Inductance Measurements for Synchronous Machines

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W.L. Soong

School of Electrical and Electronic Engineering
University of Adelaide, Australia
soong@ieee.org

Abstract – two standstill methods for measuring inductance saturation characteristics for both permanent magnet and reluctance machines are described. These are the AC steady-state impedance and instantaneous flux-linkage methods.

I. INTRODUCTION

The inductance saturation characteristics are important for characterising permanent-magnet and reluctance machines. This brief describes methods for measuring these using stationary tests. The tests are also applicable to transformers and inductors. Note that standstill methods are not suitable for use with induction machines.

A. Winding Connection

Due to the mutual magnetic coupling between the three phases, for stationary tests with single-phase excitation, inductance should be measured with all three phases excited as shown in Fig. 1.
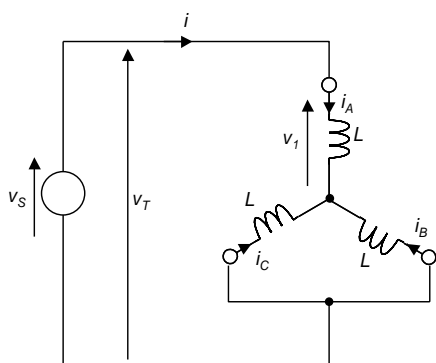

Fig. 1. Three-phase connection used when measuring inductance using a single-phase excitation.

The total inductance measured based on the voltage v_T and current i shown is 1.5 times the phase inductance. If the source is only connected across a single phase, the measured inductance could be as low as two-thirds of the actual value depending on the degree of mutual coupling between phases.

For the tests described in this brief, a single-phase, variable-magnitude, mains-frequency AC voltage from an auto-transformer is applied to the machine as shown in Fig. 1.

B. Locating the D- and Q-Axis Locations

To locate the d- and q-axes in a PM or reluctance machine the simplest method is to apply rated DC current to machine using the connection shown in Fig. 1. The rotor will then align with d-axis. The rotor can be rotated 90 electrical degrees to find the q-axis. Setting the angle can be performed with a protractor or a machinist's dividing head. The rotor should be locked in position before taking the inductance measurement. This is more important when taking q-axis inductance measurements in PM machines due to the large pulsating torque produced by the single-phase excitation.

A more accurate method for determining the d- and q-axis positions for rotors with saliency is to effectively use the machine as a resolver. This involves applying an AC voltage to the machine as shown in Fig. 1 and observing the rms current in each of the three phases, that is I_A, I_B and I_C. As the rotor is rotated there will be positions where $I_B = I_C$, that is, when the rotor is symmetrically oriented with regards to phases B and C, and thus either fully aligned or unaligned with regards to phase A. The current magnitude in phases B and C can be used to tell the difference between the two cases : when the rotor is aligned the current is smaller than when it is unaligned.

C. Inductance (LCR) Meters

It is not recommended to use an inductance meter to measure the inductances for electrical machines as the results obtained are generally much lower than the real values. This is because these meters use a low test current (mA). At this low excitation, the permeability (slope of the BH curve) is low which reduces the measured inductance. LCR meters sometimes also use high test frequencies (e.g. 10 kHz) at which skin effects can be significant which also reduces the measured inductance.

II. AC STEADY-STATE IMPEDANCE

This is the simplest method. The machine is excited with a variable-magnitude AC source using the circuit shown in Fig. 1. The input rms current I is varied in a series of steps and it and the corresponding input rms voltage V are recorded. For each current value, the equivalent series reactance can be calculated using (1) with knowledge of the total DC winding resistance R for the connection shown in Fig. 1 [1].

$$X = \sqrt{Z^2 - R^2} = \sqrt{\left(V/I\right)^2 - R^2} \qquad (1)$$

Alternatively if power readings are available, then the effective resistance for each current value can be calculated from the power reading as shown in (2) and used in (1).

$$R = P/I^2 \qquad (2)$$

The phase inductance L can be found as shown in (3). The two-thirds factor arises from the winding connection.

$$L = \frac{2}{3} \frac{X}{2\pi f} \qquad (3)$$

III. INSTANTANEOUS FLUX-LINKAGE

The instantaneous flux-linkage method [1-2] for measuring the inductance saturation curves can use the same test arrangement as shown in Fig. 1 and the same AC excitation.

It involves sampling the instantaneous terminal voltage $v(t)$ and current $i(t)$ and knowing the stator resistance, calculating the instantaneous flux-linkage $\lambda(t)$ as :

$$\lambda(t) = \int v(t) - Ri(t)dt \qquad (4)$$

This integration can be approximated for sampled data with a sufficiently high sampling rate as :

$$\lambda_{n+1} = \lambda_n + \left[v_n - Ri_n\right]\Delta t \qquad (5)$$

where Δt is the time-step between samples and the subscript represent the sample number.
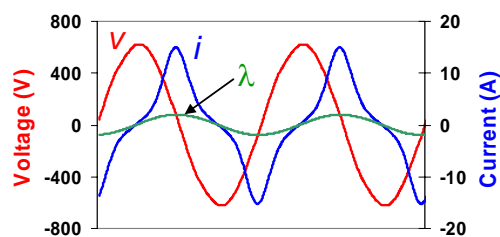
Fig. 2. High-current, *q*-axis test : two cycles of the measured voltage and current waveforms and the calculated flux-linkage waveform.
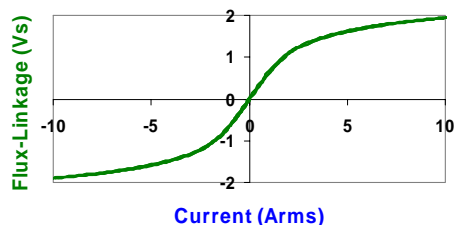

Fig. 3. High-current, *q*-axis test : calculated flux-linkage versus current plot. Note that the *x*-axis is $i(t)/\sqrt{2}$ to give current as Arms.
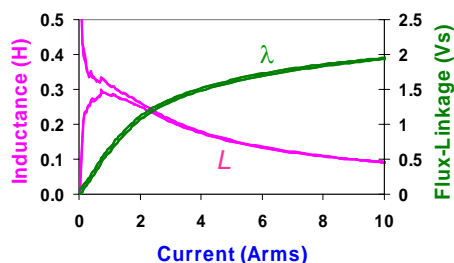

Fig. 4. High-current, *q*-axis test : calculated flux-linkage and inductance versus current curves.
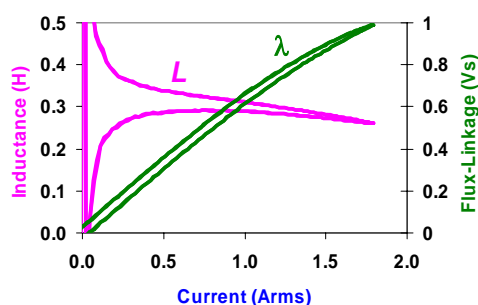

Fig. 5. Low-current, *q*-axis test : calculated flux-linkage and inductance versus current curves

A suggested test and analysis approach is as follows :

- adjust the AC supply voltage such that the peak current is a little above its rated value (say 10%);

- sample $v(t)$ and $i(t)$ to have about 200 to 1000 samples per cycle;

- select a subset of the sampled data containing an integral number of cycles (see Fig. 2), say two to five and analyse this subset in the following steps;

- remove any DC offsets in the measured voltage and current signals by calculating the mean of both signals and subtracting them from the signals;

- calculate the flux-linkage $\lambda(t)$ using the integration approach shown in (5) and remove the DC offset from the calculated flux-linkage (see Fig. 2);

- plot the flux-linkage $\lambda(t)$ versus $i(t)$, see Fig. 3;

- calculate the phase inductance $L(t)$ using (6) and plot this versus $i(t)$ as shown in Fig. 4;
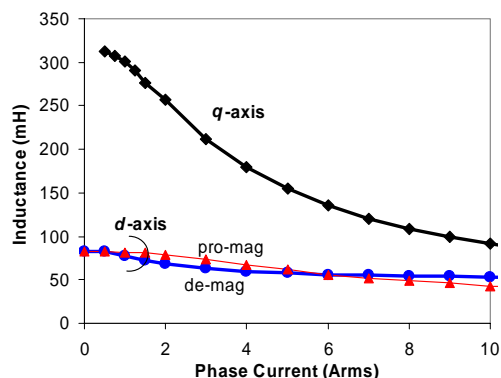

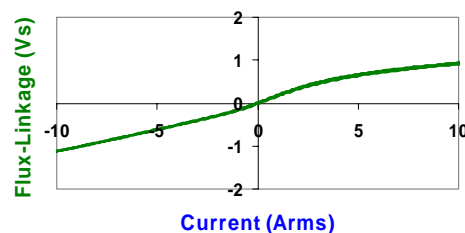Fig. 6. Measured *d*- and *q*-axis saturation curves [3].

Fig. 7. High-current, *d*-axis test : calculated flux-linkage versus current plot.

$$L(t) = \frac{2}{3}\frac{\lambda(t)}{i(t)} \qquad (6)$$

- read the inductances from the graph at the desired values of current, where the inductance curve is double-valued take the average between the upper and lower values of inductance;

- in order to get higher accuracy at low values of current, the test was repeated at a lower peak current value (see Fig. 5) to produce the composite *q*-axis inductance curve shown in Fig. 6.

The rotor was then rotated to the *d*-axis position and the same procedure was used to obtain the *d*-axis flux-linkage curve shown in Fig. 7. Note that this curve is not symmetrical due to the magnet flux. For the pro-magnetising case (positive current) the stator mmf causes the rotor bridges to come out of saturation (initially increasing the flux linkage) but also increases the airgap flux density resulting in greater saturation at high currents. For the demagnetising case, the stator mmf drives the rotor bridges harder into saturation while also decreasing the airgap flux density. The net result is a lower degree of stator saturation. The resulting *d*-axis inductance saturation curves are shown in Fig. 6. In interior PM machines the *d*-axis demagnetization curve is normally used.

IV. REFERENCES

[1] J. C. Lovatt and J. M. Stephenson, "Measurement of magnetic characteristics of switched reluctance motors," in Proc. Int. Conf. Elect. Mach., Manchester, U.K., Sep. 1992, pp. 465–469.

[2] C. Cosssar and T.J.E. Miller, "Electromagnetic testing of switched reluctance motors," in Proc. Int. Conf. Elect. Mach., Manchester, U.K., Sep. 1992, pp. 470–474.

[3] W.L. Soong and N. Ertugrul, "Inverterless High Power Interior Permanent Magnet Automotive Alternator," IEEE Transactions on Industry Applications, Vol. 40, No. 4, July/Aug. 2004, pp. 1083-1091.

A WORD FOR TODAY

"Then you will know the truth, and the truth will set you free."
John 8:31 (NIV)