions of this kind be taken there is still some appreciable variation of the air velocity from point to point over the discharge outlet, indicating a non-streamline flow. With the air flow varying in direction from point to point in this way, any particular

Pitot tube reading may not give accurately the average velocity at that part.

(2) *Venturi tube*.—The Venturi tube is a very exact instrument, but for its accuracy it is even more dependent than the Pitot tube on the flow of air being constant in direction, and it is therefore unsuitable for the present purpose.

(3) *Electrical methods*.—The electrical measurement of air velocity, based on the law that an electrically heated wire in a current of air cools at a rate that is dependent on the velocity of the air current, has been successfully carried out.* A wire of high electrical resistance-temperature coefficient, such as platinum, is employed, and either a constant voltage is maintained across it and the variation in resistance read, or the resistance is maintained at a constant value and the necessary variations of current are read. The air velocity is deduced from the readings on the basis of the law discovered by Dr. Kennelly and Messrs. Wright and Van Bylèbelt,† that with unvarying wind velocity the linear forced convection from a thin wire increases as the square root of the air velocity. A hot-wire velocity indicator operating on this principle has recently been devised by Professor J. T. MacGregor-Morris, who kindly provided facilities for the authors to inspect the instrument. Four exactly similar wires of material having a high electrical resistance-temperature coefficient are arranged as a Wheatstone bridge. One pair of opposite arms of the bridge is exposed directly to the air current; the other pair is also in the air current, but is protected by being enclosed in thin-walled tubes of high thermal conductivity. This small bridge is attached to the end of a tube of convenient length and the leads are carried inside the tube to a portable battery and to a milliammeter or millivoltmeter. The difference between the cooling of the arms of the bridge that are exposed to the air current and the arms that are shielded from it is indicated on the ammeter or voltmeter, which can be calibrated to read the air velocity directly. The indicator attains a steady reading in a few seconds and, in the form described, it is suitable for measuring velocities up to about 2,000 feet per minute. Such an instrument should be satisfactory for measuring the air discharge from a turbo-alternator, particularly since the accuracy would be little affected by the air having a non-streamline flow, as must be the case to some extent. The authors have already made arrangements for testing the suitability of the instrument for the class of work in question.

(4) *Anemometer*.—The anemometer is usually considered to be somewhat unreliable, but for the purpose in view the authors have found that a well-made instrument when properly handled gave sufficiently accurate results. Further, on account of the air flow being variable in direction, the anemometer is probably better adapted to read the absolute value of the average velocity at a given point than are more exact instruments.

The two inherent defects of the anemometer are the effects of the friction and the inertia of the moving

* *Journal of the American Society of Mechanical Engineers*, 1912, vol. 34, p. 1341.

† *Proceedings of the Royal Society*, 1906, vol. 78A, p. 410.

‡ *Engineering*, 1912, vol. 94, p. 892, and *Ibid.*, 1913, vol. 96, p. 343.

* J. T. MORRIS: British Association, Section G, Dundee, 1912—see *Engineering*, 1912, vol. 94, p. 892.

† *Transactions of the American Institute of Electrical Engineers*, 1909, vol. 28, p. 363.

parts. The effect of friction on the reading is, however, slight when the velocity of the air is considerable. The velocity of the air discharge from a turbo-alternator is of the order of 2,000 feet per minute and, with an instrument of the kind used by the authors measuring about 2.6 inches over the tips of the vanes, the frictional effect is not more than 3 per cent of the vane-wheel speed, so that even an appreciable error in the correction for friction has only a negligible effect on the result. The other inherent defect of the anemometer—the effect of inertia—is of appreciable importance only when the air flow is variable. When a

TABLE I.
Machine No. 7634.

V	..	..	4,550	7,200	8,950	10,900
n	..	..	1,500	2,400	3,000	3,600
K	..	..	3.033	3.000	2.983	3.028
Variation from mean value of K	..	..	+0.73%	-0.37%	-0.93%	+0.56%

jet of air is directed on to the vanes there is a little delay before the vane wheel assumes the velocity corresponding to the air velocity; and, on the other hand, when the jet of air is removed the vane wheel continues to rotate for some time. The retardation period is decidedly longer than the acceleration period, with the result that when measuring a variable air velocity the anemometer tends to give too high a

the fan*—that is, if V is the volume of air delivered in unit time, and n is the speed of revolution of the fan, then $V = K n$, where K is a constant. Therefore, by running an alternator at various speeds and measuring the air volume in each case, the accuracy of the anemometer readings is established if they bear a constant ratio to the speed of rotation. The authors have found that the results obtained in this way are very satisfactory, as is shown in the typical case given in Table I.

The accuracy of the anemometer readings was further checked by comparing a known loss in the alternator with the heat energy being carried away by the air. Such a proof is dependent on the accurate measurement of the average air temperature, and, in order to reduce possible error of this kind to a negligible extent, a large number of thermometers was employed. Typical results of such tests are given in Table 2, and the close agreement between the last columns will be noted.

In order to verify the consistency of the anemometer readings, two new instruments, calibrated at the National Physical Laboratory, and an instrument that had been in use for two years were mounted in succession in a given position at the discharge outlet of an alternator and were run for varying periods, during which the speed of the alternator and the load were maintained as constant as possible. The satisfactory results obtained are shown in Table 3. The instruments are necessarily delicate in construction and liable to damage by rough handling, so it is desirable that the accuracy should be tested in some such manner from time to time.

The anemometers used by the authors were supplied by Messrs. Negretti & Zambra and are of the type illustrated in Fig. 1. The makers guarantee the instruments not to vary more than 1 per cent over the range of air velocity for which they are suitable.

Determination of average velocity of air.—The first

TABLE 2.

Machine No.	Rotor Unexcited				Rotor Excited				Stator Core Loss + Excitation Loss in kw.	
	V	T_i	T_o	P_u *	V	T_i	T_o	P_e *	Calculated ($P_e - I_m$)	Measured by Driving Motor
7,541	3,160	61.7	76.0	14.4	3,290	64.0	113.7	48.8	34.4	34.6
7,729	5,220	64.0	75.0	18.3	5,400	64.0	103.0	64.3	46.0	45.5
7,325	14,400	73.0	87.0	63.3	14,800	87.5	123.0	154.5	91.2	92.0

* P_u and P_e represent the losses heating the cooling air when the alternator is run unexcited and excited respectively, and are calculated from Equation (2) below.

reading. This defect is of negligible importance for the object in view, since the air velocity does not vary at any given point.

The authors have checked the accuracy and consistency of the anemometer in several ways. When a fan delivers air to a given system of ducts, the volume of air discharged is a linear function of the speed of

difficulty that the authors encountered in the measurement of the volume and temperature of the air was a consequence of the great variation in the velocity of the air at the discharge opening of the alternator, due to the essentially peculiar shape and disposition of the openings in the stator core and frame, and also

* *Engineering*, 1915, vol. 99, p. 617.

TABLE 3.

		Calibrated Anemometer, No. 1	Calibrated Anemometer, No. 2	Test Anemometer (after two years' use)
Running for 1 minute	{ Dial reading	1,316	1,296	1,325
	{ Air velocity	1,316	1,296	1,325
	{ Variation from mean ..	0.28%	1.24%	0.97%
Running for 5 minutes	{ Dial reading	6,393	6,517	6,649
	{ Air velocity	1,318	1,304	1,329
	{ Variation from mean ..	0.08%	0.99%	0.91%
Running for 15 minutes	{ Dial reading	19,804	19,504	20,020
	{ Air velocity	1,320	1,300	1,335
	{ Variation from mean ..	0.15%	1.37%	1.29%
Running for 60 minutes	{ Dial reading	79,563	79,027	80,469
	{ Air velocity	1,326	1,317	1,341
	{ Variation from mean ..	0.15%	0.83%	0.98%

of the rotation of the rotor tending to cause the air to discharge obliquely instead of vertically.

In order to investigate the nature of the air flow, a Pitot tube was mounted on suitable gear and was slowly traversed across the discharge opening. The type of Pitot tube used is shown in Fig. 2, and the manometer used in conjunction with it was of the Roberts pattern with xylol for a fluid (specific gravity, 0.856). Before taking each reading the inclination of the Pitot tube was varied until a maximum displacement in the manometer was obtained. By taking readings in this way at frequent intervals, the variation in the direction and velocity of the air over the discharge

FIG. 2.—Pitot tube.

opening was ascertained fairly accurately. It was found that the air was eddying violently and that there was actually a reverse flow in some places. With such a variable air flow, the accurate measurement of the volume and average temperature is a matter of the greatest difficulty, and most probably the results obtained under such conditions would be quite misleading. With the object of equalizing the air flow, a temporary discharge trunk of the kind shown in Fig. 3 was fitted and the air velocity was again measured by traversing the Pitot tube across the discharge opening. The improved result obtained with the trunk is shown by curve B in Fig. 4. To equalize further the air velocity, close-mesh expanded-metal baffle plates were fitted in the trunk as shown in Fig. 3 and the improvement obtained is shown by curve A in Fig. 4. It will be

seen that although there is still some variation, yet if the anemometer readings are taken at fairly frequent intervals the average velocity can be found with a

FIG. 3.—Temporary discharge trunk to facilitate the accurate measurement of the air volume and temperature.

sufficient degree of accuracy. The resistance of the expanded metal baffles to the flow of air was found to have no appreciable effect on the temperature of the alternator. Of course, if there were any effect of this

kind it would not affect the accuracy of the determination of the losses in the alternator, for any restriction of the flow of air would only cause a corresponding increase in temperature; but the matter would be important in so far as the efficiency could not be measured during the heating test—which is desirable from the point of view of saving time and also, if running on an artificial load, expense.

For the accurate measurement of the air volume it is desirable that the discharge opening should be divided into squares, not much larger than the overall diameter of the anemometer, by stretching thin cords across the trunk as shown in Fig. 3, and an anemometer reading should be taken over each square. For small and medium-size machines the squares could conveniently be made with a length of side of 4 inches, but for very large machines the size might be increased

FIG. 4.—Curves plotted from Pitot tube readings taken at opening of temporary discharge trunk.

somewhat to avoid taking an unnecessarily large number of readings. A certain error is introduced into the readings by the delay in starting and stopping the anemometer, and also as a consequence of the manipulation of the catch that throws the recording dials in and out of gear, interfering locally with the air flow. These difficulties can readily be overcome by moving the instrument rapidly from square to square without stopping it, and the average value of the air velocity is found by dividing the total reading by the number of squares. The authors have found a slight but appreciable effect in adopting this safeguard. It is desirable to run the anemometer for an appreciable period over each square—15 seconds being the minimum desirable time and a longer period up to one minute being preferable when circumstances permit.

Determination of average temperature of air.—The average temperature of the air can be found with sufficient accuracy by using one thermometer for each square and taking the average of the readings. The thermometers can conveniently be attached to the cords in a horizontal position. The authors have tried the experiment of using several thermometers in each square, but they find that the result is not appreciably different from that obtained by using one for each square. The determination of the average temperature

of the inlet air presents no difficulty, but it should be verified that there is no external source of heat, such as a steam pipe, near the thermometers. When an air filter is used in conjunction with the alternator, the inlet temperature has to be read between the filter and the alternator, and it is particularly necessary to do so when the filter is of the wet type.

The average temperature of the air at the inlets and outlets can also be determined very accurately by measuring the change in resistance of a coil of wire, of which the electrical resistance-temperature coefficient is known, mounted in the air flow. The authors have found very close agreement between the results obtained in this way and those obtained by thermometer measurement, but for general work the thermometer is obviously more convenient.

It is not infrequently the custom with large alternators to discharge the ventilating air from the bottom of the stator and lead it away in ducts from the engine room. In such cases it is quite convenient to provide at the top of the alternator a discharge opening that can be used for making the air-volume and air-temperature measurements. Whilst the tests are being made, the lower discharge opening is temporarily closed, and for normal running the upper opening is closed with a plate. By standardizing the size of discharge opening only a few temporary discharge trunks are necessary for a wide range of sizes of alternators.

It will be seen that the precautions to be taken in the measurement of the air volume and temperature are simple, but without such precautions the authors have found that quite misleading results may be obtained.

METHOD I.

THE DETERMINATION OF THE LOSSES ON LOAD BY THE "AIR-HEATING" METHOD.

Having seen that it is quite practicable to measure the volume and temperature rise of the air with sufficient accuracy, the method of calculating the losses from the volume and temperature rise of the air will now be described. In making the following calculations the value of 0.0711 lb. is taken for the weight of a cubic foot and 0.242 for the specific heat of dry air at the assumed temperature of 100° F. and at an atmospheric pressure equal to 29.92 inches of mercury. The mechanical equivalent of heat is taken to be 778 foot-pounds per therm.

Let V = volume of air leaving the alternator discharge in cubic feet per minute,

T_i = average temperature of the air at the inlets,

T_o = average temperature of the air at the alternator discharge.

The heat energy being carried away by the air is then $P = V \times 0.0711 \times 0.242 \times (T_o - T_i) \times 778$ foot-pounds per minute,

$$= \frac{V \times 0.0711 \times 0.242 \times (T_o - T_i) \times 778 \times 746}{33,000 \times 1,000} \text{ kilowatts,}$$

$$= \frac{V (T_o - T_i)}{3.395} \text{ kilowatts} \quad \dots \dots \dots (1)$$

where T_i and T_o are in degrees Fahrenheit.

The various corrections that may have to be made to the above formula are dealt with in Appendix I. It is there shown that, for commercial testing, corrections need be made only in the event of the air temperature or barometric pressure differing appreciably from the conditions assumed and in respect of the heat energy that is dissipated from the stator frame. The correction curves given in the appendix may be used with formula (1), or this formula may be amended to include the corrections as follows:—

$$P = \frac{V(T_0 - T_i)}{3,305} \times \frac{H}{29.92} \times \frac{460 + 100}{460 + T_0} \times \frac{100}{98.5},$$

$$= \frac{VH(T_0 - T_i)}{174(460 + T_0)} \text{ kilowatts} \quad \dots (2)$$

where T_i and T_0 are in degrees Fahrenheit.

If T_0 and T_i are in degrees Centigrade

$$P = \frac{VH(T_0 - T_i)}{174(273 + T_0)} \text{ kilowatts} \quad \dots (2A)$$

METHOD 2.

THE DETERMINATION OF THE LOSSES ON LOAD BY THE "CALIBRATED AIR-TEMPERATURE" METHOD.

Various methods have been suggested for calibrating the temperature rise of the air in terms of the loss in the alternator. The following method was adopted by the authors as being convenient and independent of the use of any quantities that cannot be measured directly.

When the alternator coupled to a driving motor is being run at the works, the stator core loss with various values of the exciting current can be measured—a test that it is always desirable for the maker to carry out for his own information. When the machine is being tested on site, the temperature rise of the cooling air is measured (1) on open circuit with the rotor unexcited, (2) on open circuit with the rotor excited to a known value, (3) with the alternator on load.

Let t_c denote the temperature rise of the cooling air in test (2) with the rotor excited,

P_c the rotor copper loss,

and P_i the stator core loss corresponding to this excitation (the value of P_i is given by the core-loss curve taken at the works).

Then, if t_u denotes the temperature rise of the cooling air in test (1) with the rotor unexcited, it follows that the difference $t_c - t_u$ in the rise in temperature of the cooling air is caused by the known loss $P_i + P_c$ kilowatts. The loss in the alternator necessary to cause the temperature of the ventilating air to increase one degree is then

$$\Delta P = \frac{P_i + P_c}{t_c - t_u} \text{ kilowatts.}$$

The quantity ΔP thus represents the calibration of the temperature rise of the cooling air of the machine in question.

If now t_l denotes the temperature rise of the cooling

air in test (3) when the alternator is on load, it follows that the load loss will be—

$$P = \frac{P_i + P_c}{t_c - t_u} t_l = \Delta P \times t_l \text{ kilowatts} \quad \dots (3)$$

The formula holds good, of course, for either the Fahrenheit or the Centigrade thermometer.

The accuracy of the "calibrated air-temperature" method depends mainly upon the weight of air flowing through the machine remaining constant whilst the heating tests are being made. The effect of losses in the alternator is of course to heat the air and cause it to expand and so increase the volume for a given weight. The opposition to the flow of an increased volume of air will depend on the position of the parts where there is the greatest restriction to the air flow with respect to the position of the parts where the heating occurs. For instance, with a radially-ventilated stator the resistance encountered by the air passing from the fan chambers to the gap and from the gap to the radial ducts constitutes the principal restriction to the air flow; consequently, additional heating in the stator core would affect the weight of air flowing through the machine very little, whereas additional heating in the fan chambers and rotor would have appreciable effect. With large machines it may be found that the calibration loss cannot conveniently be made greater than about one-half the total load losses even when running considerably over-excited. On load, the loss in the body of the core will be considerably less than during an over-excited calibration test and the greater loss will be in the rotor, the stator copper, and the stator teeth. This alteration in the distribution of the loss, and the greater magnitude of it, will cause the air to increase in temperature and expand before it enters the stator ducts, and so the volume of air flowing through the machine cannot increase in quite the same proportion as the increase in the absolute temperature of the air—as must be the case for the air weight to remain constant. The effect of this reduction in the weight of air flowing through the machine under load is to make the calibration figure ΔP slightly high with respect to actual load conditions or, alternatively, the temperature rise t_l on load slightly high with respect to the calibration conditions; in consequence of which the load losses given by this method are somewhat too large. The extreme magnitude that it would be possible for this error to have would exist if the air volume on load were the same as during the calibration test; in this case the reduction in the weight of air would cause an error of about 4.4 per cent (this figure is arrived at on the assumed probable conditions of the air entering at 45° F., the windage loss causing a rise of 15 degrees F., the calibration loss a rise of 25 degrees F., and the load loss a rise of 50 degrees F.). The actual error, however, will be less than 4.4 per cent, since all the additional air-heating on load, compared with the heating during calibration, does not take place before the air flows through the points of restriction, and the authors have estimated that even in radially-ventilated machines the losses given by this method are only

2 to 3 per cent too high. This estimate is confirmed by tests (cf. Table 6). A general correction cannot be made in respect of this error, since it will be influenced by the system of ventilation apart from the different distribution and magnitude of the losses during calibration and on load. Also, for the latter reason, the slight error due to the difference in the dissipation of heat from the stator under the two conditions cannot be corrected by a constant multiplier, as is possible with the "air-heating" method. In the absence of accurate information it can be assumed that due to these causes the losses obtained by the "calibrated air-temperature" method are $2\frac{1}{2}$ per cent too high.

TESTS.

- Typical results obtained by the "air-heating" and "calibrated air-temperature" methods are given in Tables 4 and 5. A comparison of the losses so obtained

TABLE 4.

Determination of Load Loss by the "Air-heating" Method.

Machine No.	Air Volume in Cub. Ft. per Min.	Air Temp. in °F. at		Load Loss in kw. (from Equation 2)
		Inlet T_i	Outlet T_o	
5,862	16,800	45.0	116.6	352
7,001	21,330	53.0	103.9	327
7,541	3,300	66.2	114.0	46

with the "summation of losses" method as adopted by the American Institute of Electrical Engineers, and with this method when an allowance for stray loss is excluded, is given in Table 6.

GENERAL CONCLUSIONS.

"Air-heating" method.—These investigations have led the authors to the opinion that the "air-heating" method may quite well be adopted for the determination of the turbo-alternator efficiency for commercial purposes, with advantage to the purchaser and the manu-

facturer. By taking the prescribed precautions when measuring the air volume and temperature, the losses on load can be determined quite as accurately as is required and probably more accurately than in any other way. From the manufacturer's point of view a great advantage of the method is that a driving

TABLE 6.

Comparison of Results obtained by Four Different Methods.

Machine No.	Methods based on Cooling Air		Methods based on "Summation of Losses"	
	"Air-heating" Method	"Calibrated Air-temperature" Method	A.I.E.E. Method	Stray Loss Ignored
5,862	352	362	336	211
7,001	327	338	315	255
7,541	46	47	52.5	42.8

TABLE 7.

Comparison of Stray Loss on Load with Stray Loss on Short-circuit.

Machine No.	Stray Loss on Load (determined by "Air-heating" Method)	Stray Loss on Short-circuit (as determined in A.I.E.E. Conventional Method)
5,862	141	125
7,001	72	60
7,541	3.2	9.7

motor is not required—an item of importance when dealing with alternators of large output. Also, when on account of transportation difficulties the stator has to be built on site, in addition to measuring the total losses on load the method could also be employed to measure the separate losses with ease and accuracy.

TABLE 5.

Determination of Load Loss by "Calibrated Air-temperature" Method.

Machine No.	Known Loss $P_i + P_c$	Air Temperature-rise with Rotor		Air Rise due to $P_i + P_c$:— $t_c - t_u$	$\Delta P = \frac{P_i + P_c}{t_c - t_u}$	Air Rise on Load t_l	Load Loss (from Equation 3) $\Delta P \cdot t_l$
		Unexcited t_u	Excited t_c				
5,862	167.5	15.1	48.3	33.2	5.05	71.6	362
7,001	195.5	20.4	51.2	30.8	6.35	53.4	338
7,541	34.6	14.3	49.6	35.3	0.98	47.8	47

The method is independent of tests made at the works, and in the event of dispute a check test could be made at any time. The ease with which the test is applied would enable periodic readings of the losses to be taken, and useful information concerning the variation of efficiency (if any) with age could be obtained. Moreover, the measurement of the air volume that would be involved would be of value in indicating accurately if any restriction to the air flow was arising due either to the ducts in the alternator becoming choked with foreign matter or to increased resistance in the filter.

"Calibrated air-temperature" method.—This method has the one advantage, compared with the "air-heating" method, that the air volume has not to be measured, but on the other hand it has certain disadvantages. The efficiency cannot be determined solely by tests on site, and once the alternator has been despatched from the works a check test in the case of dispute cannot be made.

In addition to any error due to the weight of air flowing through the machine being somewhat less on load than during calibration as already discussed, a further possible cause of error is in the determination of the stator core loss, on which the result is based. It is usually necessary to employ reduction gearing or a belt drive between the driving motor and the alternator, and in such cases there is uncertainty as to the transmission losses. The authors have had the opportunity of comparing the losses in two sets of modern double-helical gears when transmitting power and they found an appreciable difference between the results. The loss with a belt drive when transmitting power at a high speed is liable to vary and is difficult to determine accurately.

When a driving motor is not available, as may be the case with large machines or when the stator has to be built on site, the core loss can be ascertained only by the application of some such method as the sudden cutting off of the steam supply and measuring the difference in retardation caused by the core loss. From these measurements and a calculation of the inertia of the revolving mass, the core loss can be deduced. Apart, however, from the difficulty of ascertaining the losses in this way, an accurate result is not to be expected therefrom.

Existing methods.—The "summation of losses" methods in present use which ignore the stray loss have little value except that in the absence of any standardized logical method they serve to prevent disputes between the contracting parties when the turbine builder sub-lets the contract for the alternator. With regard to the special form of the "summation of losses" method put forward by the American Institute of Electrical Engineers, it has already been noted that the total losses obtained in this way may not in some cases differ sufficiently from the true loss to affect seriously the value of the efficiency deduced therefrom (cf. Table 6); but the conventional allowance made for the stray loss may differ appreciably from the actual value (cf. Table 7). Apart from the inaccuracy of these methods in principle, there is the possibility of error in measuring the various losses.

Thus, to ascertain the excitation loss, the exciting current has to be calculated, e.g. from the open-circuit and short-circuit curves. Reference has already been made to the possible inaccuracies in measuring the core loss with a driving motor, and still more so when a driving motor is not available.

An extract from the Rules of the American Institute of Electrical Engineers relevant to the determination of turbo-alternator efficiency is given in Appendix 2.

It is unnecessary to deal with the various unsatisfactory methods of determining efficiency that are in use, with which dependence in a lesser or greater degree is placed on guess-work.

In conclusion, the authors beg to express their obligation to Mr. Douglas Vickers and Mr. W. Clark, directors of Messrs. Vickers, Ltd., for permission to carry out the experimental investigations referred to in this paper and to publish the results; also to Mr. H. P. Hayhurst and his testing staff for the care that they have taken in carrying out the tests.

APPENDIX I. ●

CORRECTIONS FOR "AIR-HEATING" METHOD.

Correction 1. Effect of temperature on air density.—

At a given atmospheric pressure, the weight per cubic foot of air varies in inverse proportion to the absolute

FIG. 5.—Correction in respect of variation of air density with temperature for use with formula (1). (This correction is allowed for in formulæ (2) and (2A).)

temperature. In making the calculations given in formula (1) the temperature of the air at the discharge is assumed to be 100° F., and a cubic foot of dry air at that temperature with the standard atmospheric pressure weighs 0.0711 lb. per cubic foot. The actual

weight of air passing through the machine per minute when the outlet temperature is T_o Fahrenheit is given by

$$\frac{(460 + 100)}{(460 + T_o)} \times 0.0711 \times V \text{ lb.}$$

This expression is for dry air and standard barometer.

If the air temperature should differ appreciably from the value assumed, as it may, an important error would arise, as will be seen from the curve given in Fig. 5. The formulæ in their final form, (2) and (2A), have the correction included, but, if formula (1) is used, the necessary correction is to be read from the curve corresponding to the temperature of the outlet air.

Correction 2. Effect of atmospheric pressure on air density.—For a given temperature, the weight of air is directly proportional to the atmospheric pressure. In this country the barometer at the sea level seldom

FIG. 6.—Correction in respect of variation of air density with atmospheric pressure, for use with formula (1). (This correction is allowed for in formulæ (2) and (2A).)

reads higher than 30.5 inches and seldom lower than 28.5 inches, but a pressure as low as 27.332 inches has been recorded in Scotland and as high as 31.62 inches in Siberia.* Allowing for some power stations being at a considerable height above sea level, an appreciable variation from the standard barometric pressure of 29.92 inches may well be experienced. The weight of air per minute passing through the machine, if dry and at the temperature of 100° F., is found from the expression

$$\frac{H}{29.92} \times 0.0711 \times V \text{ lb.,}$$

where H denotes the atmospheric pressure in inches of mercury. The formulæ in their final form, (2) and

* F. W. HENKEL: "Weather Science," p. 65.

(2A), have the correction included, but, if formula (1) is used, the necessary correction is to be read from the curve given in Fig. 6 corresponding to the barometer reading at the time the test is made.

Correction 3. Effect of humidity on air density and specific heat.—At a given pressure and temperature, the weight of a cubic foot of air varies a little according to the degree of humidity, in consequence of water vapour being lighter than air. On the other hand, water vapour has a higher specific heat than air, hence the effect on humidity is to increase slightly the specific heat of the air, so that in considering the correction the combined effect has to be ascertained.

The effect of humidity on the air density will be dealt with first. The density of water vapour varies considerably with the temperature, as is shown in Fig. 7. The pressure of water vapour at different temperatures is shown in Fig. 8. From these curves

FIG. 7.—Curve showing the weight of aqueous vapour at various temperatures (from values obtained by Regnault).

the weight of unsaturated moist air at a given temperature and pressure can be calculated. From Dalton's Law of Partial Pressures, it is known that the total pressure exerted by a mixture of two gases in a vessel is equal to the sum of the pressures that would be exerted if each filled the vessel alone. The temperature at which the air would be saturated, i.e. the dew-point, having been ascertained, the pressure of the aqueous vapour is found from Fig. 8. This pressure is deducted from the atmospheric pressure, and the weight of dry air contained in a cubic foot of the moist air is found by multiplying the weight of a cubic foot of dry air by this value and dividing by the atmospheric pressure. The weight of the water vapour contained in a cubic foot of the moist air is ascertained from the curve in Fig. 7 corresponding to the dew-point temperature. The sum of the two gives the weight of a cubic foot of

the moist air. The expression for the weight of a cubic foot of moist air is then

$$\frac{0.0711 (H - H_v)}{H} + W_v \text{ lb.},$$

where H = atmospheric pressure in inches of mercury,
 H_v = vapour pressure obtained from Fig. 8, corresponding to the temperature at which the moist air would be saturated,
 W_v = weight of a cubic foot of water vapour obtained from Fig. 7, corresponding to the temperature at which the moist air would be saturated.

FIG. 8.—Curve showing the pressure of the water vapour in saturated air at various temperatures (from values obtained by Regnault).

The effect of humidity on the specific heat will now be considered. The specific heat of moist air is expressed by

$$\frac{S_a W_a + S_v W_v}{W_a + W_v},$$

where S_a = specific heat of the air,
 S_v = specific heat of the aqueous vapour,
 W_a = weight of the dry air contained in a cubic foot of the mixture,
 W_v = weight of the aqueous vapour contained in a cubic foot of the mixture.

The weight of a cubic foot of air at the standard barometric pressure is given in Fig. 9, and the weight of a cubic foot of aqueous vapour is given in Fig. 7. The specific heat of air is to be taken at the constant value

of 0.242—the variation with temperature will be dealt with separately. The specific heat of water vapour may be assumed to have the constant value of 0.475—the variation with changes of temperature is slight, and can be ignored when applying the above formula.

With the worst conditions that are likely to arise in practice, either of these two effects *per se* might affect the value of the losses in the alternator, as determined by the “air-heating” method, by as much as about 3 per cent. As already explained, however, the one effect tends to cancel the other and the net result is as shown in Fig. 10. It will be seen that with the worst case that is likely to arise, the correction is sufficiently small to warrant it being neglected for commercial work. The final formulæ, (2) and (2A), for determining the losses by the “air-heating” method therefore do not include any correction for the effect of humidity.

FIG. 9.—Curve showing the weight of a cubic foot of dry air at various temperatures. (Barometer: 29.92 inches of mercury.)

Correction 4. Effect of temperature on specific heat.—A very careful investigation made by Mr. W. F. G. Swann* showed that the specific heat of air varies very little with increase in temperature. The result of Mr. Swann's investigation is given in Fig. 11, from which it will be seen that between 60° F. and 100° F. the specific heat increases by only 0.145 per cent. If the temperature of the air leaving the alternator were as high as 140° F. instead of the assumed condition of 100° F., the error due to the change in the specific heat would be little more than one-fourth of 1 per cent. It is therefore quite unnecessary to make a correction in respect of the variation of the specific heat.

Correction 5. Effect of heat dissipated from the stator frame.—To ascertain the heat energy that is dissipated from the external surface of a turbo-alternator, a

* Philosophical Transactions of the Royal Society, vol. 210A, p. 230.

careful test was made with a 5,000-kw. 3,000-r.p.m. machine. With the rotor at rest and the air inlets and outlets closed, a direct current was passed through

FIG. 10.—Correction in respect of variation of air density and specific heat with humidity. (This correction may be ignored for commercial work, and is not taken into account in any of the formulæ.)

the stator winding. When the temperature rise of the external surface reached a steady value it was found that the heat energy being dissipated was

FIG. 11.—Curve showing the variation of the specific heat of dry air with variation of temperature. (From values determined by Mr. W. F. G. Swann.)

0.006 watt per inch of surface per degree rise (Fahrenheit). To neglect a correction for radiation would give an error in the average case of about $1\frac{1}{2}$ per cent on the losses determined by the "air-heating" method. Although this error is small, it is practically constant

and the necessary correction is easily made. The formulæ in their final form, (2) and (2A), include this correction.

Minor causes of error.—There will be a certain tendency for the air entering the alternator to absorb heat conducted through the shaft from the bearings. Further, the small loss in the slip-rings will not be measured, since they are exterior to the alternator. It is obvious that the errors introduced as a consequence of these minor matters will be infinitesimal in degree, particularly as the error introduced by the tendency for heat to flow from the bearings into the alternator is off-set by the slip-ring loss that is not measured.

APPENDIX II.

EXTRACT FROM THE RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.*

422. In the case of machinery two efficiencies are recognized, conventional efficiency and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed.

423. Conventional efficiency of machinery is the ratio of the output to the sum of the output and losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

441. Losses to be taken into account in synchronous motors and generators.

Core losses—see Rule 452.

$I^2 R$ loss in all windings, based upon rated k.v.a. and power factor.

Stray load losses.—In approximating these losses, the method described in Rule 458 shall be employed.

Friction of bearings and windage.

452. *Core loss.*—The machine is driven from an independent motor, the difference in output of which is determined when the machine is unexcited and when it is excited to give the terminal voltage corrected for the resistance drop only. (This rule has been paraphrased.)

458. *Stray load losses in synchronous generators and motors.*—These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation. Stray load-losses are to be determined by operating the machine on short-circuit and at rated-load current. This, after deducting the windage and friction and $I^2 R$ loss, gives the stray load loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

* Transactions of the American Institute of Electrical Engineers, 1916, vol. 35, p. 1559.