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A NEW EQUIPMENT FOR THE MEASUREMENT OF TORQUE AND SPEED OF ROTATING MACHINES

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1. Introduction.

The interest in direct tests on electrical machines for large range speed drives is growing dramatically because of the increasing need for a high level of reliability, repeatability and accuracy of the energy qualification of the systems.

Referring to the output power measurement, it can be recognized that a braking device must have the following characteristics: a stable braking action, a sensitive measurement system, low consumption and minimum interference with the normal working conditions of the machine being tested.

If we examine the devices which are currently used, we find that they do not always comply with the above-mentioned requirements: as regards the torque measurement especially, both the characteristics of the braking device and those of the torque transducer itself have to be examined.

We came to the conclusion that a permanent magnet synchronous machine as a braking device could represent a convenient response to the test demands of modern drives. A load cell transducer was chosen as the torque transducer for measuring the reaction torque on the stator.

Here below a brief description of the device is given and a comparison among its characteristics and those of the traditional test benches is then made.

Results of some tests we carried out are finally shown. These allows us to make a preliminary assessment of the fitness of the device and to give some indications on how this proposal can be developed.

2. Remarks on the devices for direct tests.

For the types of motors in widespread use the direct method of determining the efficiency, or the correlated losses, still represent today, in principle, the best way to match test and operating conditions [1,2,3].

However, the error which is introduced in the evaluation of these energy characteristics increases in line with the size and efficiency of the motor under test [7]. This can be showed if we accept, at present, the hypothesis that the test is theoretically carried out under conditions of complete control of all the influencing parameters.

The maximum error in the measurement of the efficiency can be expressed as the sum of the errors of the measurement of the torque T, of the rotation speed N and of the input electrical power P_{in}:

$$(1.1) \qquad \dot{\varepsilon}_\eta = \varepsilon_\eta/\eta = \dot{\varepsilon}_T + \dot{\varepsilon}_N + \dot{\varepsilon}_{Pin} \quad .$$

In eq. (1.1), the error $\dot{\varepsilon}_T$ is the most critical element. As a matter of fact, when the power of the machine being tested increases, the errors in the measurement of the electrical power and the rotation speed can be limited, but there are increasing difficulties in the torque measurement because of problems due to the braking device and the torque transducer itself.

Thus, the relative error ε_η/η can be regarded as a growing function of the output power P_{out}.

The absolute error in the definition of the power losses, P_L, beginning from the direct method shows more openly the dependence on the variation of the output power P_{out}:

$$(1.2) \qquad \varepsilon_{PL} = [\dot{\varepsilon}_\eta/(\eta+\varepsilon_\eta)]\cdot P_{out} \quad .$$

From here we can easily obtain the expression of the relative error in the evaluation of the power losses:

$$(1.3) \qquad \dot{\varepsilon}_{PL}=\varepsilon_{PL}/P_L = \dot{\varepsilon}_\eta/[(1-\eta)\cdot(1+\dot{\varepsilon}_\eta)] \quad .$$

The above equation confirms first that the relative error in the definition of the losses increases with the power size of the machine, to which, as already stated, the increase in the efficiency is linked. On the other hand, at the same rated output, the amount of the error increases with the efficiency. This fact makes an energy comparison of two machines equally rated very critical.

Actually, a lot of factors play their role on the total error in the definition of the energy parameters. These factors are: stability of the supply and of the environmental conditions; a reliable and steady braking action; accuracy of the measurement system. Nevertheless a great importance can be attributed to the braking device and the relating torque and speed transducers. The intrinsic limits of accuracy of the direct method can be improved both by a careful analysis of the braking device, in order to increase the levels of stability, sensitivity and accuracy, and by reducing consumption and the interference level with the machine being tested under normal working conditions.

2.1 The braking device.

The braking device is a unit which applies the braking torque to the shaft of a motor and also measures this torque by means of a suitable transducer; it also permits the measurement of the rotation speed.

Different types of braking devices are currently used for direct tests; among them, some ranging in the class of the electromagnetic types are briefly described here:

-<u>Eddy current (Pasqualini) braking device</u>: it couples a high level of sensitivity with errors of various sources: of electromagnetic origin (parasitic torques, due to stray fluxes), of mechanical origin (due to ventilation losses and to possible stator-rotor misalignments), of thermal origin (total output power is transformed into heat in the disk, with consequent risk of thermal interference with the machine being tested). In addition, there is no torque at zero speed. Because of these factors, this type of braking device is not well suitable for thermal tests and can only be used for testing low power motors, unless more sophisticated solutions are chosen.

- Hysteresis braking device: this type of braking device, whose most common commercial version is the Magtrol, has certain advantages compared to the eddy current braking device: braking torque is practically independent of speed and temperature and there are no errors of electromagnetic origin. However, the working and cooling conditions of this braking device make it unsuitable for thermal tests and higher powers.
- Dynamometer braking device: the design and functional characteristics of this brake are well-known and represent one of its big assets. It is the most convenient device for higher powers and thermal tests.

However, there are certain limitations, particularly during the tests on machines for drives over a wide range of speeds. Apart from the consumption errors due to the ventilation torque, the critical element is the commutator-brushes system, owing to problems regarding the commutation, the spark, the reduced sensitivity caused by the contact pressure of the brushes, and because of maintenance. The achievement of high rotation speeds, still mantaining an acceptable service, is not possible with the employment of this type of device.

On the aforementioned basis and taking into account the demands of modern drives testing, none of the devices most currently used, not even the dynamometer, fully satisfies these requirements.
Thus, the use of a permanent magnet synchronous machine was considered, which offers the following advantages:

- it has a clearly defined good flux containment magnetic circuit which prevents the creation of parasitic torques due to stray fluxes, typical of eddy current braking devices;
- the stator frame is flexibly coupled to the bedplate by bearings, thus eliminating all the problems of knife-edge supports, which are common in eddy current braking devices;
- it has no sliding contacts, because permanent magnets are used. This eliminates the negative effects on braking stability, caused by sparking at the commutator-brushes contact in the dynamometer; it also reduces contact friction, which is one of the main causes of the reduced sensitivity of the braking device;
- during the construction of the braking device by a permanent magnet synchronous machine it is possible, thanks to the absence of rotor losses, to achieve a smoothed containment structure for the rotor. This reduces power losses due to ventilation to very low levels;
- an appropriate design and mounting of the cooling system of the synchronous machine obviates the use of an internal cooling fan mounted on the same shaft: in its place, a separate and balanced cooling system built on the stator frame can operate. In this way the influence on the torque of the braking device is reduced, which, in turn, means that the reaction torque is, with a good approximation, the torque delivered to the shaft;
- the measurement of the tested motor rotation speed is drawn from the frequency of the sinusoidal alternating voltage at the armature terminals of the synchronous machine. In this way the use of tachometer-type transducers is avoided. As the latter are a possible cause of unmeasured torque consumption, and, in any case, lead to complications in construction, this is an advantage;
- the synchronous machine is suitable for running over a wide range of speeds by simply varying the voltage and frequency at the terminals. This speed range is much wider than the one obtainable from a dynamometer;
- the regulation of the braking torque is obtained by acting on the armature circuit only, for example by a controlled thyristor bridge feeding a resistor, or by a variac.

2.2 The torque transducer.

There are various types of transducers which measure the shaft torque, all based in practice on two methods: the measurement of the torsion angle of a section of the shaft or the measurement of the reaction torque on the stator of the braking device.
In the first class the most commonly used device is a strain gauge transducer; in the other one, it is a load cell transducer.
The great advantage of the first type is that it measures directly the torque of the motor shaft: thus a stable braking action only is required from the braking system, not taking into account its torque consumption.
This could make it possible to use a self -ventilating braking device. The system presents however heavy drawbacks in setting-up, that has to be carefully repeated each time the mechanical coupling of the motor to the braking device is made. Moreover it requires the transmission of a signal from a rotating shaft and, in addition, it seems to be very sensitive to torque disturbances caused by the above-mentioned coupling. These disturbances are not filtered by the rotor inertia and by the electromagnetic transmission of the torque at the air-gap, unlike the other solution considered.

The load cell device, on the other hand, measures the torque on the stator of the braking system, thus permitting a unique calibration and set up during the assembly of the equipment.
However, as we have seen, the consumption has to be kept to very low levels, comparable with the sensitivity and accuracy of the transducer itself. It may also be necessary to measure this consumption. Furtherly, this measurement device can be affected by an accidental error due to the starting friction of the bearings between the stator frame and the bedplate, and inside the transducer itself. Both of these errors are caused by the fact that the frame cannot move freely with respect to the bedplate, apart from small movements permitted by the deformation of the torque transducer.

It is clear that we should aim at obtaining maximum levels of performance and precision, accordingly with the present level of technology, the quality of the instrumentation envisaged and the levels of cost involved.

3. Characteristics of the prototype.

During the development of the prototype, we chose a system configuration including a permanent magnet synchronous machine, a load cell type force transducer (mounted between the braking device bedplate and the floating frame), and an amplifier with a digital indicator. The speed is measured by a frequency meter connected with the armature terminals of the synchronous machine.

Since a synchronous machine purposely designed did not exist, the first prototype of this braking device was set up using a limited power rating machine, easily available on the market.

The main characteristics of the test bench are given in Table 1, together with those of the electrical instrumentation.

The most outstanding data on the system have been obtained by means of a series of tests carried out with two four-pole asynchronous motors, 1.1 and 2.2 kW rated respectively. The characteristics of these motors had already been verified be means of another direct test apparatus with an appropriate level of accuracy.
Obviously this procedure can be considered as a preliminary test only, since no investigation was made of the ranges of speeds and power which this new device was designed for.

Before analysing the direct tests, a brief study of the measurement inaccuracies was carried out, in order to show the various error contributions, also by means of experimental investigations.

Table 1 Instrumentation Characteristics

Braking device:	Perman. Magnet Synchronous Machine V_n=400 V, Y; I_n=2.17 A; A_n=1.5 kVA cosφ=0.9; f_n=50 Hz; N_n=1000 rpm N.B.: the force transducer location permits torque measurement up to 28 Nm.
Load cell:	Hottinger Baldwin Messtechnik, mod. U1 nominal load=100 N; lever arm=0.2898 m sensitivity tolerance<±0.1% rated load combined error <±0.03% rated load creep (over 30 min.)<±0.03% rated load
Amplifier with digital indicator:	HBM, mod.MVD2405 accuracy class 0.1; 3½ digits; linearity deviation [%]=±0.5 f.s. ± 1 digit resp.
Digital Frequency Meter:	Hewlett Packard,mod.5233L precision = 0.1 % reading
Digital Multimeter:	Norma, mod.D5135: N°2 (Aron connection); wattmeter measurement precision: ±0.5% reading ± 0.1% f.s. (cosφ=0.1)

First of all the level of accuracy of the torque measurement system only is to be evaluated. The maximum relative torque error depends on the relative errors of the braking device $\dot{\varepsilon}_F$, of the load cell $\dot{\varepsilon}_c$ and of the signal amplifier $\dot{\varepsilon}_a$, according to the following expression:

$$\dot{\varepsilon}_T = \dot{\varepsilon}_F + \dot{\varepsilon}_c + \dot{\varepsilon}_a \quad (3.1)$$

With regard to $\dot{\varepsilon}_F$, since the manufacturer provided no information on it, after some no load tests on a same motor, it was decided to attribute to the braking device an error equal to half its torque consumption. The errors attributed to the load cell and the signal amplifier were based on the nominal data in Table 1. As a result:

$$\dot{\varepsilon}_T\ [\text{p.u.}] = 0.001 + 0.061/T \quad (3.2)$$

where the torque T is measured in [Nm].

A static calibration check of the torque measurement system was carried out, in order to verify the actual validity of these evaluations. The zero adjustment and the gain of the amplifier at the rated load were checked and a number of cycles were runned with increasing and decreasing loads, like shown in the example of fig.1.
In this figure, the points of measurement are joined by oriented lines indicating the sequence of loads applied. The ordinates correspond to the deviations to the exact values of the applied loads, as a function of these loads, shown on the abscissa. The band of maximum error in the force measurement, corresponding to eq. (3.2), is also shown. There is an evident presence of hysteresis which can largely be ascribed to the load cell: as a result, a single calibration curve cannot take into account the errors of the measurement system.

It could be significant to examine the condition of a hypothetical measurement system which can measure the electrical power and the mechanical speed without errors, thus identifying only the effect of the error in the torque measurement during the definition of the efficiency and the losses, in the range of power the braking device is designed to operate. Bearing in mind the correlation between the rated output power and the efficiency, typical of a standardized production series of three-phase four-pole asynchronous motors (f_n=50 Hz), we have the curves shown in fig.2. Here it can be seen that the absolute error in the definition of the efficiency is about half a point and, related to this, the relative error in the evaluation of the losses is around 2%, decreasing as the power increases.

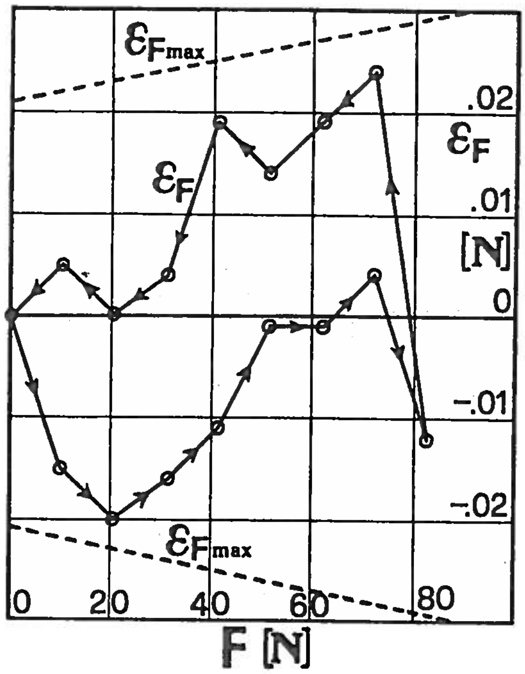

Fig.1 - Cycle of static calibration of the torque measurement system. The spreads with respect to the increasing and decreasing loads applied are given in ordinate. The cycle exhibits a hysteresis phenomenon which, however, is kept within the band of maximum calculated error.

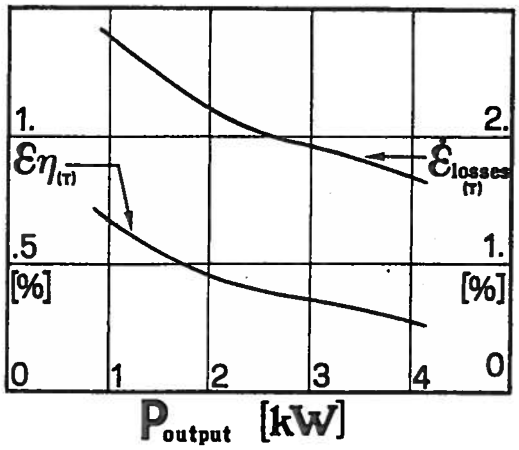

Fig.2 - Absolute error in the evaluation of the efficiency and relative error in the definition of the losses, calculated on the basis of the maximum error in the measurement of the torque only, for the system considered. The errors are given as a function of the rated output power of four-pole, three-phase, standardized asynchronous motors.

The choice of a torque measurement device which has good industrial precision characteristics clearly permits the total error to be contained within acceptable limits, as long as an appropriate instrumentation is used for the electrical measurements.

The nominal inaccuracies in the measurement system of the electrical quantities and the rotation speed were then taken into consideration and the calculations of error in the losses and efficiency were repeated. The results, with regard to the actual efficiency and power factor of the above mentioned 1.1 and 2.2 kW motors as a function of the load, are shown in the curves of fig.3. The error shown here is the probable one, evaluated on a statistical basis. This constitutes a more realistic index compared with the maximum error (worst case), when the system includes a sufficiently large number of instruments.

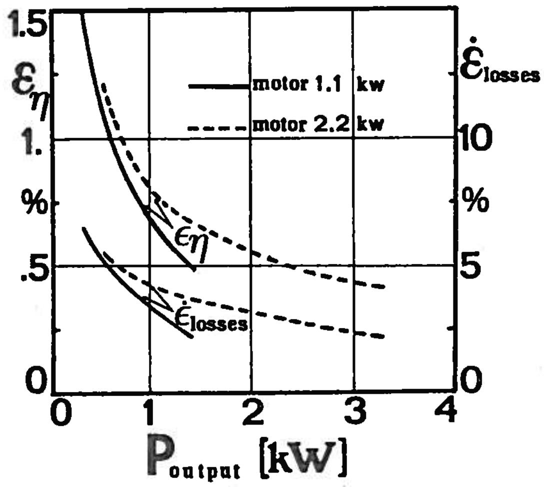

Fig.3 - Curves of the probable error in the definition of the efficiency and the losses for the instrumentation of Tab.1. These curves are calculated on the basis of actual values of efficiency and power factor of the two asynchronous motors tested. They are plotted as a function of the output power of the motors.

The curves have been drawn on the assumption that the total error occurrence probability is equal to that of the single instrument; with regard to the latter, its guaranted maximum error is assumed to be twice the standard deviation of a normal error distribution, considering the gaussian probability-density function.
From the curves of fig.3 can be seen that the error, high at low loads, tends to decrease as the output power increases; in particular, at the rated power of the two motors, the error calculated in the efficiency is around 0.6 points, while that of the losses is approximately 3% .
Considering the total error, when the curves in fig.3 are compared to those of fig.2, the effect of measurement inaccuracies of other quantities, besides the torque, is clearly shown. This suggests that it would be most opportune to employ instruments of the same accuracy class for the measurement system.

However, it must be noted that the measurement precision is also affected by the stability of the surrounding conditions during the carrying out of the tests: waveform, average value of the RMS supply voltages and their dissymmetries, ambient temperature and braking torque. The effects of these external factors can vary from motor to motor and they are very difficult to evaluate when calculating the errors.

4. Experimental results.

A series of tests was performed using the measurement system described above, with the objective of defining the efficiency and losses of two motors 1.1 and 2.2 kW, V_n=220 V, f_n=50 Hz rated, delta connection.
The tests were carried out by repeating a number of measurements at different load points, under various thermal steady-state conditions, the latter being controlled by thermocouples installed over the frame, in appropriate positions.
No-load tests at variable voltages, performed under rated no-load thermal steady-state operation, were also carried out, in order to evaluate the separate losses, according with the procedures recommended in IEEE Std.112-NEMA Std.MG1 [4,5].
The variations in the supply voltage and the ambient temperature were maintained within the tolerances allowed in the IEEE Std.112.
Some of the results obtained are given below, together with comments.
Table 2 exhibits the values of the efficiency and the losses at different quarters of the rated load, for the 1.1 kW motor, operating at 4/4 load steady-state thermal condition, as a function of the output power.
The shown values are obtained as the average of several measurement points, repeated at the various load quarters, while it is assumed that the uncertainties are equal to twice the related standard deviations: it can be noted that these measurement uncertainties are lower than the corresponding probable errors that can be evaluated by the curves of fig.3.

Table 2 Motor 1.1 kW; 4/4 load thermal conditions

P_{out} [W]	340±1	548±4	822±4	1102±1	1373±2
P_{los} [W]	209±4	243±4	320±3	475±4	765±6
η [%]	62.0±.5	69.3±.6	72.0±.2	69.9±.2	64.2±.2

It should be observed that these measurement uncertainties correspond in practice to accidental errors; in fact, possible systematic errors (that remain constant within an appreciable range of the measurement points) cannot be noticed in the standard deviation values.
From this point of view, useful hints can be obtained from a comparison with the values measured on the same motor, under the same working conditions but using a measurement system with higher levels of accuracy. It is not easy to set up such a comparison since there is no measurement system which can be considered sufficiently accurate to act as a sample for the system being examined here. An acceptable criterion of evaluation would be to compare the performance values obtained by the two systems considered and then to look whether the differences between these values are within the range of the calculated error, i.e. whether the margins of uncertainty of the two systems overlap.
The comparison was made on the basis of some tests which had been previously carried out with another instrumentation, using an eddy current braking device for the mechanical part; the results for the most significant load points are shown in Table 3. The difference in the efficiency values is always less than half a point and this difference does not always have the same sign. In addition, as displayed from Fig.3, the probable error calculated for the system using a P.M. synchronous machine as a braking device is noticeably greater than the size of the above mentioned difference; finally, the comparison allow us to conclude that the results obtained with the two systems basically agree. Other tests carried out with a dynamometer of an appropriate accuracy level are not described here but provided a fair confirmation of these results.

Table 3 Efficiencies by different instrumentations

Load[p.u.]	.50		.75		1.00	
η [%]	(1)	(2)	(1)	(2)	(1)	(2)
Mot. 1.1kW	69.3	69.1	72.0	72.2	69.9	69.5
Mot. 2.2kW	76.5	76.8	79.3	79.5	79.1	79.3

(1) = system with P.M. synchronous machine
(2) = system with an eddy current braking device

During the tests the phase voltages and currents and the stator resistance values were also measured, in order to be able to apply the procedures followed in IEEE Std.112-NEMA Std.MG1.

Fig. 4 shows the best fitting straight line between stray-load losses (evaluated on the basis of the calculation of the separate losses) and the square of the torque for the 1.1 kW motor.

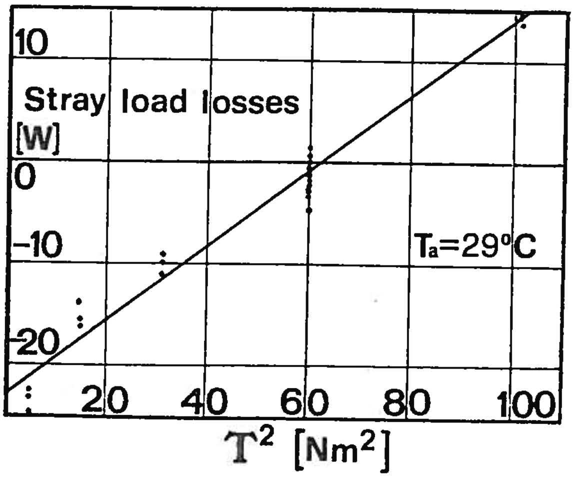

Fig.4 - Best fitting straight line between evaluated stray-load losses and the square of the torque: the curve, calculated on the basis of 24 measurement points according to the procedures of IEEE Std.112 - NEMA Std.MG1, refers to a 1.1 kW motor, operating at rated load steady-state thermal condition. Best fitting correlation coefficient: 0.98.

This straight line, obtained from 24 measurement points (at rated load thermal condition), refers to tests carried out under five different load conditions, between 1/4 and 5/4 loads. The 6/4 load was not considered, because too close to maximum torque: therefore it was not only too far from normal working conditions but also from the conditions in which the linear relationship between stray-load losses and the square of the torque can be considered valid. The best fitting correlation coefficient (0.98) is proof that there is a good overall level of accuracy.

Fig. 5 gives efficiency and losses curves for the same 1.1 kW motor, obtained by the direct method using the instrumentation of Tab.1, for 3/4 and 4/4 load thermal conditions. The effect of the operating temperature on the energy parameters is clear.

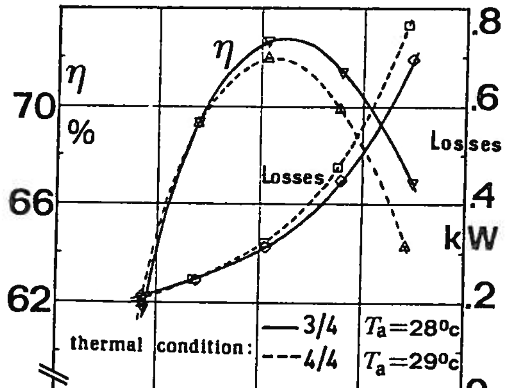

Fig.5 - Curves of efficiency and losses for the 1.1 kW motor as a function of the load, for tests carried out at 3/4 and 4/4 load steady-state thermal conditions.

5. General discussion and design suggestions.

From the point of view of the tests in general, the employment of a braking device consisting of a permanent magnet synchronous machine, associated with a load cell mounted on the stator, has demonstrated that the system has considerable advantages. Among these it especially has a high level of sensitivity and accuracy; the braking action is highly stable, load regulation is simple and there is no thermal interference with the machine being tested.

However, it could be noted that a permanent magnet excitation does not allow the operation with very low braking loads, just corresponding to the mechanical losses of the braking device itself. In fact, even with the alternator armature circuit open, the machine being tested must supply the torque corresponding to the iron losses in the stator of the alternator; in any case, this torque is correctly measured by the transducer.

Since it is a basic requirement to avoid the presence of slipping contacts, a possible alternative would be the use, as a braking device, of a synchronous machine with a field winding fed by an auxiliary armature circuit and a rectifier, both rotating. This solution would produce, however, further problems: apart from the more complex construction and regulation in service of the machine, the presence of powered circuits on the rotor would imply, in turn, an adequate built-in self-cooling system and, as a consequence, the ventilation torque consumption would be considerably increased. The latter can still be measured by means of a transducer sensitive to the torsion effect of a section of the shaft, but we have already referred to the troubles which arise with this device. On the other hand, this ventilation torque cannot be measured as a reaction torque on the stator (at least apart from the drag torque due to the fluid), because it is not electromagnetically transmitted.

To sum up, the device including the permanent magnet synchronous machine here presented in prototype, even if not yet optimized, looks extremely interesting because:

- it eliminates the commutator-brush system;
- the speed measurement is obtained by means of a frequency measurement;
- the unmeasured ventilation losses are limited to negligible values compared to the power size of the device;
- a braking device for high speed tests can be easily implemented.

From the first experience obtained with this prototype, using as a braking device a standard alternator available on the market, some indications have been obtained for the design of a larger machine which would be more relevant for the power and speed range of drives, as from the previously referred requirements:

- in the design of the stator, a reference frequency of 100÷150 Hz should be employed, taking into account the increased conditioning in the choice of the magnetic material;
- in order to limit the amplitude of the harmonic fields which cause additional losses and possible disturbances in the braking stability, a winding using a fractional number of slots per pole and per phase should be used;
- in the utilization of the active materials, it must be remembered the absence of built-in self-ventilation, which reduces the dissipation of the losses. This can be improved by a circumferential stator finning, the stator frame possibly provided with separate and balanced ventilation cooling;
- it could be convenient to provide the rotor with an auxiliary winding, normally not powered, to be utilized when necessary for remagnetizing the magnet;
- the rotor should be enclosed in a smoothed non-magnetic cylinder since this action would produce a large reduction in the ventilation losses. The

cylinder has to be made of conducting material (for example, copper) which would act as a screen against the influence of any harmonic field of the stator.

6. Conclusions.

After some brief consideration on the characteristics of braking and measuring devices for direct testing of machines for electrical drives operating over a wide range of speeds, this paper has dealt with the use, for the same purpose, of a permanent magnet synchronous machine, combined with a load cell for the measurement of the reaction torque.

The theoretical considerations, the error evaluations and the tests performed up to this point were carried out over a power range of between one and some kW: this limitation was not due to any inherent construction or size constraints but was solely due to the practical need to use, as a braking device, a machine already available on the market, which could be easily adjusted to this specific purpose.

Though the results of the experimental tests are not exhaustive, nevertheless they show a good level of repeatability, sensitivity and accuracy, while a comparison with the values obtained by means of another measurement system indicate that the level of precision is adequate.

We found there are a lot of functional and measurement advantages achievable from just using as a braking device a permanent magnet synchronous machine, compared to other devices. These benefits grow in importance with the increase in the power considered and the extension of the range of working speeds.

In the end, it must be recognized that the direct method has intrinsic limits in defining correctly the losses: these limits become evident as the efficiency and the power of the machines being tested increases and they cannot be completely eliminated.

However, the field of application of the direct method can be extended, within an assigned margin of uncertainty, as long as innovative solutions are adopted for the components of the measurement system and on condition the tests be performed with due care and attention to all the influencing parameters.

Acknowledgement.

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