RESEARCH IN AUSTRALIA AND SWITZERLAND ON MEASURING ENERGY EFFICIENCY OF ELECTRIC MOTORS AND MOTOR-DRIVE COMBINATIONS

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Paper structure:

1 The Australian-Swiss collaborative research project

1.1 Introduction

There is increasing interest throughout the world in motor energy efficiency, and the potential for (electrical) energy savings which result from the use of power electronic converters with conventional motors, and the introduction of new motor technologies. Consequently, there is a corresponding interest in updating existing motor standards, and the production of new standards, particularly in relation to new motor technologies and energy efficiency considerations applicable to electronic power conversion equipment and the behaviour of electrical machines which they supply.

Standards development work raises significant questions around measurement procedures applicable to the above equipment. Thus, in 2012, a collaborative research project was established, involving the *Electrical Machines Laboratory at the Ecole Polytechnique Federale de Lausanne (EPFL)* in Switzerland, and the commercial laboratory *CalTest*, in South Australia.

The objective was to establish motor and drive testing and measurement facilities in both locations, employing ‘state of the art’ instrumentation, which would serve for the investigation of some of the many questions which arise from the standards development process.

It was decided that the two laboratories should be designed and built independently, with a careful and detailed comparison at the end of that process, in order that the best aspects of the two facilities could then be identified.

This paper outlines the way in which the Australian laboratory has been designed and constructed, and provides information about some of the technical topics which have so far been investigated using that facility. It is expected that the Swiss laboratory, EPFL will be fully set up and have test results available at the end of 2013.

The central objective of this project has been to develop a ‘state-of-the-art’ dynamometer system for the evaluation of those high efficiency motors and driven systems in which it is not possible to determine losses or efficiency by separation of losses methods. The project has sought to identify the most precise instruments and test methodologies for making high precision efficiency measurements, and to quantify the associated uncertainties. This has included the provision of controlled laboratory ambient temperature conditions, since it is not possible, in general, to determine the way in which the losses and efficiency of motor-drive systems vary with temperature. Without control of ambient temperature, it is difficult to compare test and measurement results obtained in different laboratories.

When suitable test and measurement facilities have been developed in both Australia and Switzerland, ‘round-robin‘-type tests will be undertaken by exchanging test objects, including ‘new technology’ motors and motor-drive systems. Comparison of the test results obtained in both facilities should provide useful information which will aid the generation of new measurement standards and technical specifications.

1.2 The South Australian laboratory

In order to demonstrate the feasibility of maintaining controlled laboratory ambient air-temperature conditions, a special purpose laboratory environment has been established: A window-less, heavily insulated room with approximate dimensions 12 m x 6 m x 2.2 m has been equipped with an unmodified ‘inverter-type’ reverse-cycle domestic split-system air-conditioner. A large (800 mm diameter) multi-blade fan, driven very slowly (at approximately 100 r.p.m.), is used to stir the air in the laboratory, breaking up any tendency for the air-conditioner indoor unit to form local air circulation loops, but does so without creating any appreciable draught. This system maintains the laboratory ambient air temperature at the desired value of 25 ± 0.5°C, and with a high degree of spatial uniformity.

Electrical supply is provided by a precisely speed controlled alternator whose 50 (or 60) Hz very low distortion three phase output has a frequency stability of better than ±0.01%, and voltage stability and balance better than 0.1%.

Loading of a motor under test is achieved using a 30 kW shunt wound d.c. machine which forms part of a Ward-Leonard-type drive system. Highly stable loading of the test machine is achieved by varying the field excitation to both the Ward-Leonard machines.

Electrical input power to a motor or drive-system under test is measured using a precision power analyser made by Yokogawa (Model WT 3000 - Motor Version) having a claimed basic power accuracy of ±0.02%.

Voltage signals are obtained directly from the terminals of the motor under test.

Mechanical output power is calculated by the power analyser, as above, from speed and torque pulse-trains supplied by the torque transducer.

The power analyser displays all measured electrical and mechanical data in real time, including calculated efficiency, and logs that data for later analysis.

Mechanical output power is measured using an HBM model T12 'ultra precision' torque transducer, ('class 0.03'), with a full scale rating of 100 Nm. (This full-scale torque value represents the most sensitive transducer available at the time, and with 'flange'-type construction). That transducer also supplies shaft speed information generated by an optical chopper, producing 360 pulses per revolution.

A flange-type transducer was chosen because it has no bearings or slip-rings, with power supply and signals to and from the moving part transferred electromagnetically. No correction is therefore required to account for bearing or slip-ring frictional losses. The mechanical connection between the motor and torque transducer is by means of a carefully aligned Cardan shaft, incorporating two universal joints.

Laboratory ambient air temperature is measured using a T-type thermocouple in a radiation screen, located one metre from the air-intake of the motor along the axis of the motor shaft.

Motor temperature, for the purpose of determining temperature stability, is measured using a thermocouple either secured with self-adhesive aluminium tape to the outer surface of the motor casing, or placed into the lifting-eye socket, from which the eye has been removed and replaced with a small quantity of light oil.

Temperatures are continuously monitored and logged.

Following construction and commissioning, the laboratory has been used for a number of tests and investigations associated with international standards development work, examples are below.

2 Efficiency measurements on Line Start Permanent Magnet (LSPM) motors

2.1 Introduction

In these motors, synchronous operation is achieved by embedding high strength rare-earth permanent magnets in the rotors of what would otherwise be induction machines. When energized, induction torque rapidly accelerates the rotor from stand-still, and synchronization occurs as the rotor approaches synchronous speed, as a result of the permanent magnets.

Even with a light load, LSPM motors do not start smoothly, however, exhibiting significant oscillatory torque and large line-current transients prior to synchronisation. Such behaviour has the capacity to overload or even damage precision torque and power analysis equipment with which the mechanical and electrical measurements are to be made.

Manufacturers also warn that LSPM motors may experience difficulty in pulling into synchronism with the supply if the driven load has high inertia. Another possible problem is that the permanent magnets in the LSPM rotor represent full rotor excitation at all times, and significant a.c. voltage is produced at the motor terminals when the rotor is driven externally.

A procedure is therefore required to start an LSPM in a controlled manner. The technique employed in this project is that which is commonly used for the synchronisation of a.c. generators: With its terminals open-circuit, the LSPM motor is driven up to approximately synchronous speed using the (active) d.c. dynamometer machine and its associated speed control system. The LSPM motor terminal voltage is then phase-synchronised with its supply, whose value had been adjusted to match the open-circuit voltage generated by the test motor, at which point the motor terminals are switched on to the supply. The motor supply voltage is then raised to its rated value and maintained for the whole of the subsequent testing and measurement process. The dynamometer machine then reverts to its normal role as a mechanical load for the motor under test.

In addition to possible starting problems, as above, synchronous motors represent unusual loads, since their torque-speed characteristics are vertical straight lines, and excessive load torque may cause loss of synchronism. Many conventional dynamometers are essentially *speed*-controlled and as such are quite unsuitable for loading synchronous machines. In such circumstances, stable loading is achieved by operating the dynamometer loading system in controlled-*torque* mode. In this project, such a characteristic is obtained by the introduction of significant resistance into the armature circuit of the d.c. Ward-Leonard system which controls the dynamometer machine.

2.2 Test results

The LSPM under test was allowed to run under each of several loaded conditions until the temperature rise of the motor case was 2 K per hour or less. Direct efficiency measurements were then made using the WT3000 analyser. Since testing took place in controlled ambient temperature equal to the reference temperature in the standard (25°C), no further corrections were necessary.

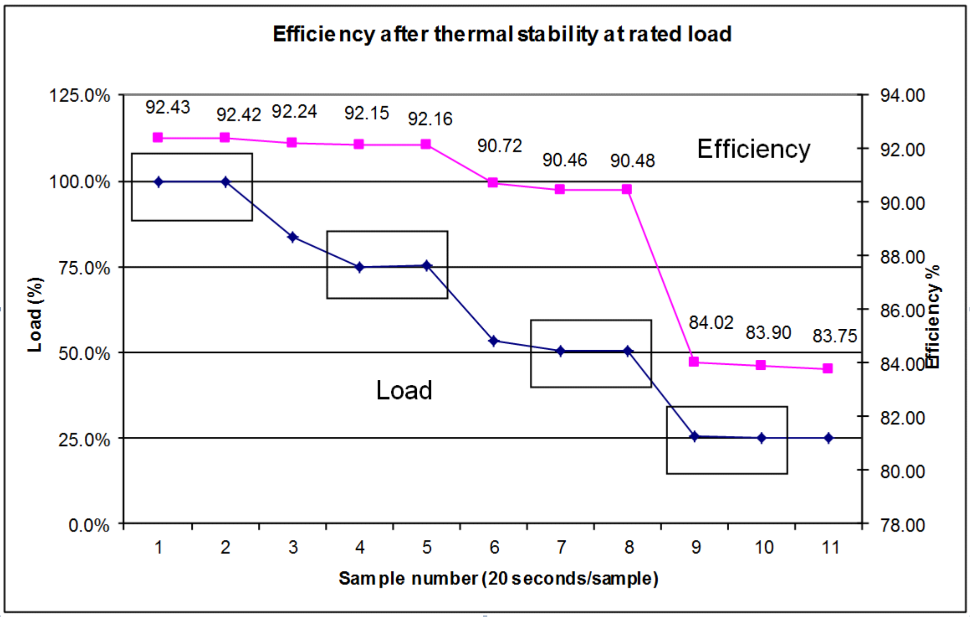

Figure 1: Test results after motor temperature stability at rated load. Samples at 20 second intervals match the averaging time of the analyser.

Load (%)	Efficiency with thermal stability at each load point (%)	Efficiency with thermal stability only at 100% (%)	Difference (percentage Points)
100	92.4	92.4	–
75	92.3	92.2	0.1
50	90.7	90.5	0.2
25	84.1	83.9	0.2

Table 1: Measured efficiency with and without thermal stability at each load point

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2.3 Summary

The laboratory and its equipment provided a precisely ambient temperature-controlled environment for making measurements on an as yet uncommon motor type. The resulting efficiency values indicate that attainment, or otherwise, of thermal stability in the motor under test leads to an additional uncertainty in the measured efficiency value of up to 0.2 percentage points.

3 Efficiency measurements on motor-drive systems

3.1 Introduction and test method

Using the output/input method, a series of measurements on a motor-drive system were undertaken to determine overall efficiency at a range of loads with motor temperature stability at different load points in controlled ambient air-temperature conditions.

Those tests and measurements were undertaken in order to trial the suggested "Draft standard for determination of efficiency of new technology motors and motor-drive systems using output/input measurements" developed by the South Australian laboratory in March 2013. That document is available on the 4E[1] Electric Motor Systems Annex website, at www.motorsystems.org/testing. Two complete sets of efficiency measurements were made on consecutive days in order to check the reproducibility of the test results.

The motor drive system under test comprised an SEW-Eurodrive 1.1 kW 'Movitrac' single phase variable speed drive and an SEW-Eurodrive 3-phase, 1.1 kW, 4 pole cage-rotor induction motor.

Physically, the VSD was mounted 2 m behind the motor under test, and in line with the axis of the motor shaft, with the ambient temperature monitoring sensor and associated radiation screen again on the above axis, and mid-way between the converter and motor. The VSD was arranged such that its cooling fan blew its exhaust air in the opposite direction from the motor under test.

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[1] 4E is the Efficient Electrical End-Use Equipment Implementing Agreement of the International Energy Agency: www.iea-4e.org.

For each of the load points shown in bold type in Table 2, measurements were made after the rate of change of motor case temperature-rise (above laboratory ambient temperature) became less than 2K per hour. The remaining load points for that speed were then measured as quickly as possible, down from 100% load.

Test runs were made on two consecutive days to confirm repeatability of the measurements. In all cases, the laboratory ambient temperature was maintained, by the air-conditioning system described above, at 25 ± 0.5°C.

3.2 Results:

Day 1			Speed			
			25%	**50%**	**75%**	**100%**
			375 rpm	**750 rpm**	**1125 rpm**	**1500 rpm**
Load	**100%**	1100 W	58.5%	71.2%	76.5%	**73.6%**
	75%	825 W	58.9%	70.8%	**76.3%**	77.1%
	50%	550 W	55.9%	**68.1%**	73.5%	77.1%
	25%	275 W	**45.1%**	57.7%	63.4%	69.4%

Day 2			Speed			
			25%	**50%**	**75%**	**100%**
			375 rpm	**750 rpm**	**1125 rpm**	**1500 rpm**
Load	**100%**	1100 W	58.7%	71.4%	76.4%	**73.7%**
	75%	825 W	59.4%	70.9%	**76.3%**	77.0%
	50%	550 W	56.8%	**68.6%**	73.1%	77.0%
	25%	275 W	**45.9%**	57.5%	63.5%	69.6%

Table 2: Efficiency values at the different load and speed points for the two test runs on consecutive days.

Figures in bold are the speed-load points at which (motor) thermal conditions were allowed to stabilise

3.3 Conclusion

The objective of the draft standard has been to provide a test and measurement procedure for the determination, by the output/input method, of drive efficiency which balances the conflicting requirements of accurate and realistic measurements over a wide range of operating conditions versus a reasonable time taken in which to make those measurements.

Two complete sets of measurements were made in two working days, and it is clear that a working day is more than sufficient time for all the necessary measurements to be made and for motor temperature stability to be achieved at the number of points specified.

The repeatability of the measured efficiency values was good. Efficiencies measured in the two experimental runs agree within 0.4 percentage points or better at the higher load - speed points. Agreement at the lowest speed and power points is not quite so good, and this was attributed to slight loading instability at very low torque values, a problem which has now been corrected.

It has been demonstrated that closely-controlled laboratory ambient air temperature may be achieved using unmodified domestic-type air-conditioning equipment which is readily available, and that a requirement in a published standard for closely controlled ambient temperature conditions should not therefore be difficult to achieve in laboratories around the world.

4 Efficiency measurements on small motors

Work on the measurement of energy efficiency in small motors was prompted by the extension, by IEC TC2 Working Group 31, of the range of motor ratings covered in the draft second edition of IEC 60034-30-1 (IE-code) from a lower output power rating of 0.75 kW downwards to 0.12 kW.

Meanwhile, IEC TC2 Working Group 28, which is responsible for the efficiency tests and measurement standard IEC 60034-2-1, has identified the method of separation of losses with additional losses determined by smoothing of residual losses (‘Method B’) as the preferred method for efficiency measurements on *all* three phase machines.

Measurement of efficiency of rotating machines with rated outputs as low as 120 W poses special problems, however, and a survey has indicated that many laboratories do not have facilities for testing motors with this rating. Rated output torque for a 120 W, 2 pole motor is only 0.38 Nm at synchronous speed when operated from a 50 Hz supply, and even lower (0.32 Nm) at 60 Hz. An uncertainty in the measurement of output mechanical power of only 1 W thus causes an error in the final efficiency figure of almost one percentage point.

Measurement of output shaft torque in such machines is by no means straight-forward: ‘Torque flanges’, with the advantage of having no bearing between the motor under test and the torque sensitive element, appear to be an obvious instrumentation choice. Such flanges tend, however, to be available only with comparatively high full scale ratings, with the most sensitive having full scale ratings of 50 or 100 Nm.

Other types of ‘in-line’ transducers suffer from the great disadvantage of having bearings at each end, and although the power required to drive the bearing at the loading end is easily accounted-for, the bearing between the motor and the torque sensitive element has losses which are not measurable by the transducer.

A possible means of measuring the mechanical losses in that bearing could be to use an electrically operated clutch between the motor under test and the torque transducer, and to note the difference in the electrical input power to the motor when the clutch is operated. That difference would, however, give information about *both* bearings, and assumptions would need to be made about the way in which the mechanical power losses were distributed between the two. Further, the loss characteristics of such bearings tend to be temperature dependent, adding further uncertainty to the measurement process.

Work is currently underway to investigate means by which efficiency measurements may be made on very small motors with minimum uncertainty, and to verify (or otherwise) that the 'preferred method', as specified in the current draft edition of IEC 60034-2-1 is, in fact, readily applicable to such machines.

That work involves the comparison of different ways in which very small torques may be measured and traced to international standards of measurement. These involve the use of mechanical coupling systems with very low windage and other losses, the use of currently available 'torque flanges' operating at very small fractions of their ratings, and the use of ultra-low friction 'pendulum' mounting arrangements for motors under test, involving the use of porous air-bearings, and the subsequent measurement of (test motor) stator reaction torque by means of lever arms and precision load cells.

This experimental work is currently being carried out as part of the Australian-Swiss collaborative research project, with results and experience to be compared with the Swiss researchers at the end of the process.

5 Converter-fed motor terminal voltage measurements

5.1 The need for a 'flux voltmeter'

Draft Technical Specification IEC 60034-2-3 seeks to quantify the additional losses suffered by rotating electrical machines when converter-fed. This Specification was initially based on the idea that the principal additional losses produced in converter-fed motors were iron losses, and that these could be identified by finding the ratio of the no-load losses produced in a given machine by a converter and an essentially sinusoidal supply respectively. The ratio between the two measured power values would then be called the 'harmonic loss ratio'.

A problem arose, however, with what constitutes an 'equivalent' voltage applied to a motor for the above purpose, given the very different waveforms generated by the two supplies, as above.

The measurement of voltage derived from a (nominally) sinusoidal supply to a motor is straight-forward, and requires the use of a voltmeter responsive to the mean value of the rectified voltage, but scaled to read the r.m.s. voltage of a sinusoidal wave having the same mean value.

(This is recognized by international standards relating, for example, to the measurement of power transformer core losses: See, for example, IEC 60076-1).

If a moving-coil voltmeter is connected to the terminals of a motor or transformer winding via a full-wave rectifier, then that instrument will respond in direct proportion to the peak flux value established by that supply voltage. This will always be the case, providing the magnetic flux contains no d.c. components or even harmonics, and that there are no subsidiary flux minima.

Thus a rectified-average responding instrument is always the best way to measure the voltage applied to the terminals of a motor (or transformer) under test, when the supply is essentially, but not perfectly, sinusoidal.

If the supply *is* purely sinusoidal, then the readings on average rectified- and r.m.s. responding instruments will be identical.

Measurement of voltage supplied to rotating machines from electronic converters poses additional problems, as the magnetic flux produced in those machines does not meet the above criteria, since it contains an alternating component at the converter switching frequency, and is not, therefore, without subsidiary minima which prevent accurate averaging by a simple rectifier-type voltmeter.

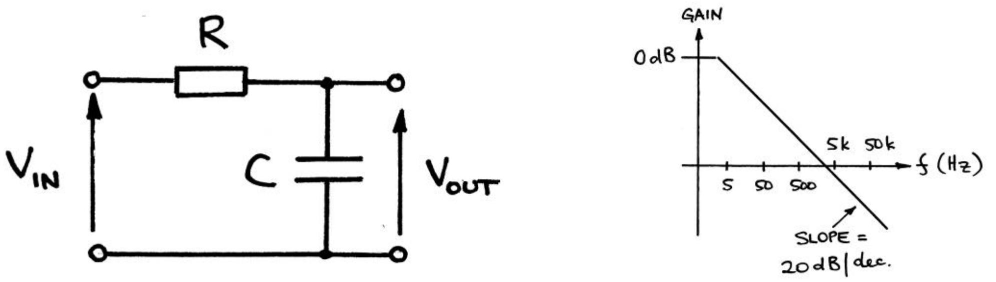
Various commercially available digital multimeters are claimed, by their manufacturers, (e.g. Fluke, Yokogawa) to be suitable for such measurements, and such instruments generally include filters of various types. There is apparently no agreement, however, as to the ideal characteristics of such filters.

Consider, now, the problem of comparing the performance of a given motor when fed with an essentially sinusoidal supply, with the performance under converter supply conditions, as above. What instrument should be used to ensure that the motor has comparable voltages at its terminals in each case?

A measurement system which responds essentially to the fundamental frequency magnetic flux excursions in the motor under consideration provides the required information.

Motor flux is closely related to the terminal voltage and frequency, the flux approximated by the time integral of the terminal voltage. A measuring system capable of measuring this integral would thus provide the necessary reference measurement method.

Such a measurement is very simple to make: A single ‘L-section’ RC network (see Figure 2) with a ‘corner frequency’ which is very much lower than the lowest frequency component in the motor supply voltage provides such a time integral.



(a) (b)

Figure 2: (a): A single pole passive R-C network accurately integrates signals whose frequency components are significantly greater than the cut-off or corner frequency. (b): Passive integrator frequency response characteristic

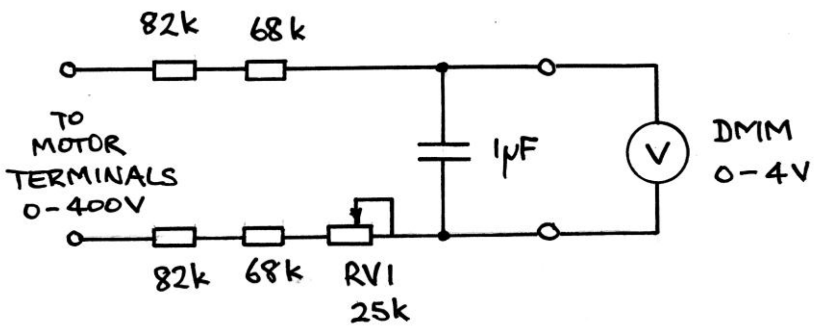


Figure 3: Practical (balanced) flux voltmeter according to the above design. The variable resistor allows adjustment.

Because of the low-pass filter characteristics of the above network, the output voltage waveform is nearly sinusoidal, but with a small amount of super-imposed ripple at the converter PWM 'carrier' frequency. Its output may therefore be read with a rectified-averaging responding meter without significant error.

A flux voltmeter of the above type has been used to compare the (total) no-load losses of a number of 2, 4 and 6 pole 1.1 kW cage-rotor induction machines, with the results shown graphically in Figure 4. The increase in no-load losses is shown as the portion at the top of each of the bars, but that figure also shows that motors are not re-ranked according to the nature of the supply.

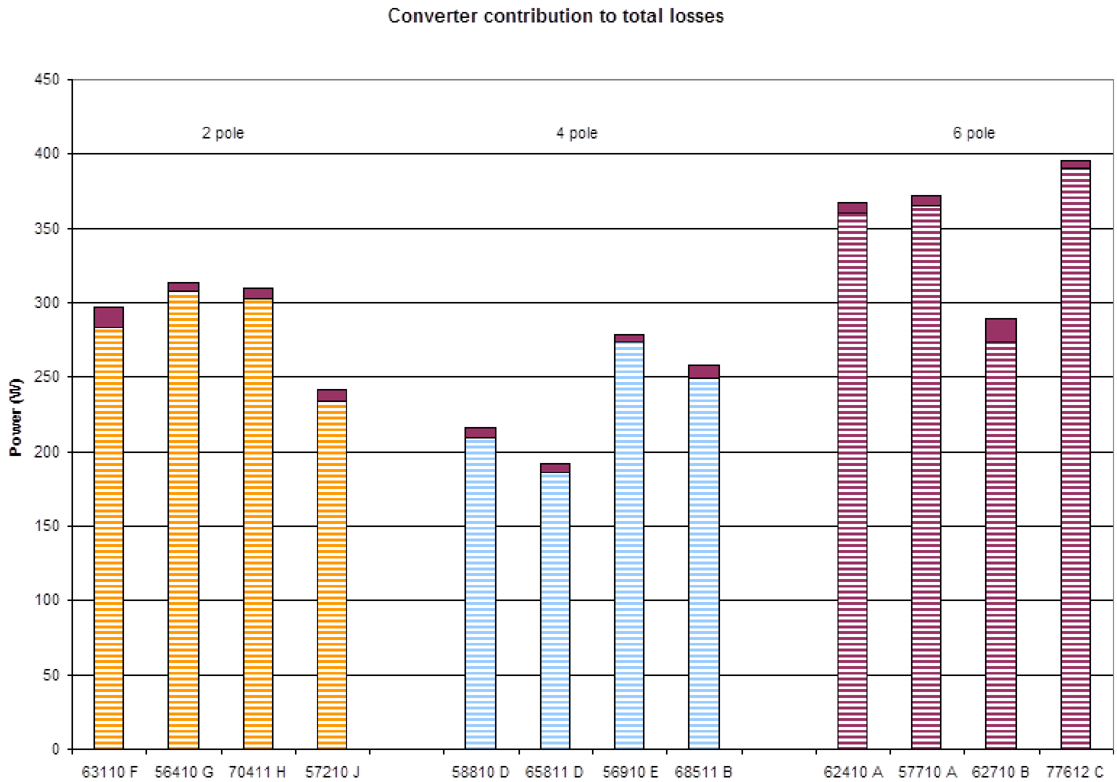


Figure 4: No-load loss measurements on 2, 4 and 6 pole motors with essentially sinusoidal and converter supply, the sections at the tops of the bars representing the additional losses under converter supply. These measurements were facilitated by the use of a flux voltmeter to adjust the motor supply voltages to comparable values

5.2 Other uses for the flux voltmeter

The curve in Figure 8 was produced by connecting a ‘flux voltmeter’ to the terminals of a small motor fed from a converter which had been set up to produce (as closely as possible) a ‘reference converter’ output waveform (as defined in Draft TS IEC60034-2-3) at 50 Hz.

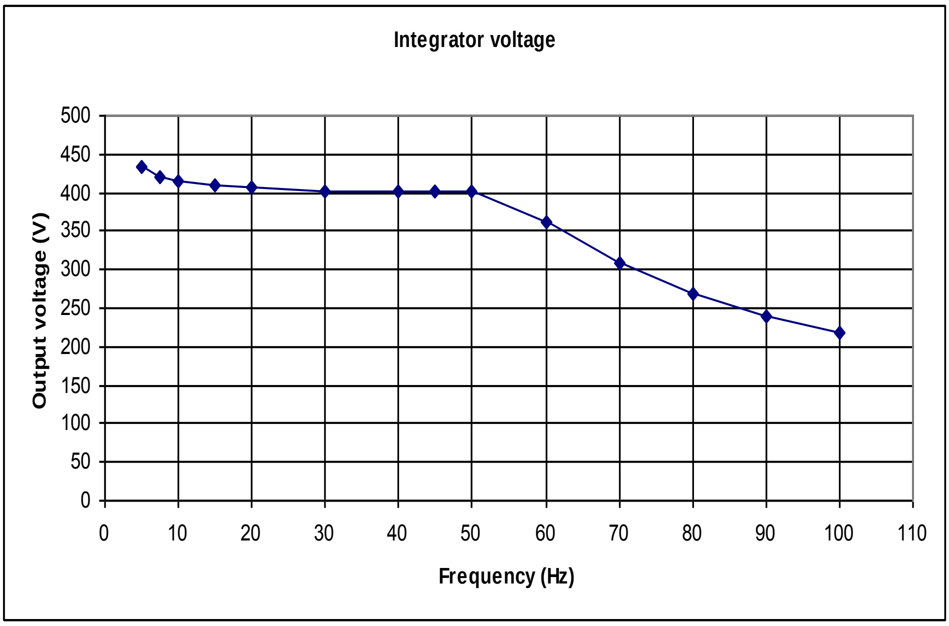


Figure 5: Flux voltmeter (‘Integrator voltage’) readings vs. frequency for a converter set to produce a ‘reference converter’ waveform at a fundamental output frequency of 50 Hz

The ‘flux voltage’ readings in Figure 5 clearly show:

1. constant motor flux as the frequency drops below 50 Hz
2. the effects of ‘voltage boost’ at low frequencies, a technique which is used to compensate for resistive voltage drop at those frequencies
3. the way in which flux drops at converter output frequencies above 50 Hz and
4. that the transition between (1) and (3) occurs at 50 Hz, indicating that the converter set-up is correct

The flux voltmeter is thus a useful tool for setting-up and adjusting variable speed drive equipment, since it clearly shows the transition between the various operating modes. The actual voltage applied to the motor terminals may be calculated from the flux voltmeter reading by multiplying the latter by the fundamental converter output frequency divided by the frequency at which the voltmeter was set up (50 Hz in the above case).

6 Methods for determining the efficiency of totally enclosed air-over (TEAO) motors

6.1 Background

Totally enclosed air-over (TEAO) motors are a type of rotating electrical machine designed specifically for driving axial-flow fans, and which are mounted in the resulting air-stream. Such machines are not equipped with their own external cooling fans, and rely, therefore, on the air-stream in which they are mounted to transfer heat away from the external surface of the motor. Enquiries directed to manufacturers show that TEAO motors are sold in significant quantities, and that this type of machine is widely used for ventilation of mines, traffic and other tunnels, and for cooling associated with high-density indoor livestock farming.

Because such motors are reliant on their driven loads for cooling, the usual methods for determining motor efficiency are not applicable, and TEAO motors have therefore been exempt from MEPS requirements as set out, for example, in draft revisions of IEC60034-30-1, the IE-Code.

Such a situation is unsatisfactory, however, as the availability of copious quantities of cooling air presents an opportunity for an unscrupulous manufacturer to supply high-loss motors for this type of duty.

The problem of measuring the efficiency of such motors has formed part of the present project, and the following outlines possible solutions to the problem of making efficiency measurements on such machines.

A motor without a means of self-cooling is likely to overheat if subjected to a conventional dynamometer test for the measurement of efficiency. A cooling air stream is therefore required, but the amount of cooling air provided from an external source must be carefully adjusted in order to neither under- or over-estimate the motor's efficiency. There are several ways in which the problem of providing the correct amount of cooling air may be overcome.

6.2 On-line resistance measurements

One possibility is the use of 'on-line' resistance measurement techniques which allow stator winding resistance, and therefore stator winding average temperature, to be measured while the machine is running. Measurements of this type are described in the (now withdrawn) IEC standard 60279 (First edition – 1969-01): '*Measurement of the winding resistance of an a.c. machine during operation at alternating voltage*'. That standard describes a number of ways in which the resistance of the winding of (for example) an electric motor, may be measured in real time whilst the motor is energised under rated a.c. supply conditions. As can be seen from the date of issue, that standard was written well prior to the present digital instrumentation era, and some of the methods described are quite cumbersome, and difficult to carry out. The current availability of high quality and very accurate digital instrumentation has changed that situation, however, and the principles of 'on-line', 'hot-line' or 'energised' winding resistance measurement are well worth revisiting, especially in the electric motor measurements context.

Instruments which offer 'energised' winding resistance measurements are now commercially available. Figure 6 shows a circuit which allows direct current to be injected into motor terminals and the resulting d.c. voltage drop to be measured, from which winding resistance may be determined continuously, and in real-time. Such a technique facilitates the 'rated load thermal test' which forms part of the preferred (separation of losses) method for the determination of induction machine efficiency, allowing the velocity of cooling air blown over external motor surfaces to be adjusted in order, for example, to produce winding temperatures corresponding to the insulation class, or to a maximum value specified by the manufacturer.

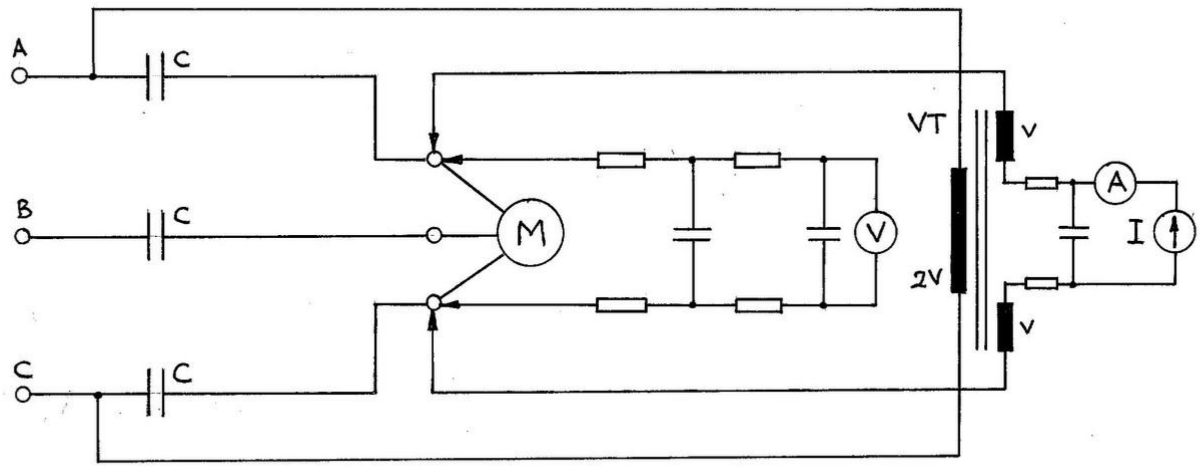


Figure 6: On-line resistance d.c. resistance measurement principle

In the above figure, the motor under test is energised from its normal a.c. supply via three d.c. blocking capacitors, C. The motor's stator winding d.c. resistance may be measured, even in the presence of the normal a.c. supply, by introducing a small direct current via a simple low pass filter and a voltage transformer, 'VT', connected so as to remove the motor a.c. supply voltage from the current injection circuit. The resulting d.c. voltage drop across the motor stator winding is measured using a low pass filter (to reduce the a.c. voltage component) and a digital voltmeter.

Note that such a technique could very usefully be used in measurements made on conventional machines, obviating the need to make stator resistance measurements within the time intervals after switch-off specified in IEC 60034-1, or back-extrapolation of resistance values. It is hoped to generate interest in revisiting IEC 60279 and to rewrite it in order to update these very useful on-line techniques.

6.3 Methods for making TEAO motor efficiency measurements

The ability to measure the d.c. resistance of energised machine windings facilitates the determination of efficiency of TEAO motors.

One proposed method is based on the provision of external motor cooling arrangements, and the use of 'energised' d.c. winding resistance measurements to allow a specified winding temperature to be reached and maintained.

The following sketch (Figure 7) shows a suggested test set-up, in which the motor under test is connected to a conventional dynamometer, and cooling is provided by means of a cylindrical sleeve fitted around the motor, through which air, initially at laboratory ambient temperature, is blown at a controllable rate. The instrumentation includes an energised d.c. resistance measurement system for the real-time indication of average stator winding temperature.

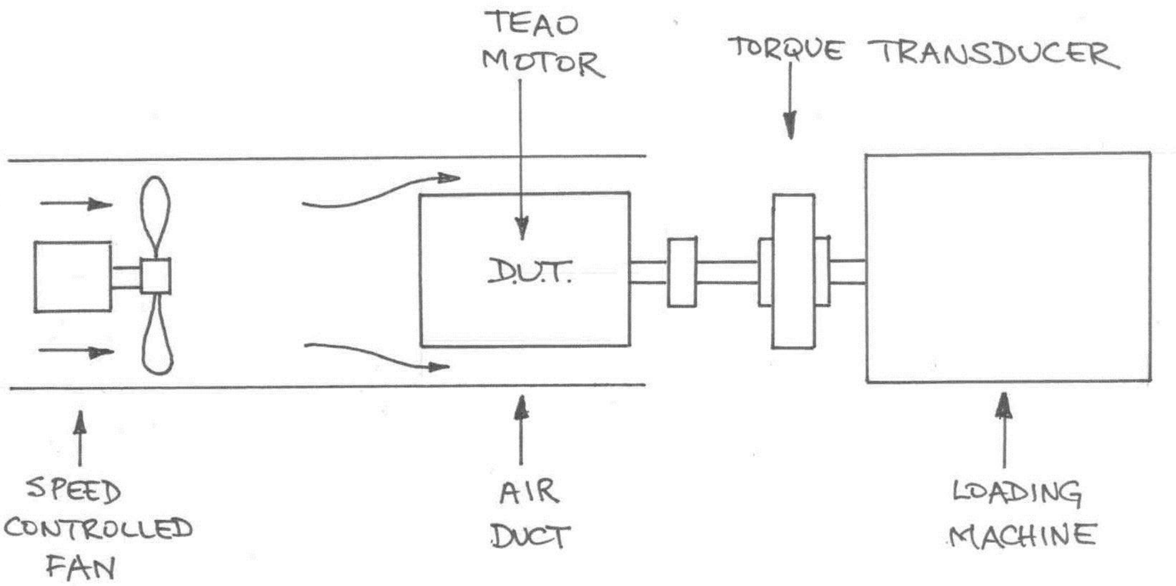


Figure 7: Suggested TEAO efficiency measurement set-up

The test and measurement procedure is carried out according to the requirements of IEC 60034-2-1 (Method B (see draft edition) – separation of losses, with additional load losses determined by the residual loss method).

The rated load thermal test proceeds with the motor loaded mechanically to its rated output, and with the flow of cooling air adjusted until the average stator winding temperature (inferred from stator winding d.c. resistance) stabilises at a predetermined value.

The required temperature may be selected from the following possibilities:

- The temperature corresponding to the stator winding insulation class, as in IEC 60034-2-1, Table 4 ('Reference temperature'), with Class B insulation corresponding to: 95˚C, class F: 115˚C, class H: 135˚C etc.
- A temperature-rise designated by the manufacturer

Note that the external cooling air-stream may be adjusted by a number of means, including a variable-speed blower or fan, or the provision of an adjustable input-air damper system.

The load-curve test would then be carried out maintaining the same cooling air system settings as were determined during the rated load thermal test.

The cooling air system would run whenever the motor under test runs, and is stopped when the motor is de-energised.

6.4 An alternative TEAO motor efficiency measurement test method

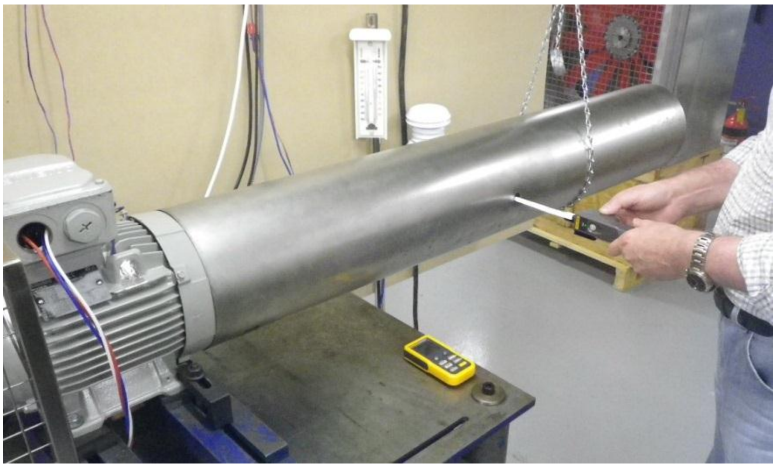
Another way in which the efficiency of TEAO motors might be treated is for manufacturers to be required to state, on the nameplate of such machines, the minimum air velocity (at full load) which is required to pass over the body of the motor.

As part of this study, air velocity over the bodies of conventionally cooled TEFC motors which might be considered ‘parents’ of corresponding TEAO motors, has been investigated, and comparisons made between efficiency figures obtained from a given TEFC motor which was then modified by removal of the fan cowling and fan. The resulting TEAO motor was then cooled by external means, with air velocities over the motor body matched as closely as possible.

<u>Experimental Method:</u>

A normal, TEFC 2.2 kW 2 pole induction motor was randomly chosen for testing as the ‘parent’ motor. Using the Precision Dynamometer laboratory as previously described above, efficiency, determined using both the separation of losses and direct output/input methods, was measured at a controlled ambient temperature of 23 ± 0.5 °C.

Using methods developed by the HVAC industry, the air inlet flow velocity to the cooling fan of the (TEFC) motor was measured using a hot-wire anemometer probe inserted into in a long sheet-metal circular duct fitted over the motor’s fan cowling, having previously determined that the presence of the duct had minimal effect on motor temperature rise.



Photograph 1: measuring the air velocity in the duct: TEFC motor

By removing the integral fan and cowling, the motor was then converted to TEAO construction. An external speed-controlled centrifugal blower was then used to supply air through the same sheet-metal duct at the same average velocity as measured for the TEFC motor. Since the diameter of the duct was the same as the internal diameter of the original fan cowling, it was reasoned that the same air flow velocity at the same temperature would have the same cooling effect.

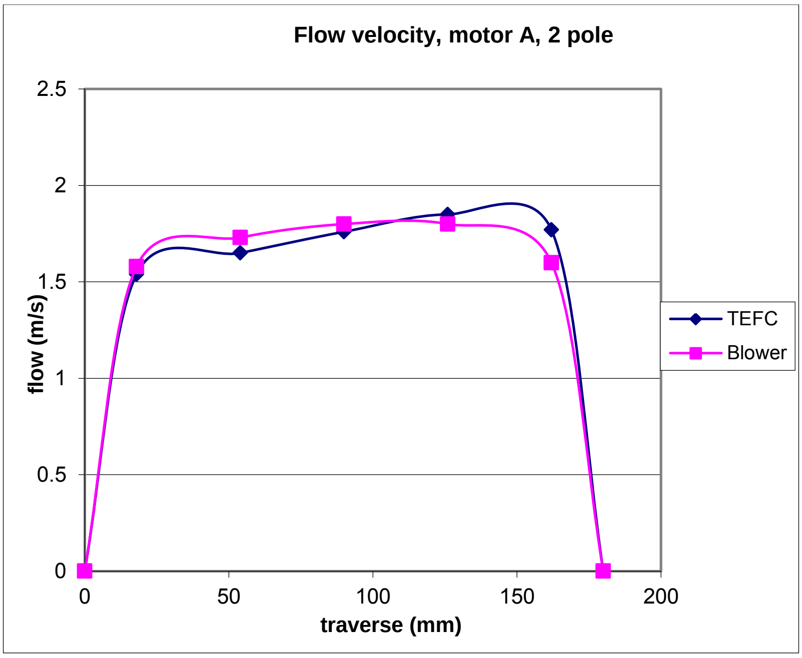


Figure 8: Air velocity in the duct, 2 pole motor. Velocity profile is flat in both modes, indicating low turbulence.

Measurements of motor efficiency were then repeated.

The above procedure was then repeated using a 2.2 kW 4 pole motor.

Results:

Condition	Mode	Efficiency (separation of losses)	Constant loss	Efficiency (output/input)	Intercept, B	Stator rise
Normal cooling	TEFC	86.2 %	87.2 W	86.3 %	-1 W	42.2 K
External air flow, speed matched	TEAO (no fan or cowling fitted)	86.4 %	70.9 W	86.7 %	-5.7 W	52.4 K
External air flow, speed matched	TEAO (fan cowling refitted)	86.3 %	70.9 W	86.3 %	1.47 W	51.3 K

Figure 9: Results, 2.2 kW 2 pole motor, TEFC and TEAO mode

An increase of efficiency of 0.4 % was measured in TEAO mode. The constant loss is reduced due to the removal of the cooling fan. However, the stator temperature rise was 10 K greater despite the air flow replication. Thus the measured efficiency was slightly lower due to the temperature.

Refitting the original fan cowling (but without fan) inside the duct in TEAO mode, and with the airflow velocity matched as before, had no significant effect on the stator rise or efficiency.

Condition	Mode	Efficiency (separation of losses)	Constant loss	Efficiency (output/input)	Intercept, B	Stator rise
Normal cooling	TEFC	84.7 %	102.7 W	84.9 %	-3.5 W	68.1 K
External air flow, speed matched	TEAO (no fan or cowling fitted)	84.2 %	98.8 W	84.6 %	-8.6 W	76.6 K

Figure 10: Results, 2.2 kW 4 pole motor, TEFC and TEAO mode

In the above table, the efficiency (measured by separation of losses) is 0.5 % lower for TEAO operation, compared with TEFC. Again, the constant loss shows a small decrease due to the removal of the fan, but the stator temperature is higher, reducing the efficiency slightly.

Conclusion: Air flow velocity can be accurately measured and replicated. Efficiency measurements, with good agreement between separation of losses and output/input methods, show a change in constant loss and efficiency when changing a TEFC motor to a TEAO. However the increase in stator temperature with the same cooling-air velocity is not yet understood.