Diagnostics of Bar and End-Ring Connector Breakage Faults in Polyphase Induction Motors Through a Novel Dual Track of Time-Series Data Mining and Time-Stepping Coupled FE-State Space Modeling

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Summary

Abstract: This paper develops the fundamental foundations of a technique for detection of faults in induction motors that is not based on the traditional Fourier transform frequency domain approach. The technique can extensively and economically characterize and predict faults from the induction machine adjustable speed drive design data. This is done through the development of dual-track proof-of-principle studies of fault simulation and identification. These studies are performed using our proven Time Stepping Coupled Finite Element-State Space method to generate fault case data. Then, the fault cases are classified by their inherent characteristics, so called "signatures" or "fingerprints." These fault signatures are extracted or mined here from the fault case data using our novel Time Series Data Mining technique. The dual-track of generating fault data and mining fault signatures was tested here on 3, 6, and 9 broken bar and broken end ring connectors in a 208-volt, 60-Hz, 4-pole, 1.2-hp, squirrel cage 3-phase induction motor.

I. THE METHODOLOGY

Three-phase induction motors are presently in common use as the machine of choice in a majority of electronically controlled adjustable/variable speed drives (ASDs). During the past twenty years, there have been continuing efforts at studying and diagnosing of induction motor faults and associated performance characteristics [1]. As stated in [1] "performing reliable and accurate fault detection and diagnosis requires understanding the cause and effect of motor faults to motor performances." Accordingly, this paper demonstrates a method for detection of faults in induction machine adjustable speed drives (IMASDs).

Our approach to the problem of diagnosing faults in IMASDs is new and unique. First, we can generate data for a plethora of fault conditions by Time Stepping Coupled Finite Element-State Space (TSCFE-SS) simulations [2-6] without the need to encounter and acquire data for faults in actual field experience with IMASDs. Second, through data mining, hidden patterns and nuances of differences between healthy performance and various fault signatures are automatically and efficiently identified and made use of in fault identification and prediction.

This paper presents the development of the conceptual framework and proof-of-principle for a comprehensive set of algorithms for fault simulation, and fault identification/diagnosis in IMASDs. This proactive approach can head off the costly and catastrophic cascading of faults that lead to plant shutdowns and consequent long repair/maintenance periods. The resulting fault identification and diagnostic information also can facilitate the creation of efficient and effective maintenance schedules.

The faulty operations include, but are not restricted to the following:

1. Broken bars and/or end-ring connectors in the squirrel-cages of induction motors [2],
2. Dynamic and static airgap eccentricities arising from assembly defects or subsequent mechanical/bearing problems that may develop in the field during operation [3], and
3. Phase unbalances in stator armatures developing due to partial internal turn-to-turn short circuits, or phase unbalances resulting from unbalances in the inverter power electronic portion of a drive, or other phase voltage unbalances due to factors external to IMASD systems.

In this summary only the first type of these faults, namely broken squirrel-cage bars and end-ring connectors are addressed.

The study of the effects of such faulty operations occurs through a dual track. The first track generates databases of fault signature profiles through TSCFE-SS simulation of healthy and faulty modes of operation of IMASDs [2-6]. The advantage of this method lies in its rigor in predicting effects of motor faults, including the incipient variety, on performance. The second track identifies and extracts hidden patterns and nuances that are characteristic and predictive of faults and incipient faults through Time Series Data Mining (TSDM) [7, 8] of the fault signatures.

The TSCFE-SS technique computes on a time instant-by-instant basis the input phase and line currents, voltages, and developed powers (torque) of a motor as functions of the particular magnetic circuit, winding layouts, and materials as well as inverter (power conditioner) operating conditions. Computations include ohmic and magnetic core losses as well as the effects due to modern fast electronic switching on overall motor-controller/drive interaction and resulting performance [6, 9]. Thus, the TSCFE-SS algorithms can be used in parametric studies.

The TSCFE-SS aspect fully incorporates the nonlinear effects of magnetic saturation in the machine and makes full use of the natural machine winding's frame of reference [2-6], see Figure 1 for the functional flow chart block diagram summarizing the essence of this approach. Hence, this assures inclusion of all significant space harmonics due to the physical design and nonlinear nature of the motor as well as the time harmonics generated from the inverter switching in the motor-drive modeling and simulations. Accordingly, the simulated fault signatures are derived from time domain phase current, voltage waveforms, and from simulated instantaneous torque profiles that rigorously incorporate the motors' design characteristics.

The validity of this simulation was verified by actual laboratory tests results on balanced sinusoidal 3-phase, 208-volt (line-to-line) and inverter sources, which were reported in detail in references [4-6, 10, 11].

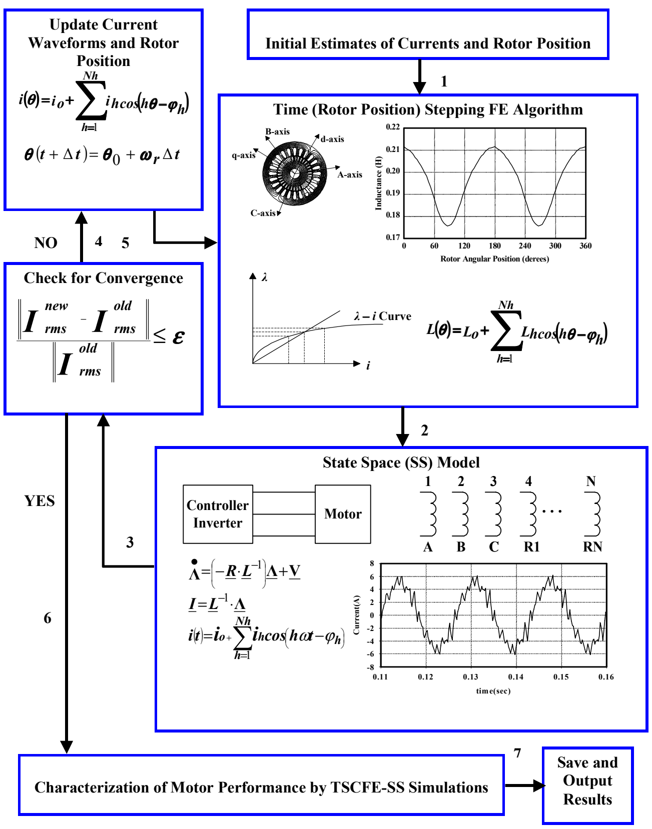

Figure 1 – Functional Block-Diagram/Flow Chart of the TSCFE-SS Method

II. APPLICATION AND RESULTS

The TSCFE-SS algorithm was used to simulate two types of faults (1): 3, 6, and 9 adjacent broken squirrel-cage bars, and (2): 3, 6, and 9 adjacent broken squirrel-cage end-ring connectors. Only the three bar and connector results are given in this summary.

The phase current waveforms for the healthy motor case and the cases with three broken bars and three broken connectors are given here in Figures 2 through 4 respectively, see references [2, 9, 11]. In this work, the TSCFE-SS based model is used to generate the necessary database of motor current, voltage, and torque waveforms and profiles under healthy and faulty motor conditions.

The TSDM technique extracts fault signatures indicative of faults from the waveforms generated by the TSCFE-SS module. The TSDM method overcomes limitations (including stationarity and linearity requirements) of traditional time series analysis techniques by adapting data mining concepts for analyzing time series. Based soundly in dynamical systems theory [12], the TSDM method reveals hidden patterns in time series data.

A process called time-delay embedding [13] is used to transform the current time series into a reconstructed state space, also called a phase-space. Given the current time series $I=\{i(k), k=1,\ldots,N\}$, where k is a time index, and N is the number of observations, a two dimensional phase-space is created by plotting $i(k\text{-}10)$ on the x-y plane's abscissa and $i(k)$ on the ordinate. The resulting phase-spaces are given for the healthy cage case, the three broken bar case, and the three broken connector case in Figures 5, 6, and 7, respectively, for the current time series (waveforms) given in Figures 2, 3, and 4, respectively.

On a one to one correspondence basis, the reader can distinctly see a difference in pattern between the healthy cage case of Figure 5 and the two faulty cage cases of Figures 6 and 7. However, a distinction between the patterns of the phase-space for the three broken bars, Figure 6, and the phase-space for the three broken connectors, Figure 7, is not at once obvious.

The TSCFE-SS model simulation resulted in time-domain torque profiles [2, 11], shown in Figures 8 through 10, for the healthy, the three broken bar, and the three broken end-ring connectors cases, respectively. A first difference time series, $\Delta\tau(k) = \{\tau(k) - \tau(k\text{-}1)\}$, was generated from each of the three torque time series, which are illustrated in Figures 8 though 10. Time-delay embedding was then applied to the torque first difference time series. The resulting phase-spaces are shown in Figures 11, 12, and 13, respectively. The distinction in shape between the three torque first difference phase-spaces is strikingly obvious at first glance. This suggests that monitoring of torque for fault diagnosis and detection can be exploited as a powerful diagnostic tool, at least in critical motor drive systems.

These visual differences, obvious at first glance, are automatically extracted using our TSDM techniques. These techniques search the phase space for hyperspherical regions that are maximally distinguishable. That is regions that maximize $|c(P_1)-c(P_2)|$, where P_1 represents the set of points from one time series (for example the healthy torque first differences time series) contained in a hyperspherical region, and P_2 represents points from another time series, meanwhile $c(*)$ is the cardinality operator.

A genetic algorithm was used to find the desired hyperspherical regions. Examples of such regions are shown in Figures 11, 12, and 13. In Figure 11, the solid circles indicate a healthy condition. In Figure 12, the solid circles indicate a 3 broken bars fault. In Figure 13, the solid circles indicate a three broken end-ring connectors fault type. These hyperspherical regions were verified on out-of-sample portions of the torque time series to ascertain the validity of this approach.

III. CONCLUSIONS

The above demonstrates a method that potentially can be incorporated in drive software to diagnose faults in the field. Additional studies will be reported in the literature.

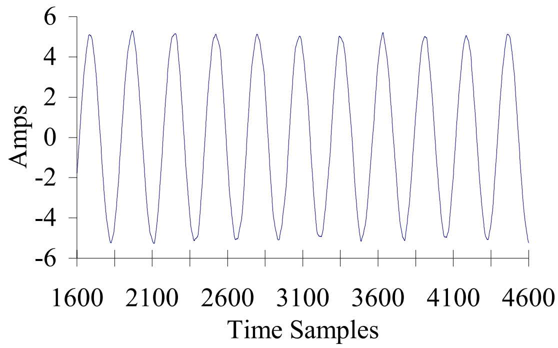

Figure 2 – Phase Current for Healthy Motor

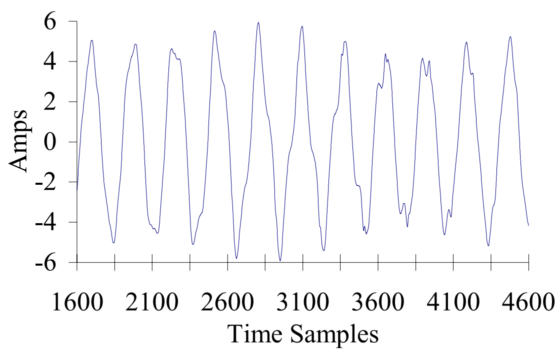

Figure 3 – Phase Current for Three Adjacent Broken Bars

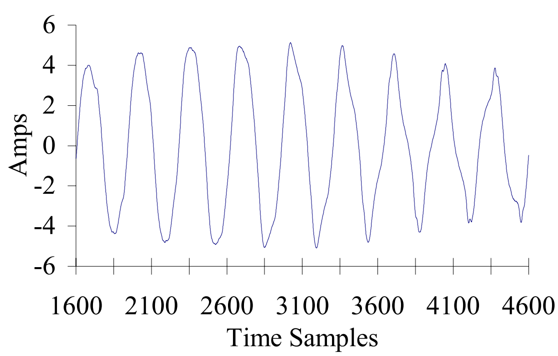

Figure 4 – Phase Current for Three Adjacent Broken Connectors

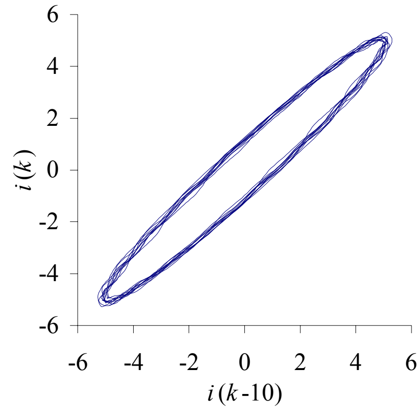

Figure 5 – Phase-Space for Healthy Motor Current

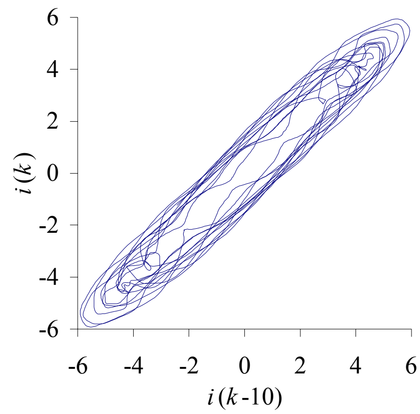

Figure 6 – Phase-Space for Three Adjacent Broken Bars Current

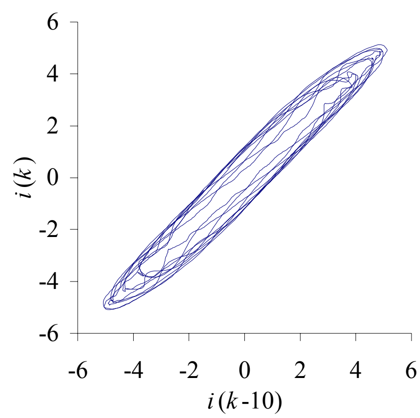

Figure 7 – Phase-Space for Three Adjacent Broken Connectors Current

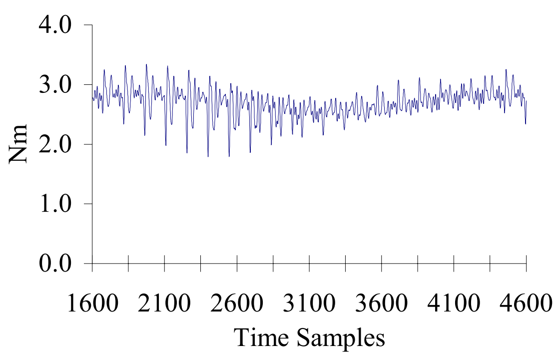

Figure 8 – Torque Profile for Healthy Motor

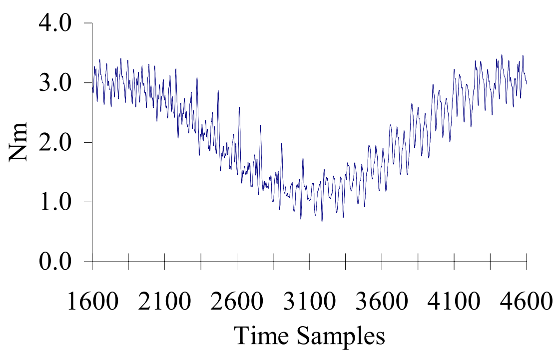

Figure 9 – Torque Profile for Three Adjacent Broken Bars

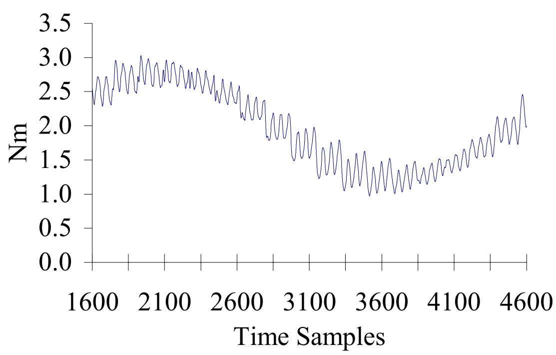

Figure 10 – Torque Profile for Three Adjacent Broken Connectors

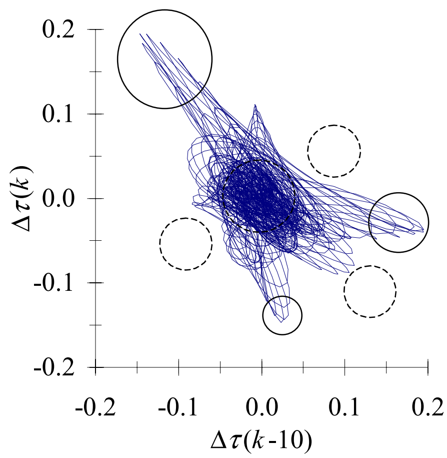

Figure 11 – Phase-Space for Healthy Motor Torque First Difference

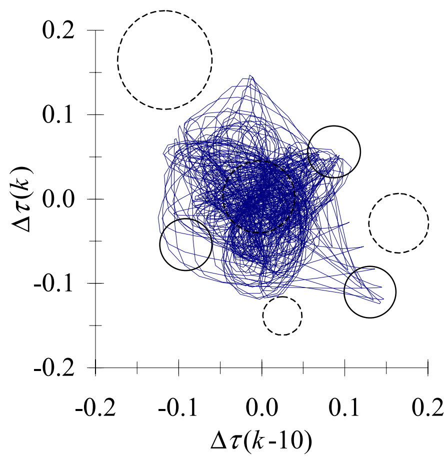

Figure 12 – Phase-Space for Three Adjacent Broken Bars Torque First Difference

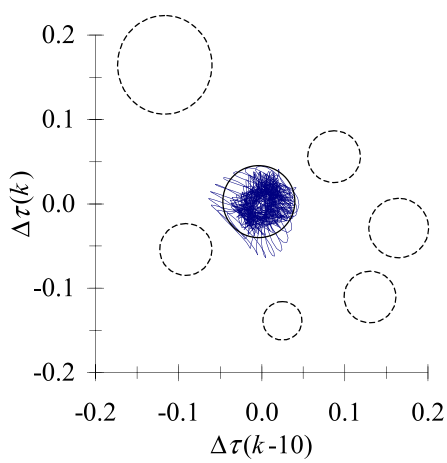

Figure 13 – Phase-Space for Three Adjacent Broken Connectors Torque First Difference

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