MONITORING OF DEFECTS IN INDUCTION MOTORS THROUGH AIR-GAP TORQUE OBSERVATION

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Monitoring of Defects in Induction Motors Through Air-Gap Torque Observation

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Abstract: **This paper suggests a method to monitor defects such as cracked rotor bars and the shorted stator coils in induction motors. Air-gap torque can be measured while the motor is running. No special down time for measurement is required. Data of the air-gap torque for a motor should be periodically kept for comparison purposes. Since more data than just a line current are taken, this method offers other potential possibilities that cannot be handled by examining only a line current.**

The theoretical foundation for this proposed method is presented. Experiments conducted on a 5-hp motor show the validity and potential of this approach. Further studies are planned to extend the proposed method in detail and to monitor defects developed in other types of rotating machines.

I. Introduction

Presently, the commercially available methods for detecting rotor bar defects of induction motors are based on various identifications of side bands of a line current.[1,2,16] This study suggests a new method for detecting not only the rotor defects but also the stator shorted coils. Since more data than just a line current are taken, this method offers other potential possibilities that cannot be handled by checking only a line current.

The summation of the products of the instantaneous phase currents and voltages is the instantaneous terminal power fed through a rotating machine. A portion of this power includes the charging and discharging of the energy stored in the windings. Therefore, this instantaneous power cannot represent the instantaneous torque. Even when under a constant speed and after subtracting the losses, the average value of the instantaneous power is only proportional to the average torque.

Air-gap torque is the torque produced by the flux linkages and the currents of a rotating machine.[3-14] Because the rotor, shaft, and mechanical load of a rotating machine constitute a specific spring system that has its own natural frequencies, the attenuations of the torque components of the air-gap torque transmitted through the spring system are different for different harmonic orders of torque components. Generally speaking, the waveform of the air-gap torque curve is different from that of the torque measured from the shaft.

Air-gap torque represents the combined effects of all the flux linkages and currents in both the stator and the rotor of the entire motor. It is sensitive to any unbalance created by defects. Air-gap torque tells distinctively whether the unbalance is caused by cracked rotor bars or by stator winding defects. Previous measurements can be used as reference to indicate defects developed in the induction motor.

Air-gap torque can be measured while the motor is running. No down time is required for its measurement. This can be financially attractive to many industries, where an unscheduled down time of a motor posts a heavy loss in the operation of a production system.

Instrumentation required for the air-gap torque measurement is not expensive. With aid from a well developed, data-acquisition facility and personal computer that has sufficient high-memory capacity, the testing procedure is not complex. Time required for a measurement of the air-gap torque is generally short, especially, when a computer program is written for handling the raw data for the calculation of the air-gap torque. The subsequent process for application of this method involves waveform plotting, frequency domain scanning, and fault indicating.

The theoretical foundation for this test is presented for the understanding of how the unbalance caused by either rotor or stator defects is detected and distinguished.

Experiments conducted on a 5-hp motor clearly show the validity and potential of this approach. Further studies are planned to extend the proposed method for detailed investigation and for monitoring defects developed in other types of rotating machines.

II. Equations and Frequencies of Air-Gap Torque

A. Air-Gap Torque Equations

Instantaneous input power of a three-phase induction motor is the summation of the products of the instantaneous phase voltages, v_a, v_b, v_c, and phase currents, i_a, i_b, and i_c.

$$Power = v_a i_a + v_b i_b + v_c i_c \tag{1}$$

In order to see how the power is distributed, the following voltage equations,

where

$\psi_a, \psi_b,$ and ψ_c = flux linkages of windings a, b, and c respectively

r = the phase resistance

$$v_a = \frac{d\,\psi_a}{d\,t} + r\,i_a,\quad v_b = \frac{d\,\psi_b}{d\,t} + r\,i_b,\ and\ v_c = \frac{d\,\psi_c}{d\,t} + r\,i_c \tag{2}$$

are substituted into (1) to give

$$Power = \left[i_a\left(\frac{d\,\psi_a}{d\,t} + r\,i_a\right) + i_b\left(\frac{d\,\psi_b}{d\,t} + r\,i_b\right) + i_c\left(\frac{d\,\psi_c}{d\,t} + r\,i_c\right)\right] \tag{3}$$

From (2), the flux linkages can also be given as

$$\psi_a = \int (v_a - r i_a)dt, \quad \psi_b = \int (v_b - r i_b)\ dt$$

and

$$\psi_c = \int (v_c - r i_c)\,dt$$

Subtracting the copper losses and the terms pertinent to the energy stored in the windings, the air gap torque equation [6,15] can be written for the line data as indicated in Fig. 1 where the symbols are denoted by an upper case suffix.

$$Torque\,[Nm] = \frac{P}{2\cdot\sqrt{3}}\left\{ \begin{array}{l} (i_A - i_B)\cdot\int[v_{CA} - R(i_C - i_A)]\,dt \\ -\ (i_C - i_A)\cdot\int[v_{AB} - R(i_A - i_B)]\,dt \end{array}\right\} \tag{4}$$

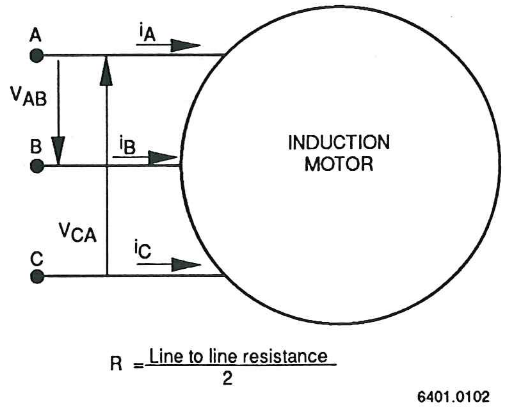

Fig.1. Line data for air gap torque computation

Equation (4) is valid for either Y- or Delta-connected motors,

where

P = number of poles

i_A, i_B, and i_C = line currents

R = half of the line-to-line resistance value

From the definition of R, the following two expressions are for Y– and delta-connected motors, respectively.

R = phase resistance, r for Y-connected motor

R = r/3 for delta-connected motor

When three leads for Y-connected motors without a neutral connection or three leads for delta-connected motors are used, (4) can be further simplified by using $i_B = -(i_A + i_C)$. The above equation can be rewritten to the known format that uses only two line voltages, two line currents, and one half of the line to line resistance as the input data for the calculation of the air-gap torque.

$$Torque\,[Nm] = \frac{P\cdot\sqrt{3}}{6}\left\{ \begin{array}{l} (2\cdot i_A + i_C)\cdot\int[v_{CA} - R(i_C - i_A)]\,dt \\ -\ (i_C - i_A)\cdot\int[-v_{BA} - R(2\cdot i_A + i_C)]\,dt \end{array}\right\} \tag{5}$$

B. Numerical Evaluation of Integrals

The integrals,

$$\int [v_{CA} - R(i_C - i_A)]dt$$

and

$$\int [-v_{BA} - R(2\cdot i_A + i_C)]dt$$

of windings corresponding to lines CA and AB in (5) represent flux linkages. Generally speaking, for an alternating current machine under steady state condition, the flux linkages do not contain any dc component. The following assumption is used in this study during numerical evaluation of the integrals:

1) The horizontal axis of a flux linkage curve lies between the maximum and the minimum flux linkages.

2) Any dc component that consistently makes the integral increase or decrease in a constant slope for the entire data acquisition period that is substantially longer than the period of the double slip frequency has to be eliminated. Normally an integral is computed twice. The first computation is to find out if there is any constant slope. The second computation is to subtract the slope from the integration. The reason for this constant slope may be caused by the instrumentation for measurement, such as Hall-effect sensors located in a magnetic medium, and acquisition that contains a slightly unequal property towards a positive and a negative signal.

Since the time increment between data points is small, a simple trapezoidal method is used in this study. Other methods using Simpson's rule or Gauss's rule for numerical evaluation of integrals can also be used. Such as those given in [13].

C. Frequencies of Major Air-Gap Torque Harmonics

Frequencies of the major torque harmonics that associate with defects in induction motors are discussed for three extreme cases: 1) normal operation, 2) single-phase stator, and 3) single-phase rotor. Defects are related to these extreme cases in various degrees.

Induction motor under normal operation: Fig. 2 shows under normal operation the stator rotating magnetic field is at angular speed ω_S, the rotor angular speed is ω_S (1 – s), and the rotor rotating magnetic field angular speed is $s \cdot \omega_S$ observed from the rotor. The symbol, s, denotes the slip, and $\omega_S = 2 \pi f$.

where

f = power-source fundamental frequency

The sign of the torque depends upon the relative position of the stator and the rotor fields. In other words the angular frequency of the torque is derived from the relative speed of these two fields.

Zero frequency means the ideal air-gap torque for normal operation is constant.

Angular frequency of torque
= *Stator field angular speed* –
[*Rotor angular speed* + *Rotor field angular speed observed from rotor*]

$$= \omega_s - \left[\omega_s (1-s) + s \cdot \omega_s\right]$$
$$= 0$$

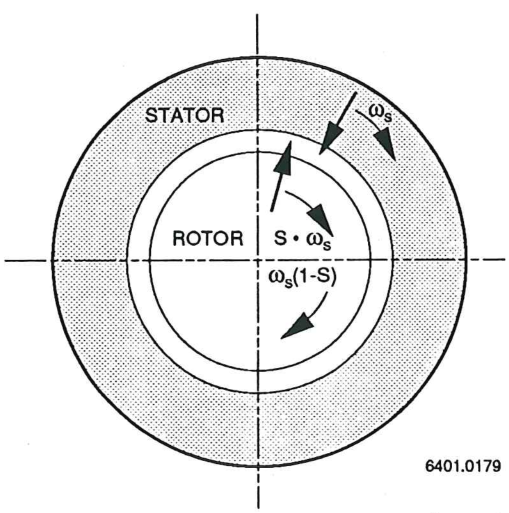

Fig. 2. Stator and rotor rotating fields under normal operation

Induction motor with single-phase stator: Under the situation of a motor with a single-phase stator winding, Fig. 3 shows the forward and backward stator rotating fields at angular speeds $\pm\omega_S$, the rotor angular speed is ω_S (1–s), and the rotor rotating magnetic field angular speed is $s \cdot \omega_S$ observed from the rotor. The forward stator rotating field produces a constant torque. The backward stator field interacting with the rotor field produces a harmonic torque. Its frequency is:

Angular frequency of torque
= *Stator backward field angular speed* –
[*Rotor angular speed* + *Rotor field angular speed observed from rotor*]

$$= -\omega_s - \left[\omega_s (1-s) + s \cdot \omega_s\right]$$
$$= -2\, \omega_s$$

The double fundamental frequency torque indicates an unbalanced stator winding.

Induction motor under single-phase rotor: For a motor with a single-phase rotor winding Fig. 4 shows the forward and backward rotor rotating fields at angular speeds $\pm s \cdot \omega_S$ observed from the rotor, the rotor angular speed is ω_S (1 – s), and the stator rotating magnetic field angular speed is ω_S. The forward rotor rotating field produces a constant torque. The backward rotor field interacting with the stator field produces a harmonic torque. Its frequency is:

Angular frequency of torque
= *Stator field angular speed* –
[*Rotor backward field angular speed observed from rotor* + *Rotor angular speed*]

$$= \omega_s - \left[- s \cdot \omega_s + \omega_s (1-s)\right]$$
$$= -2\, s \cdot \omega_s$$

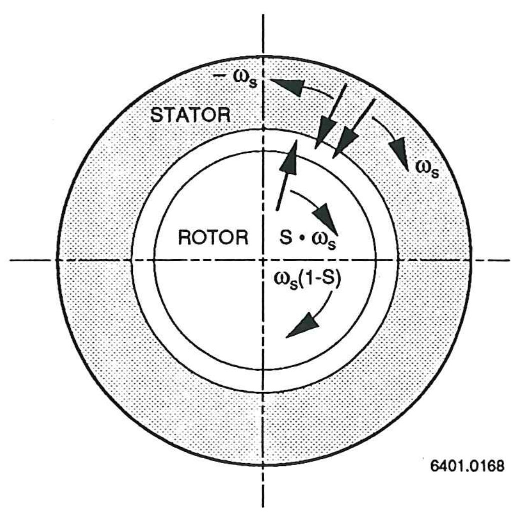

Fig. 3. Stator and rotor rotating fields under a single-phase stator situation

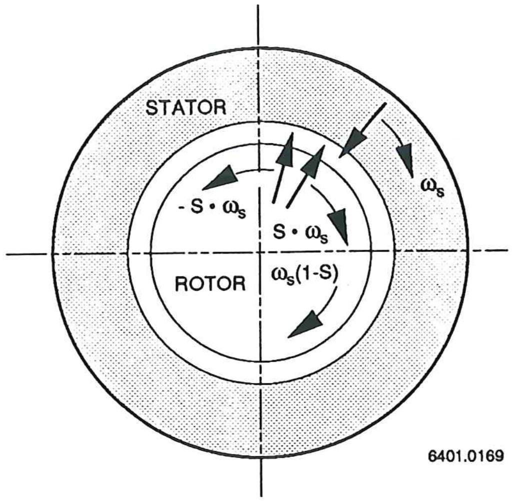

Fig. 4. Stator and rotor rotating fields under a single-phase rotor situation

The double slip frequency torque indicates an unbalanced rotor cage.

III. Measurement of Air-Gap Torque

A. Experimental Setup

Experimental setup is shown in Fig. 5. Isolated type of current and voltage transducers are used. The advantage of using isolated transducers is the signals can be connected to a single common point. This gives a great convenience to the data acquisition system. The disadvantage is that additional errors associated with the band width and the property of the sensors may be generated.

A four-channel, dc to 5 MHz, digital storage scope is used. It has a GPIB (IEEE488) input/output interface capability. Maximum sample rate is 20 megasample per second, per channel at 50 μs/div. Its storage capacity is 50 x 1 k or 5 x 50 k.

Sample time differences among different channels are neglected in this study. This can be included easily if the specific time differences are given; however, when the time increment for sampling is small, the error relating to the time differences is negligible.

A 5-hp, 4-pole, 230-V, 13-A, three-phase induction motor is coupled to a synchronous generator through a torque gauge. Output of the synchronous generator is connected to a resistor bank. The load of the induction motor can be adjusted by changing the field current of the synchronous generator.

A personal computer with over 1 megabyte of memory is connected to the digital scope through a GPIB/(IEEE488) interfacing cable. Talk and listen commands are handled through a commercial GPIB/(IEEE488) software.

B. Air-Gap Torque of a Motor Under Normal Operation

Fig. 6 shows the air-gap torque of the experimental motor. Torque is basically steady with a small ripple. Flux linkages corresponding to the integrals for lines CA and AB are shown in Fig. 7. They have been adjusted according to the assumptions that the constant slope is eliminated and the horizontal axis lies between the maximum and the minimum flux linkage values.

C. Air-Gap Torque of a Motor with Single-Phase Stator

Fig. 8 shows the line voltages and currents of the sample induction motor with a single-phase stator winding. A double frequency air-gap torque is obtained from the test and shown in Fig. 9.

D. Air-Gap Torque of a Motor with a Defective Rotor Cage

Fig. 10 shows that one end of a small portion of the rotor bars of the experimental motor is cut.

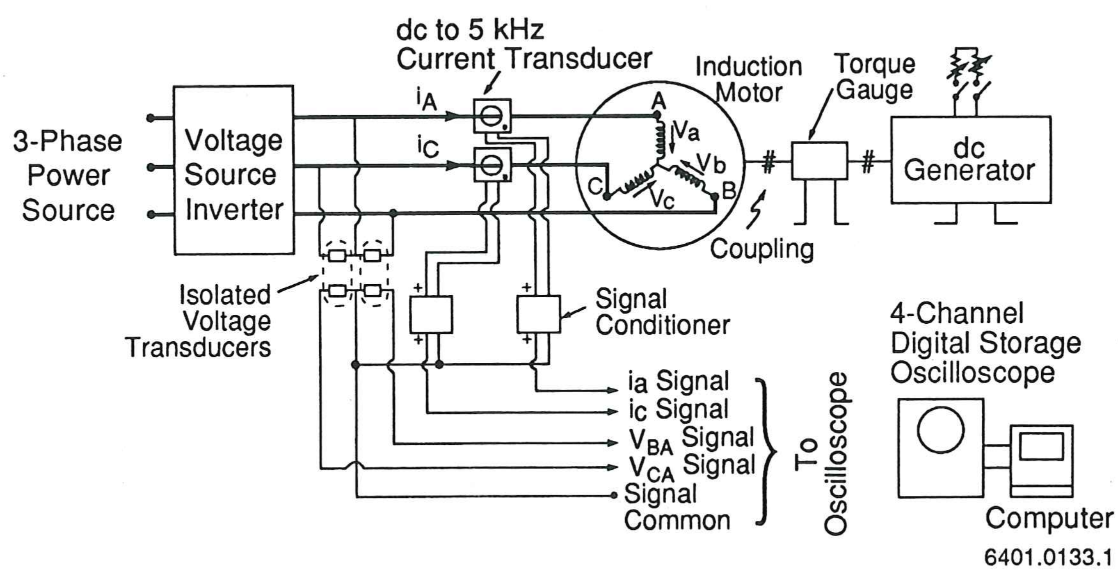

Fig 5. Experimental setup

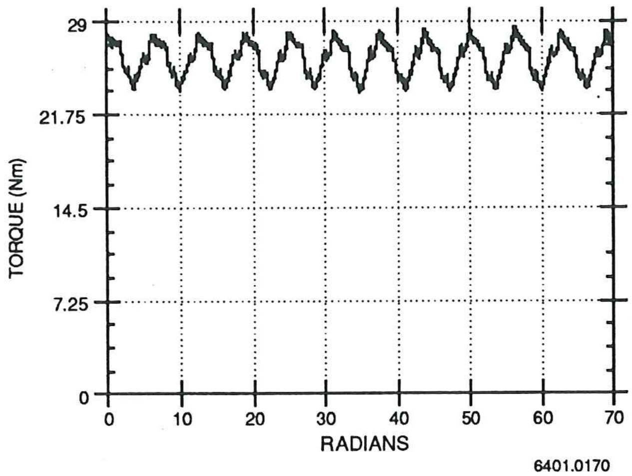

Fig. 6. Air-gap torque of sample motor under normal operation

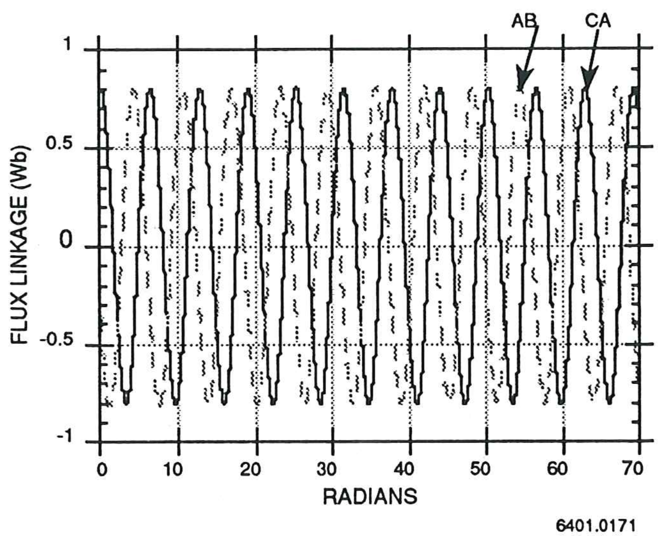

Fig. 7. Flux linkages corresponding to the integrals of lines CA and AB under normal operation

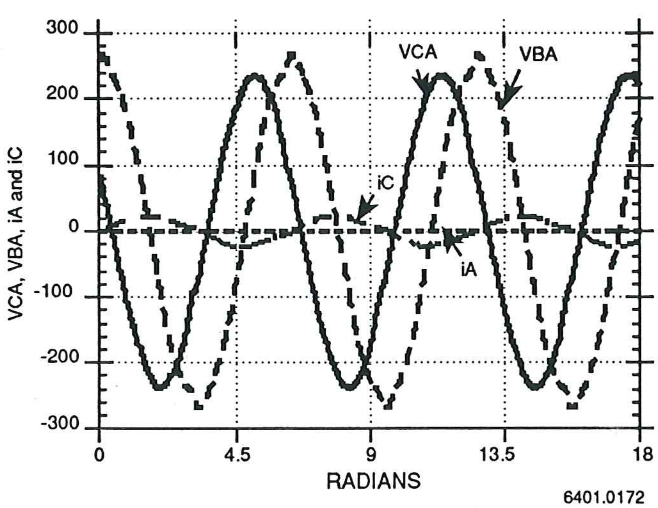

Fig. 8. Line voltages and currents of sample motor with a single-phase stator

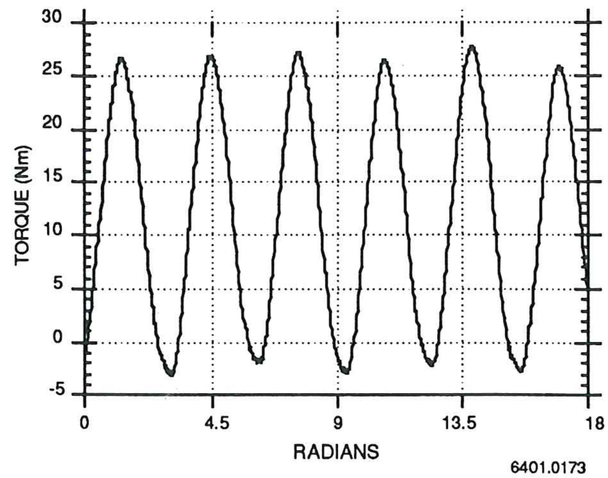

Fig. 9. Double frequency air-gap torque of sample motor with single-phase stator

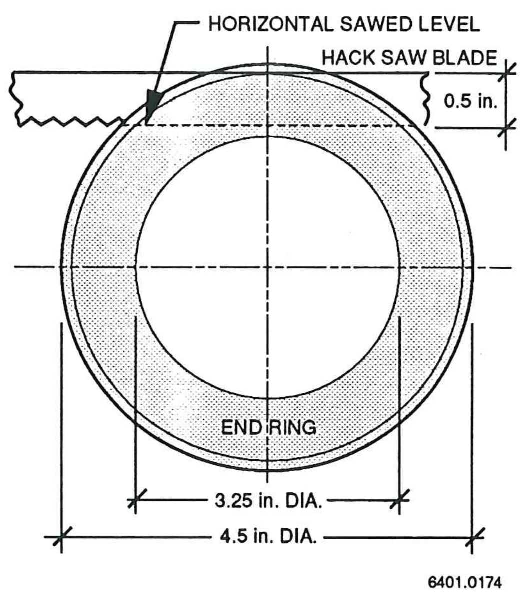

Fig. 10. One end of rotor bars of the sample motor is partially sawed

Fig. 11 shows the line current i_A. Fig. 12 clearly shows the existence of a double-slip-frequency, air-gap torque pulsation for the sample motor with a defective cage. The slip, s, is calculated from the rotor speed denoted by rpm, and the supply frequency f.

$$s = \frac{\frac{120 \cdot f}{P} - rpm}{\frac{120 \cdot f}{P}}$$

For the sample 4-pole, 60-Hz motor operating at 1748 rpm, the double slip frequency is $2 \cdot s \cdot f = 3.5$ Hz. It is advisable to have at least one full cycle of the double slip frequency for the Fourier analysis of its torque component. A frequency domain scanning of air-gap torque should indicate its components at various frequencies.

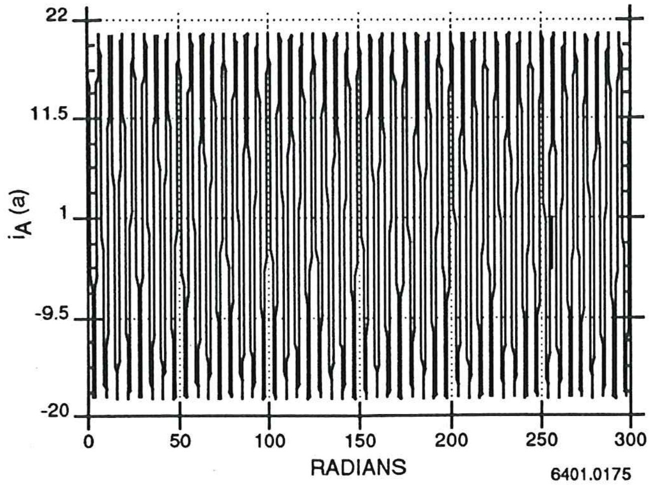

Fig. 11. Line current i_A of sample motor with defective cage

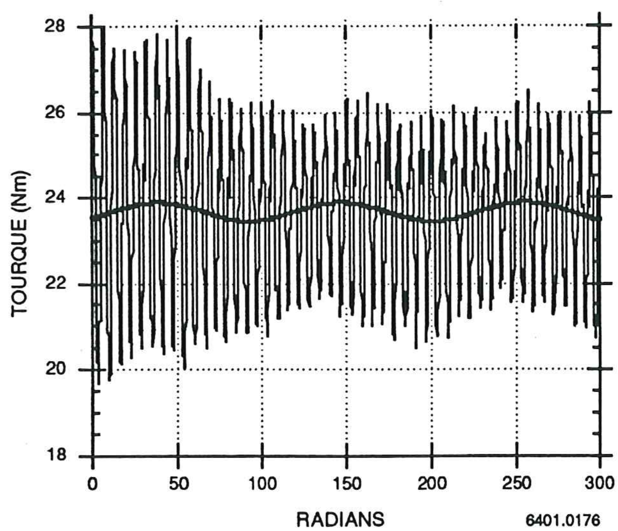

Fig. 12. Air-gap torque with double slip frequency component

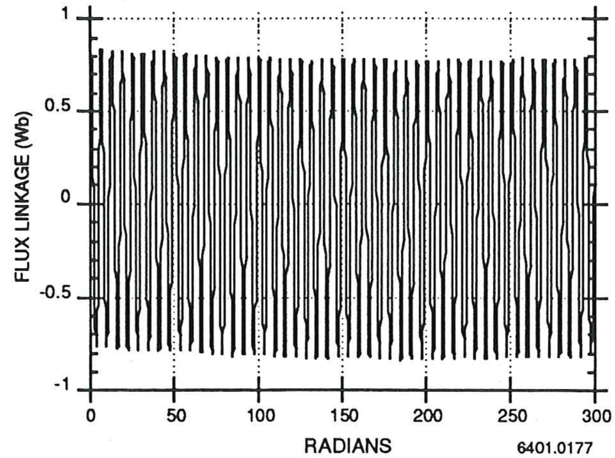

Fig. 13. Flux linkage corresponding to integral of line CA of sample motor with defective rotor cage

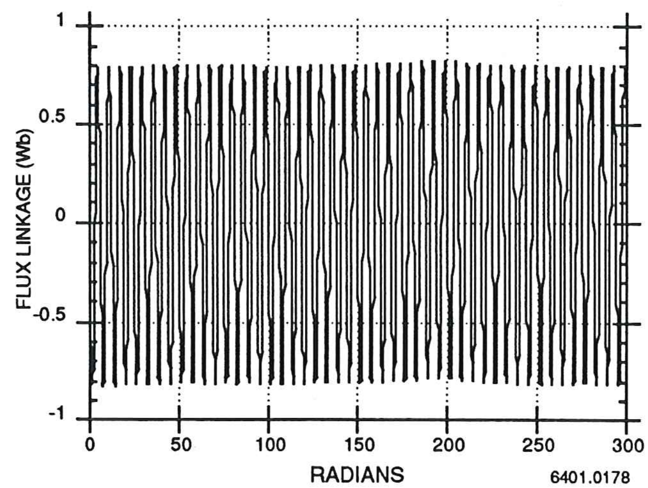

Fig. 14. Flux linkage corresponding to integral of line AB of sample motor with defective rotor cage

Figs. 13 and 14 show the flux linkages corresponding to the integrals for lines CA and AB, respectively, of the sample motor with a defective cage.

IV. Conclusions

Air-gap torque is the torque produced by the flux linkages and the currents of a rotating machine. Generally speaking, the air-gap torque is different from the torque measured from the shaft.

Air-gap torque is sensitive to an unbalance created by defects. Shape of the air-gap torque distinguishes whether the unbalance is caused by the cracked rotor bars or by unbalanced stator windings.

Air-gap torque can be measured while the motor is running. No down time is required for measurement. This can be financially attractive to many industries that unexpected down time of an induction motor, such as those used in power generation plants, posts a huge loss in production.

Instrumentation required for the air-gap torque measure is simple. Data can be stored in a magnetic floppy disc, and the waveform of the present air-gap torque can be compared with previous records.

Time required for a measurement of the air-gap torque is generally short, especially, when a computer program is written for handling the raw data for the calculation of the air-gap torque.

Analysis is conducted on three extreme cases. They are: the normal operation, the single-phase stator, and the single-phase rotor situations. Defects of an induction motor are related to these extreme cases in various degrees.

Experiments conducted on a 5-hp motor clearly show the existence of a double-slip frequency, air-gap torque for a defective rotor and the double fundamental frequency for a defective stator. Detailed study on other potential possibilities that cannot be handled by examining only a line current will be presented in the near future.

The proposed method can be further extended for monitoring defects developed in other types of rotating machines.

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After his arrival in the United States in 1971, he worked in research and development areas for Emerson Electric Company and later for Westinghouse Electric Corporation. He established the technical innovations for the Westinghouse World Series motors. Many of his design programs are currently used by industry.

He served as head of the Rotating Machines and Power Electronics Program, Center for Energy Studies, the University of Texas at Austin for over four years. Presently, he is the manager of the Industrial Drive Program at the center for electromechanics at the University of Texas at Austin. He is the author or coauthor of over seventy technical publications and the inventor or co-inventor of six patents.

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