DRAFT

ORIGINAL

Shaft Signals Corresponding to Cracked Rotor Bars of Induction Machines

John S. Hsu (Htsui)
IEEE Senior Member
Center for Electromechanics
The University of Texas at Austin
BRC, Mail Code 77000
Austin, TX 78712

John H. Gully

Center for Electromechanics
The University of Texas at Austin
BRC, Mail Code 77000
Austin, TX 78712

Key words: cracked bar, induction machine, rotor, shaft signal, broken cage, detection

***Abstract* -- Ratings of induction machines range from tens of thousands horsepowers to fractional horsepowers. Unexpected downtime of large induction motors, such as those used in power plants, can be very costly. Cracked rotor bars of induction machines may overheat rotors, lower outputs, and cause non-retrievable damages.**

This study presents a new observation that links shaft signals to cracked rotor bars. Theoretical foundation for this observation is derived. Experimental results clearly confirm the theory that under loaded conditions, double-slip-frequency shaft signals can be detected while there are cracked rotor bars in induction machines.

The new method suggested in this study is simple and reliable. No disassembling is required.

I. Introduction

Induction motors are the most popular motors in electric drives. Their ratings range from tens of thousands horsepowers to fractional horsepowers. It is commonly agreeable that unexpected downtime of large induction motors, such as those used in power plants, can be very costly. This method provides a mean to give early warnings on eccentricities and cracked rotor bars of induction machines without shutting down or disassembling for examinations.

Shaft voltages and currents have been noticed for many years [1-4]. Using shaft voltages for detecting defects in turbogenerators [3,4] has been proposed recently. The method presented in this paper for induction machines is new. Unlike turbogenerators, induction machines do not run at synchronous speeds.

This new method differs from the air-gap torque approach for detecting defects of induction motors [5]. This technology may be used simultaneously with the air-gap torque method to increase the detection reliability. This method is different from the existing commercial methods that are based on various identifications of side bands of a line current [7, 8].

This detection is associated with eccentricities, literatures on eccentricity topics are given in references [10-13].

II. Theoretical Derivations

A. Relationship between shaft signals and eccentricities

Air gaps of induction motors are small. It is rather difficult to locate rotors absolutely without any eccentricities. Even with an absolutely centered rotor, local stray short-circuited paths in punching stacks may cause asymmetries. Hence, shaft voltages occur. Fig. 1 shows that under situations with eccentricities, portion of the rotating flux is linked with shaft and generates shaft voltages. The main frequency of shaft voltages is the rotating field's frequency.

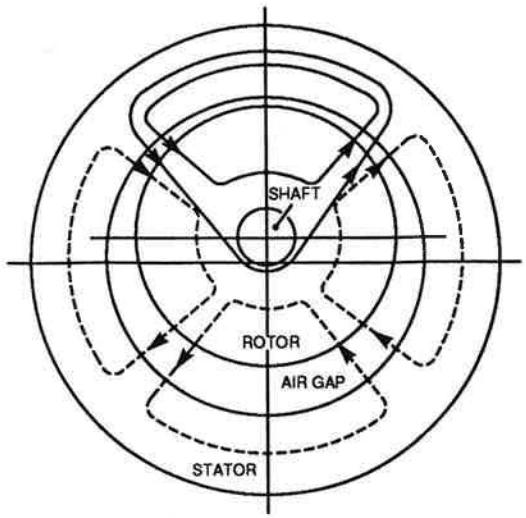

Fig. 1. Shaft flux linkages with respect to air gap rotating fluxes

B. Slip-Frequency Rotor Currents and Rotating Fields Associated with Cracked Rotor Bars

Major rotor-current frequency of induction motors is slip frequency that equals the product of slip, s, and line frequency, f. Fig. 2 shows that under normal operation with symmetrical multiphase rotor windings, the rotating field generated by rotor currents and viewed from rotor itself rotates at electrical angular speed

$$s \cdot \omega_S$$

where

$$\omega_S = 2 \cdot \pi \cdot f.$$

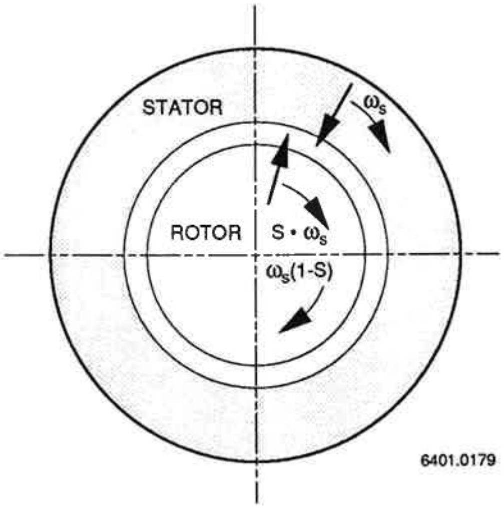

Fig. 2. Stator and rotor rotating fields under normal operation

When rotor has cracked bars, the rotor windings are not symmetrical. Hence, a single-phase rotor winding component appears. Fig. 3 shows that the single-phase winding component produces a forward and a backward rotor field rotating at electrical angular speeds, $+s \cdot \omega_S$ and $-s \cdot \omega_S$, with reference to the rotor. The rotor angular speed is $(1-s) \cdot \omega_S$. Adding the rotor angular speed to the rotor-field angular speeds gives the angular speeds of two rotor fields viewed from the stator. They are:

$$(1-s) \cdot \omega_S + s \cdot \omega_S = \omega_S$$

and

$$(1-s) \cdot \omega_S - s \cdot \omega_S = (1-2 \cdot s) \cdot \omega_S$$

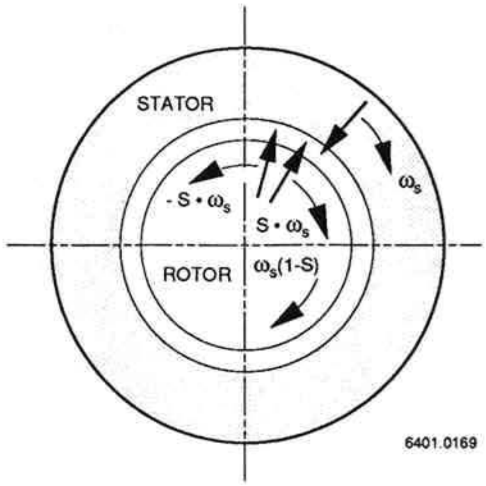

Fig. 3. Stator and rotor rotating fields under a single phase rotor situation

C. Double-Slip-Frequency Shaft Signals Corresponding to Cracked Rotor Bars under Eccentricities

When induction machines are loaded, the rotor currents become relatively significant than those of no-loads. If a machine has eccentricities, the frequencies of shaft signals reflect those of the rotating fields. For an induction machine with cracked rotor bars, the resultant rotating field contains a component that is the sum of the backward rotor-current field rotating at electrical angular speed, $(1-2 \cdot s) \cdot \omega_S$, and the main field rotating at ω_S.

A component of resultant rotating field

$$= \sin [p \cdot \vartheta - (1-2 \cdot s) \cdot \omega_S \cdot t] + \sin[p \cdot \vartheta - \omega_S \cdot t] \qquad (1)$$

where

p = number of pole pairs.
ϑ = angular position in mechanical degrees

Simplification of (1) gives a component of resultant rotating field

$$= \sin[p\cdot\vartheta - \omega_S \cdot t] \cdot \cos[2\cdot s\cdot\omega_S\cdot t] + \cos[p\cdot\vartheta - \omega_S \cdot t] \cdot \sin[2\cdot s\cdot\omega_S\cdot t] + \sin[p\cdot\vartheta - \omega_S \cdot t] \quad (2)$$

Equation (2) clearly shows that the main rotating field rotating at synchronous angular speed, ω_S, is partly modulated by a double-slip-frequency, $2\cdot s\cdot\omega_S$, envelop.

III. Experimental Setup

Fig. 4 shows a setup for the signal measurements. For large induction machines, insulated bearings and/or insulated couplings are commonly used to prevent shaft currents. Shaft voltage signals can readily be obtained without disassembling the machines. Hardware needed for picking up shaft signals of a machine are two brushes and holders. Experimental works shown in this study are conducted with both insulated bearings and non-insulated bearings. The lubricant films of bearings act as sufficient insulation for the shaft signals of the experimental machines. Hence, this method may be used for machines without insulated bearings. However, additional works are being conducted for further confirmations on larger frames.

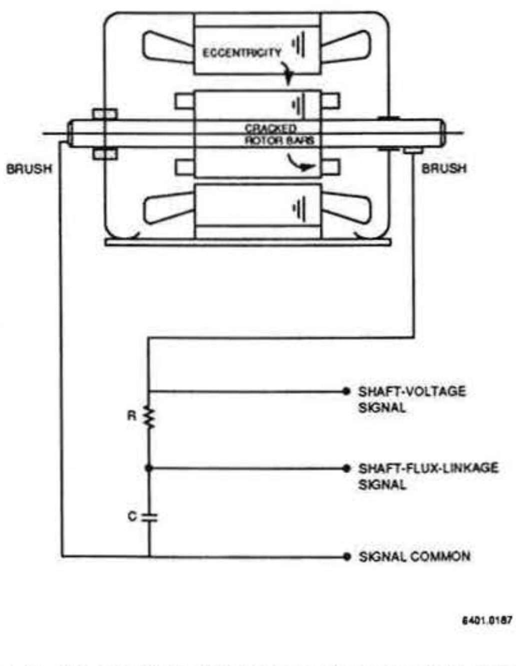

Fig. 4. Measurements of shaft voltage and shaft flux linkage

IV. Tested Shaft Voltages and Flux Linkages

Fig. 5 compares shaft flux linkages (and voltages) between a normal good rotor and a rotor with cracked rotor bars of two induction motor assemblies that use the same stator successively. The two assemblies are tested under the same load. When the rotor has cracked bars, the envelop of the shaft flux linkage as shown in Fig. 5b clearly depicts the envelop of two times the slip frequency. Fig. 5a shows that there is no such an envelop under the same load when the rotor is good.

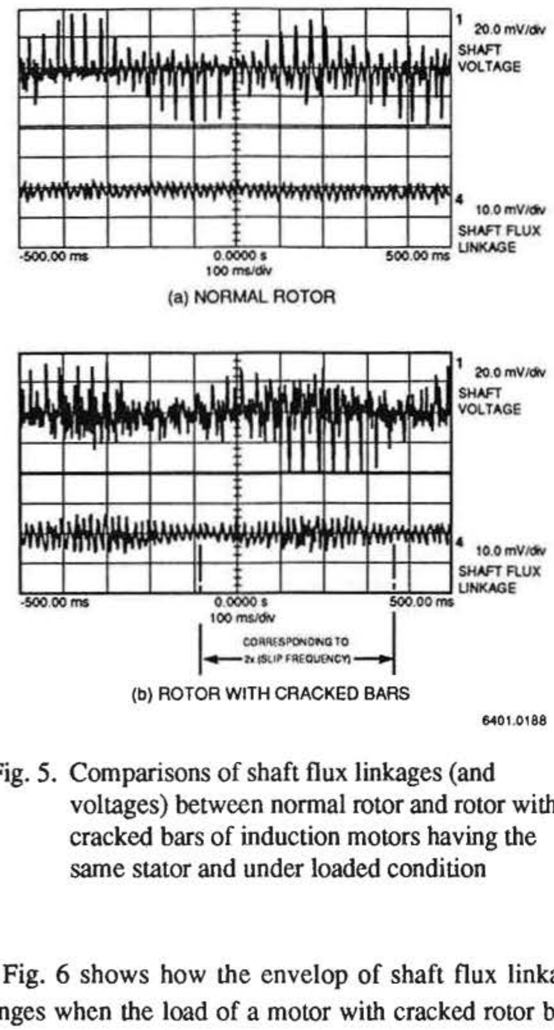

Fig. 5. Comparisons of shaft flux linkages (and voltages) between normal rotor and rotor with cracked bars of induction motors having the same stator and under loaded condition

Fig. 6 shows how the envelop of shaft flux linkage changes when the load of a motor with cracked rotor bars changes. For a heavier load the slip goes up, hence, as illustrated in Fig. 6b the envelop frequency of two times the slip frequency unmistakably increases.

Fig. 7 shows the comparisons of shaft flux linkages between two different eccentricities of a motor under a loaded condition. The magnitude of shaft flux linkage goes up when there is greater eccentricity.

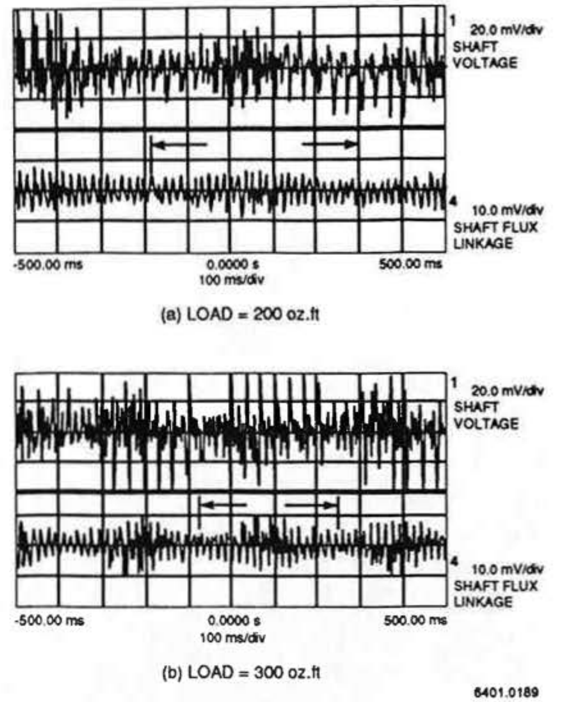

Fig. 6. Comparisons of shaft flux linkages (and voltages) under different loads and subsequently different slips of an induction motor with cracked rotor bars

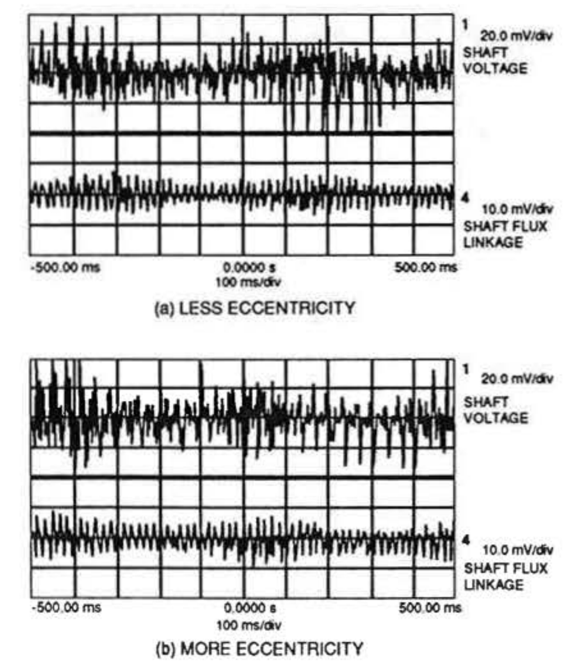

Fig. 7. Comparisons of shaft flux linkages (and voltages) between less and more eccentricities of an induction motor under loaded condition

V. Conclusions

Cracked rotor bars of induction machines may overheat rotors, lower outputs, and cause non-retrievable damages.

This paper presents a unique observation that links shaft signals to the cracked rotor bars of induction machines. Theoretical foundation for this observation is derived. Experimental results clearly confirm the theory that under loaded conditions, double-slip-frequency shaft signals, which modulate shaft voltages and shaft-flux linkages, can be detected while there are cracked rotor bars in induction machines. The magnitude of shaft flux linkage goes up when there is greater eccentricity.

The new method suggested in this study is simple and reliable. No disassembling is required. Instrumentation can be developed according to this new method.

VI. Acknowledgments

The authors would like to thank the State of Texas for financial support through a grant under Texas Advanced Technology Program, Grant No. 1591 and 003658-181. Thanks are due to the Center for Electromechanics, The University of Texas at Austin, for the support staff and facilities provided for the research work. The typography was conducted by Ms. Lori Moore. Finally, the authors would like to express their appreciations to Prof. William F. Weldon and Dr. Herbert H. Woodson for their supports and discussions in this research.

References

[1] P. L. Alger, H. W. Samson, "Shaft Currents in Electric Machines," Transactions AIEE, February 1924, pp. 235-245.

[2] S. P. Verma, R. S. Girgis, "Shaft Potentials and Currents in Large Turbo Generators," Report for the Canadian Electrical Association, Research & Development, Suite 580, One Westmount Square, Montreal, Quebec, H3Z 2P9, May 1981.

[3] A. Meyer, R. Joho, Z. Posedel, K. Reichert, C. Ammann, "Shaft Voltages in Turbosets: Recent Development of a New Grounding Design to Improve The Reliability of the Bearings," International Conference on Large High Voltage Electric Systems, 1988 Section, 28th August - 3rd September, Paris.

[4] C. Ammann, K. Reichert, and Z. Posedal, "Shaft Voltages in Turbosets: Operating Experience with RC-Grounding Device and New Possibilities for Monitoring the Condition of Turbogenerators,"

[5] John S. Hsu, "On-Line Monitoring of Defects Developing in Induction Motors through Air-Gap Torque Observation," Invention Disclosure, The University of Texas at Austin, UTSB506.

[6] G. B. Kliman, Rudolph A. A. Koegl, Max W. Schulz, Jr., "Rotor

Fault Detector for Induction Motors," United States Patent No. 4,761,703, August 2, 1988.

[7] G. B. Kliman, "Spectral Analysis of Induction Motor Current to Detect Rotor Faults with Reduced False Alarm," United States Patent No. 5,049,815, September 17, 1991.

[8] J. Martin, D. Rankin, "Critical Maintenance Evaluation and Industrial Application of ON-Line Phase Current Analysis to Detect Rotor Winding Faults in Induction Motors," Proceedings of the 25th University Power Engineering Conference, pp. 771-4, vol. 2, Robert Gordon, Aberdeen, U. K., 1990.

[9] J. L. Kohler, J. Sottile, F. C. Trutt, "Alternatives for Assessing the Electrical Integrity of Induction Motors," IEEE, IAS Conference Record, 1989, vol.2, pp 1580-6.

[10] John S. Hsu, "Detections of Eccentricities and Cracked Rotor Bars of Induction Machines through Shaft-Voltage and Shaft-Flux-Linkage Signals," Invention Disclosure, The University of Texas at Austin.

[11] G. B. Pollock, J. F. Lyles, "Vertical Hydraulic Generators Experience with Dynamic Air Gap Monitoring," IEEE Transactions on Energy Conversion, Vol. 7, No. 4, December 1992, pp. 660-7.

[12] J. R. Cameron, W. T. Thomson, A. B. Dow, "Vibration and Current Monitoring for Detecting Air Gap Eccentricity in Large Induction Motors," IEE Proceedings, Vol. 133, Pt. B, No. 3, May, 1986, pp. 155-163.

[13] A. J. Marques Cardoso, E. S. Saraiva, M. L. Sousa Mateus, A. L. Ramalho, "On-Line detection of Air Gap Eccentricity in 3-phase Induction Motors by Park's Vector Approach," Fifth International Conference on Electrical Machines and Drives, Conference Publication No. 341, 11-13 September 1991, pp. 61-66.

John S. Hsu (or Htsui) was born in China. He received a BS degree from Tsing-Hua University, Beijing, China, and a PhD degree from Bristol University, England, in 1959 and 1969, respectively. He joined the Electrical and Electronics Engineering Department of Bradford University, England, serving there for nearly two years.

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 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 a researcher at the Center for Electromechanics at The University of Texas at Austin.

Dr. Hsu is a chartered engineer in the United Kingdom and a registered professional engineer in Texas, Missouri, and New York.

Mr. John Gully has been a member of the professional staff of the Center for Electromechanics at The University of Texas at Austin (CEM-UT) since its establishment in 1977 and from 1975 to 1977 he was a member of its predecessor organization, the Energy Storage Group. Mr. Gully is currently managing the CEM-UT Industrial Applications Program. This includes the development and transfer to industry of advanced high energy, high rate processes such as pulsed welding, pulsed powder consolidation and electrospraying.

Mr. Gully has served as the CEM-UT engineering and laboratory manager since 1979. In 1983 he became Associate Technical Director, and in 1984 was promoted to the position of Deputy Director. His research specialty is machine design, with particular interest in high speed bearings and seals, rotors, and current collection. Mr. Gully was chairman of the 1987 International Current Collector Conference. At this time he has six patented concepts and two patent applications. He is a member of Tau Beta Pi, the author or co-author of more than 45 technical publications and a Registered Engineer in Texas, and has been selected for inclusion in the 17th edition of AMERICAN MEN & WOMEN OF SCIENCE.