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A Novel Method for Measuring Induction Machine Magnetizing Inductance

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Abstract— *This paper presents a novel method for measuring the magnetizing inductance of an induction machine. The method uses a static DC excitation technique which can be employed whenever the neutral of the machine is accessible. The proposed method measures only the magnetizing inductance and not the self inductance which normally includes the effect of the stator leakage inductance. Because this test uses a DC excitation, the iron losses in the motor are considerably reduced as well and minimally influence the measurement when compared to the traditional 60 Hz no-load test. By using the proposed method for measuring only the magnetizing inductance, the stator leakage inductance can be later individually determined by performing a separate no-load test.*

Test results using the method are compared with theoretical values and confirm its feasibility.

I. Introduction

Traditionally, the magnetizing inductance along with other induction machine parameters have been measured by performing 60 Hz no-load and locked-rotor tests [1, 2, 3, 4]. The values of the rated voltage and the no-load current at rated voltage and frequency are used to calculate the magnetizing inductance under the assumption that the leakage (measured by locked rotor test) has been split into arbitrary stator and rotor portions (typically half for each). In order to determine the correct stator and rotor leakage inductances, an iterative procedure must be applied to account for the effect of the magnetizing inductance. More recently, static tests using time domain [5, 6] and frequency domain [7] techniques have been proposed for measuring the induction machine parameters.

This paper proposes a novel, static method for measuring the magnetizing inductance of an induction machine using only a switched DC excitation. An accurate value for the magnetizing inductance is obtained with the proposed method because it measures only the magnetizing inductance of an induction machine. The proposed method does not measure the self inductance which includes the effects of the stator leakage inductance. The magnetizing inductance is calculated directly in the proposed method while the traditional method obtains the magnetizing inductance indirectly. The influence of the iron loss is also reduced when the proposed method is applied.

In addition to this test, the primary leakage inductance can be determined as a separate term by performing a separate no-load test. It should be mentioned that the proposed method follows the pioneering work by C.V. Jones [8]. This work, proposed in 1967, involves the direct current measurement of rotational self inductances. However, unlike the proposed test, Jones's method does not utilize the open circuit voltage of an adjoining phase to determine the magnetizing inductance.

II. Theoretical Derivation

The induction machine can be represented by the circuit model shown in Figure 1. If the rotor is assumed to have

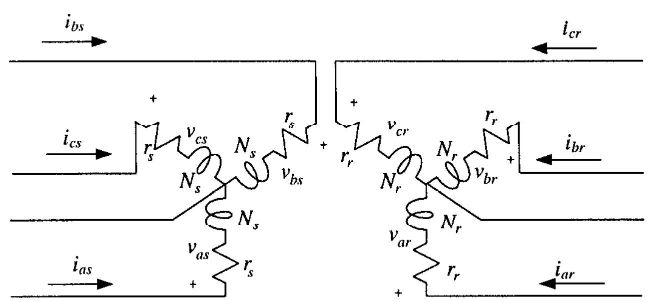

Fig. 1. Induction Machine Circuit Model

a squirrel cage construction, then the effective rotor phase windings can be assumed to be spatially aligned with the stator windings. The flux linkage equation for the stator a-phase winding is

$$\lambda_{as} = (L_{ls} + L_{ms})i_{as} - \frac{L_{ms}}{2}i_{bs} - \frac{L_{ms}}{2}i_{cs} + L_{sr}i_{ar} - \frac{L_{sr}}{2}i_{br} - \frac{L_{sr}}{2}i_{cr} \quad (1)$$

while the voltage equation for the a-phase winding is

$$v_{as} = i_{as}r_s + \frac{d\lambda_{as}}{dt}. \quad (2)$$

If the a- and c-phase windings are open circuited and only the b-phase winding is excited by utilizing the neutral connection, Equation 2 becomes

$$v_{as} = \frac{d}{dt}\left[-\frac{L_{ms}}{2} i_{bs} + L_{sr} i_{ar} - \frac{L_{sr}}{2}(i_{br} + i_{cr})\right]. \quad (3)$$

Now, using the Fundamental Limit Theorem from Calculus, we can integrate both sides with respect to time from zero to infinity to obtain

$$\begin{aligned} \lambda_{as} = \int_0^\infty v_{as} dt &= -\frac{1}{2}\int_{L_{ms}i_{bs}(0)}^{L_{ms}i_{bs}(\infty)} d(L_{ms} i_{bs}) \\ &+ \int_{L_{sr}i_{ar}(0)}^{L_{sr}i_{ar}(\infty)} d(L_{sr} i_{ar}) \\ &- \frac{1}{2}\int_{L_{sr}i_{br}(0)}^{L_{sr}i_{br}(\infty)} d(L_{sr} i_{br}) \\ &- \frac{1}{2}\int_{L_{sr}i_{cr}(0)}^{L_{sr}i_{cr}(\infty)} d(L_{sr} i_{cr}). \quad (4) \end{aligned}$$

The machine is assumed to be initially not excited, so all of the machine currents are initially zero. If a voltage step function is applied to the b-phase winding, after the transients die out the rotor currents will return to zero. This simplifies Equation 4 to the form

$$\begin{aligned} \lambda_{as} = \int_0^\infty v_{as} dt &= -\frac{1}{2}\int_0^{L_{ms}i_{bs}(\infty)} d(L_{ms} i_{bs}) \\ &= -\frac{L_{ms}}{2} i_{bs}(\infty). \quad (5) \end{aligned}$$

This result implies that by measuring and then integrating the a-phase winding voltage when the b-phase winding is excited by the step function, the magnetizing inductance can be measured directly as

$$L_m = \frac{3}{2} L_{ms} = \frac{3\lambda_{as}}{i_{bs}} \quad (6)$$

Note that the result of this integration is entirely independent of the variation of inductances L_{ms} and L_{sr} with current so that saturation is inherently included.

Under balanced three-phase excitation, the armature currents create a rotating magnetic flux in the air gap which is 1.5 times the magnitude of the flux due to one phase alone. Hence, on a per phase basis, three phase operation corresponds to the inductance $\frac{3}{2}L_m$ [4]. In the proposed test, only one phase is excited and therefore Equation 5 needs to be multiplied by 3 on both sides to obtain the conventional magnetizing inductance of the per phase equivalent circuit.

This method determines the actual ratio of the flux linkage to the winding current and therefore measures the chorded inductance as opposed to the small signal inductance.

This test can be conducted with a step increase (turn-on) or step decrease (turn-off) in voltage. However, experiments indicate that the turn-on method is less noisy because the energy stored in the stator leakage inductance creates an arc across the switch which affects the calculation.

III. Proposed Experimental Method

The experimental set up is shown in Figure 2. If the machine is a dual-voltage type, then the windings can be connected either in series or in parallel as in Figure 3. In both cases, the neutral has to be made accessible in order to perform the measurements. If the first and second sets of windings are connected in parallel as in Figure 4 during normal operation, both neutrals need to be shorted in order to apply the proposed method. If both neutrals are not connected as in Figure 5 then the unbalanced currents

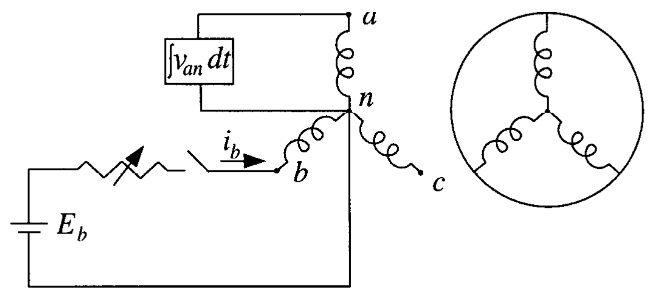

Fig. 2. Experimental set up

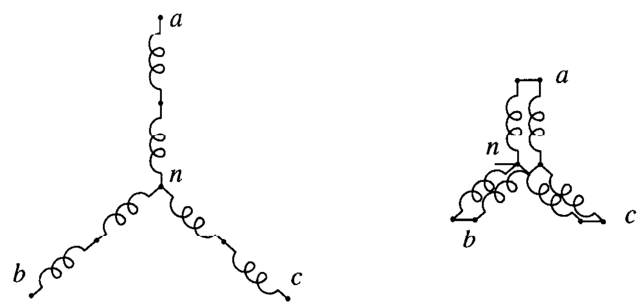

Fig. 3. Dual Voltage Machine Connections

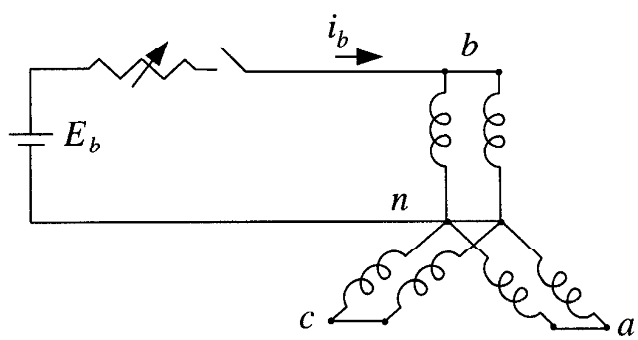

Fig. 4. Low Voltage Machine Connection for L_m Measurement

i'_a and i'_c flow in the two three phase groups and this can cause measurement errors. The series resistor limits the

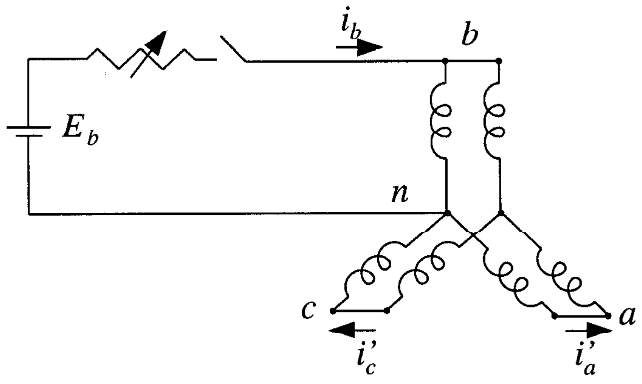

Fig. 5. Machine Connection with Circulating Currents

applied current to the desired value. When the switch is closed, the measured voltage is integrated to obtain the flux linkage λ. The steady-state current, i, is measured and Equation 6 is used to compute $\frac{3}{2}L_m$. This measurement can be performed with different current levels to obtain the magnetizing inductance verses current curve.

In order to verify the results obtained by the proposed method, a no-load test was also performed. From the per-phase equivalent circuit, the sum of the magnetizing and the stator leakage inductance was obtained. This measurement was performed for a number of different flux levels.

A. Theoretical comparisons between the DC and the AC measurements

In order to compare the value of the magnetizing inductance obtained by the DC test to that obtained by the AC test, as a function of current, it must be recognized that the DC current is proportional to the peak of the AC current. Hence, the DC current must be divided by $\sqrt{2}$ in order to be equivalent to the AC RMS current. In the proposed DC test, only one phase is excited, while in the AC test, all three phases are excited. Therefore, the current of the DC test must be divided by $\frac{3}{2}$ in order to obtain the same MMF as produced by a balanced three phase excitation. Thus, the graph which represents the magnetizing inductance as a function of the DC current has to be shifted by dividing its current axis by $\frac{3}{2}\sqrt{2}$.

IV. Experimental Results

The proposed method was first tested on a dual-voltage 1HP, 230/115V, 86Hz motor. The windings were connected in series and access was provided to the neutral point.

The magnetizing inductance, L_m, as a function of DC current obtained from the DC test is shown in Figure 6

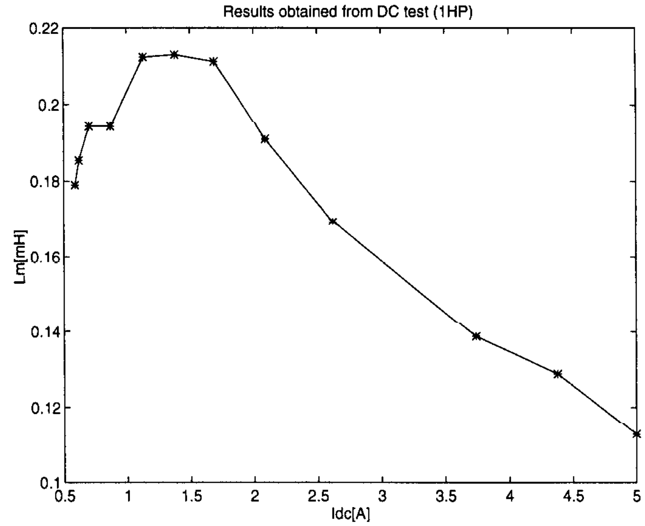

Fig. 6. 1 HP DC Excitation Test L_m

while the sum of the magnetizing inductance and the stator leakage, L_{ls}, as a function of the RMS current obtained in the no-load test is shown in Figure 7.

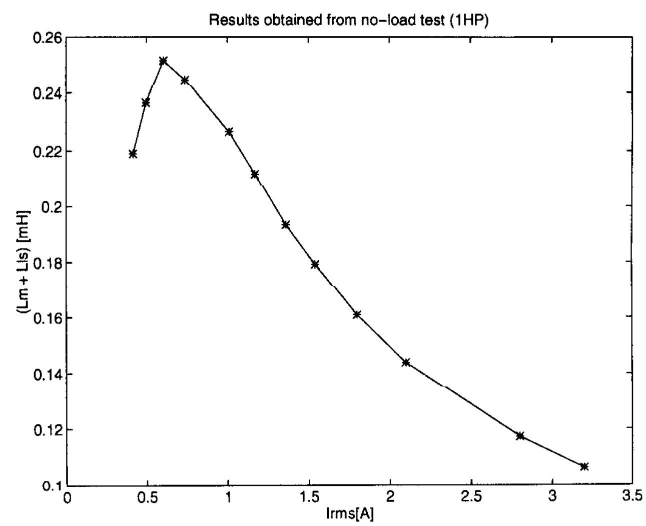

Fig. 7. 1 HP No-load Test $L_m + L_{ls}$

In order to compare these two figures, the DC test curve was shifted by $\frac{3}{2}\sqrt{2}$ along the current axis and plotted on the same graph with the results from the no-load test. This comparison is shown in Figure 8. The difference between the two curves clearly represents the stator leakage inductance, L_{ls}.

Next, the proposed method was tested on a dual-voltage 15 HP, 460/230 V, 60 Hz motor. When the switch was closed as shown in Figure 2, voltage (V_{an}) was measured and integrated. The measured voltage V_{an}, its integrated

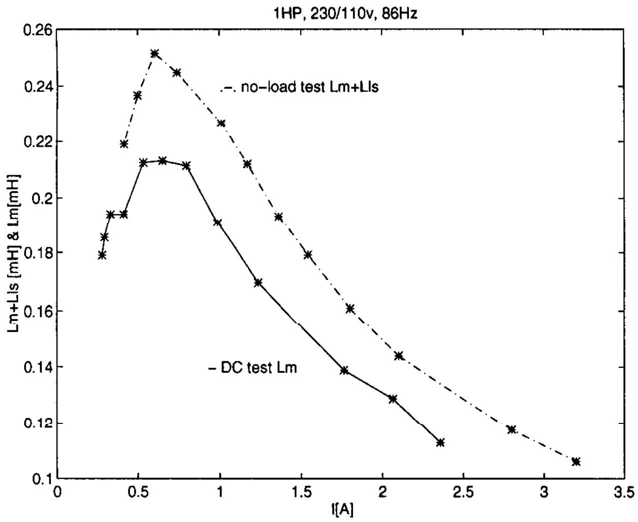

Fig. 8. 1 HP DC Excitation L_m and No-load Test $L_m + L_{ls}$

value (flux) and the DC current i_b are shown in Figure 9. This oscilloscope trace can be used to calculate one point

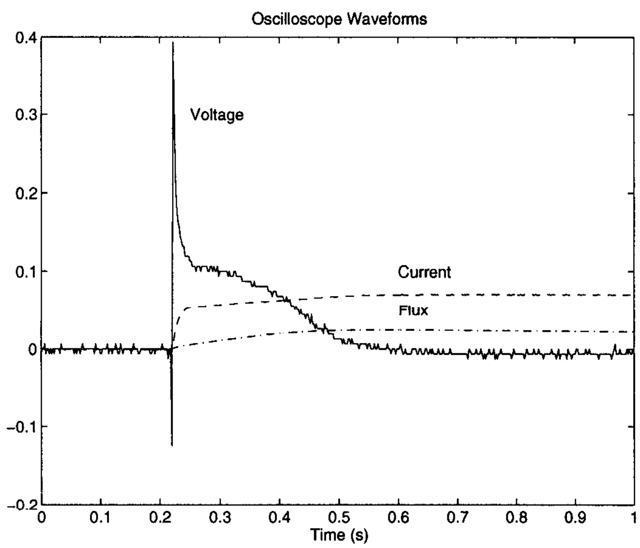

Fig. 9. 15 HP Oscilloscope traces for V_{an}, $\int V_{an}dt$ and i_b

on the L_m verses I_{dc} curve. The current levels are varied and the measurement repeated to obtain the complete curve.

In order to verify the value of the magnetizing inductance obtained by the proposed test, the manufacture's propritary design program was used to obtain a theoretical L_m verses I curve. This theoretical curve is compared with the emperical curves obtained by using the proposed and traditional methods. The comparison is shown in Figure 10. The vertical line indicates the rated no-load

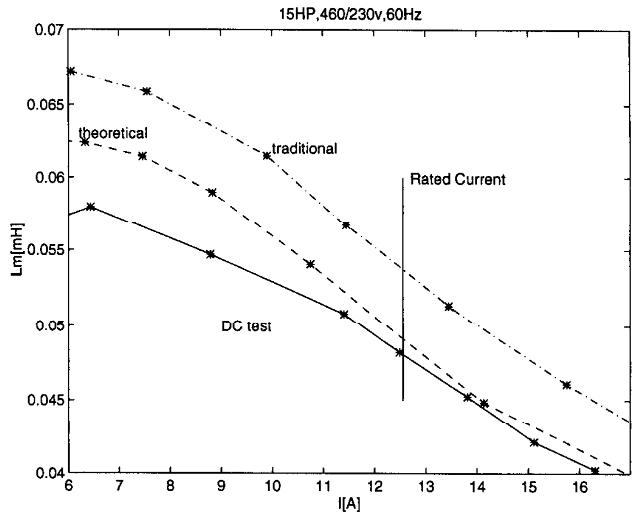

Fig. 10. 15 HP Theoretical and Experimental L_m

current. Its intersection with the inductance curves shows the location of the magnetizing inductance L_m at rated no-load current for each method. Therefore, it is clear that the proposed method calculates the magnetizing inductance accurately.

Having identified the magnetizing inductance, it is evident that the stator leakage inductance can be uniquely determined from the no-load test. The difference between the two curves in Figure 11 represents the stator leakage

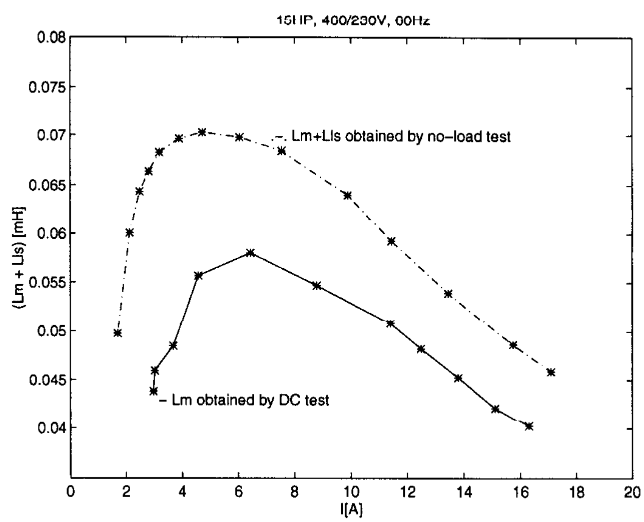

Fig. 11. 15 HP DC Excitation L_m and No-load Test $L_m + L_{ls}$

of the 15 HP motor.

V. Conclusions

This paper presents a new approach to identify the induction machine magnetizing inductance by using a DC excitation test with the motor at stand-still. The proposed method measures only the magnetizing inductance and makes it possible to calculate stator leakage inductances separately without any approximation or using iterative methods. The difference between the two curves in Figure 8 and in Figure 11 represents the stator leakage inductance. The proposed method greatly reduces iron losses and therefore they minimally affect the measurement. Verification of the proposed method was performed by comparing the inductance measured by this method with the theoretical value of the inductance calculated from a proprietary design program. Figure 10 clearly shows the improvement as compared to the traditional no-load and locked-rotor test. Verification of the proposed method was also performed by comparing the magnetizing inductance measured by this method with the total inductance (the sum of the magnetizing and the stator leakage inductance) calculated by a no-load test over a range of current. A constant difference between these two inductances was observed between both methods as the current is increased. Since the difference between the two inductance values corresponds to the stator leakage inductance, this result indicates that the proposed method correctly measures the effects of saturation.

VI. Acknowledgements

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