PM Machines : Parameter Measurement and Performance Prediction

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Abstract – this brief describes the experimental measurement of the following PM machine parameters : back-emf, inductance, tooth/yoke flux, open/short-circuit iron loss and cogging/ripple torque. It concludes with an example of the calculation of the efficiency map of a surface PM machine.

I. Measurement Techniques

Testing of electrical machines involves measurement of the mechanical torque and speed and the electric voltage, currents and powers.

The most accurate (~0.1%) but most expensive means for measuring torque is to use a brushless in-line rotary torque transducer (see Fig. 1a). An alternative is to mount the stator of the machine on bearings and measure the reaction torque on the stator using a lower cost linear force sensor (see Fig. 1b). Finally a DC machine can be used both as a dynamometer motor and torque sensor (using the armature current and knowledge of the back-emf constant).

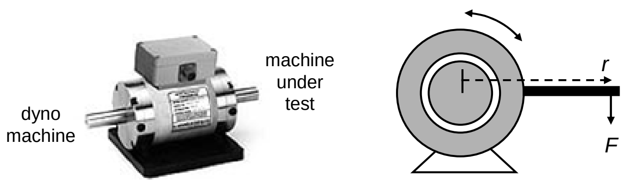

Fig. 1. a) In-line torque transducer and b) reaction torque measurement test arrangement.

Speed measurement can be performed using an encoder, resolver or optical tachometer, however for synchronous machines the simplest and most accurate method is to measure the fundamental frequency of the machine voltages or currents.

A precision power analyser offers the most convenient and accurate method for measuring the electrical quantities such as voltage, current and power. Power analysers often also allow inputs from torque and speed sensors and so can calculate and display efficiency.

II. Back-EMF and Flux Coil Testing

The back-emf waveform can be obtained by spinning the open-circuited machine at constant speed. The line voltage is normally used rather than the phase voltage as this does not have a third harmonic component and so is more sinusoidal.

The magnet flux-linkage is obtained by dividing the back-emf voltage by the speed (determined from the electrical frequency of the voltage). If the speed is varying during the measurement interval, a more accurate calculation of the magnet flux-linkage can be obtained by integrating the back-emf voltage using the procedure described in [1] and taking the peak of the resultant instantaneous flux-linkage waveform.

When validating finite-element models, in addition to the back-emf waveform, it is often useful to measure the stator tooth and yoke flux waveforms using search coils [4]. The induced voltages from these coils can be integrated [1] and if appropriate, scaled by dividing by the number of turns and magnetic area to give the equivalent flux density.

III. Resistance and Inductance Measurement

Methods for measuring the stator resistance and the *d*- and *q*-axis inductance saturation characteristics for PM machines under standstill conditions were described in detail in [2].

IV. Open-Circuit Iron Loss

The open-circuit (no-load) iron loss can be obtained by measuring the input torque as a function of speed when driving the open-circuited machine.

Correct zeroing of the torque sensor is particularly important in this test. It is not possible to simply set the torque reading to zero under standstill conditions because of the cogging torque of the PM machine. One solution is to measure the no-load torque at a low speed in both directions and adjust the zero offset so that the torque readings are equal in magnitude. A more accurate method is to measure the no-load torque as a function of speed in both directions (see Fig. 2) and use symmetry to determine and remove any zero offset.

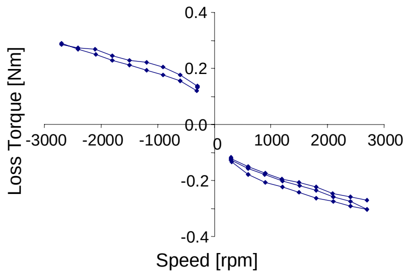

Fig. 2. Open-circuit torque as a function of speed measured over a number of test runs.

A DC machine can also be used to measure the open-circuit losses of the AC machine. This involves first measuring the DC machine's back-emf constant and no-load torque losses [3]. The DC machine is then used to drive the open-circuited AC machine and its input current and hence input torque is measured as a function of speed. The AC machine open-circuit losses can be obtained by subtracting the DC machine losses from the combined AC and DC machine losses.

V. Cogging Torque and Torque Ripple

The cogging torque can be obtained by measuring the machine torque under open-circuit conditions as a function of rotor position. If required, the instantaneous rotor position can be estimated by measuring the three back-emf voltage waveforms, integrating each to obtain the flux-linkage [1] and plotting the space vector of these to obtain the position.

The torque ripple at a given output current can be obtained using the same method. The instantaneous rotor position estimate can be obtained by using the space vector of the three-phase stator currents.

When taking cogging torque and torque ripple measurements it is important that the speed be sufficiently low (typically tens of rpm or less) so that the mechanical dynamics do not affect the results. This can be checked by comparing the test results at a given speed with the results obtained at half the speed to see if they are consistent.

VI. Forced-Running, Short-Circuit Test

The short-circuit test can be performed on PM machines with relatively high stator inductance where the short-circuit current is sufficiently low not to run the risk of demagnetisation of the permanent magnets or rapid overheating of the stator windings. It provides a useful check of the accuracy of the measurement of stator resistance and *d*-axis inductance. During the test, the short-circuited PM machine is driven over a range of speeds and the input torque and stator current are measured (see Fig. 3).

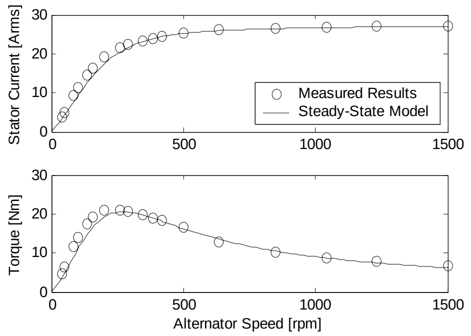

Fig. 3. Short-circuit current and torque results for an interior PM machine, comparison of measured results with calculated results based on measured inductances, resistance and back-emf [6].

The iron (and mechanical) loss under short-circuit conditions can be obtained by subtracting the stator copper losses from the input mechanical power (see Fig. 4). As the stator resistance varies with temperature, it is recommended that the resistance be measured at regular intervals.

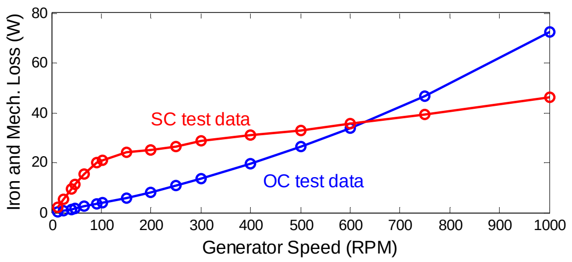

Fig. 4. Examples of measured open and short-circuit iron loss for a surface PM machine [5].

The iron loss under short-circuit conditions can be significantly different to that under open-circuit conditions (see Fig. 4) and this provides an extra method for model validation.

VII. Performance Prediction

Once the machine parameters have been obtained it is possible to calculate the machine performance under a wide range of operating conditions.

For example an efficiency map for the AC machine can be obtained using a similar approach to that for DC machines [3]. Fig. 5 shows an efficiency map for a surface PM machine which is based on the measured stator resistance, back-emf constant and iron loss [5]. For simplicity it is assumed that the iron loss is only a function of speed and not affected by the current and that the machine is operated with only *q*-axis current. The Matlab code is provided in the Appendix.

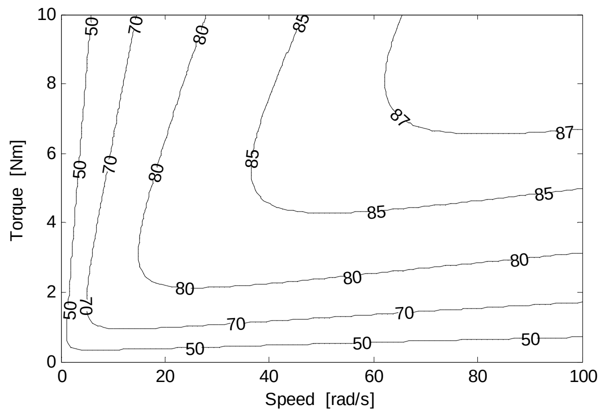

Fig. 5. Calculated efficiency map for an AC machine.

Appendix : Matlab Code for Efficiency Map

```
% file : acmachine.m
% draws an efficiency map for an AC machine (F&P)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 1 : Create Torque and Speed Matrices
clear;          % clear all variables
NPoints = 100;  % array size for efficiency calculation
Tmax =  10;     % rated torque in Nm
Wmax = 100;     % rated speed in rad/s
T_vector = linspace(0,Tmax,NPoints);   % vector of torque values
w_vector = linspace(0,Wmax,NPoints);   % vector of speed values
[w,T] = meshgrid(w_vector+Wmax/1000,T_vector+Tmax/1000);
   % the terms Wmax/1000 and Tmax/1000 prevent divide-by-zero errors
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 2 : Calculate Efficiency Map
R1 = 6.83;     % stator phase resistance, ohms
k = 2.055;     % back-emf constant, rms phase volts per mech rad/s
Tloss = -7.68E-06 .* w.^2 + 5.10E-03 .* w + 2.73E-01;
   % loss torque equation determined from no-load test results
Temag = T + Tloss; % electromagnetic torque = load + loss torque
E = k .*w;      % rms phase voltage
I = (Temag .* w)./ (3 .* E);
   % rms phase current assuming I is in phase with E, from 3EI = Tw
eff= (T .* w) ./ (Temag .* w + 3 .* I.^2 .* R1 );
   % efficiency calculation including iron loss and stator resistance
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3 : Plot Out Efficiency Map
[c,h] = contour(w_vector,T_vector,eff*100,[50 70 80 85 87],'k');
clabel(c,h);     % show contour labels
xlabel('Speed  [rad/s]');
ylabel('Torque  [Nm]');
```

VIII. References

[1] W.L. Soong, “BH Curve and Iron Loss Measurements for Magnetic Materials,” PEBN #5, May 2008. Available from http://www.eleceng.adelaide.edu.au/research/power/pebn/

[2] W.L. Soong, “Inductance Measurements for Synchronous Machines,” PEBN #2, May 2008. Available from http://www.eleceng.adelaide.edu.au/research/power/pebn/

[3] W.L. Soong, “DC Machines : Parameter Measurement and Performance Prediction,” PEBN #1, May 2008. Available from http://www.eleceng.adelaide.edu.au/research/power/pebn/

[4] V. Zivotic-Kukolj, W.L. Soong and N. Ertugrul, “Iron Loss Reduction in an Interior PM Automotive Alternator,” IEEE Transactions on Industry Applications, Vol. 42, Issue 6, Nov./Dec. 2006, pp. 1478 – 1486.

[5] D.M. Whaley, W.L. Soong and N. Ertugrul, “Investigation of Switched-Mode Rectifier for Control of Small-Scale Wind Turbines,” IEEE Industry Applications Society Annual Meeting, Vol. 4, Oct. 2005, pp. 2849 – 2856.

[6] C.Z. Liaw, D.M. Whaley, W.L. Soong and N. Ertugrul, “Implementation of Inverterless Control of Interior Permanent Magnet Alternators,” IEEE Trans. on Ind. Appl., Vol. 42, No. 2, Mar./Apr. 2006, pp. 536 – 544.

A Word for Today

Jesus provided far more God-revealing signs than are written down in this book. These are written down so you will believe that Jesus is the Messiah, the Son of God, and in the act of believing, have real and eternal life in the way he personally revealed it.

John 20:30-31 (The Message)