Diagnostic and model validation of a faulty induction motor drive via wavelet decomposition

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***Index Terms* -- Wavelet transforms, multi-resolution analysis, computer modeling, state equations.**

I. INTRODUCTION

THE problems of low-cost diagnostic systems and model validation can be interpreted within the same framework: identification of significant information in the signals. The system under consideration in this work is an induction motor drive. A desirable low-cost diagnostic method would allow the extraction of information about healthy or faulty operating conditions from measurement that are external to the box of the drive and that would be performed anyway. In particular, the current at the AC side of the device is measured for the purpose. This method is intended for the identification of dramatic faults, such as incipient opening of a stator phase. The problem investigated in this perspective is therefore the amount of information concerning the fault that can be extracted from AC side current and what is a convenient method that isolates the desired information. In the field of validation of models for advanced simulation environments, the problem is to find a method to compare the simulated signal and its effects on other parts of the system with the actual signal and its actual effects of other parts of the system.

The method proposed in this work relies on the comparison between the coefficients resulting from the wavelet decomposition of the signals. This approach allows the identification of the main information contribution among the various time instants and scale (frequency) ranges. This study can provide insight on the information content of the variables at a specified stage of the complex system, helping the designer in choosing the trade-off between available information and cost of the acquisition and processing.

II. THE PRINCIPLE OF THE PROPOSED APPROACH

The target system of this work is an induction motor drive. This is a rather common element of complex systems and is readily available for laboratory testing in a variety of operating conditions. Having in mind the recent trend to more and more integrated systems, where the drive can be considered as a "black-box", we assume that the only accessible points of the system are the AC input terminals, Fig. 1~~Fig. 1~~.

In what follows the underling philosophy of the work and the method will be presented.

A variety of faults can occur within the system downstream from the AC side, such as bearings and bars faults, loose connections, failure of power switches. In a wider perspective, the aim of the study of which this work is part, is the development of very complete and multi-physics simulation models that allow the simulation of the motor drive in a variety of faulty conditions. As a consequence of the coupling between electrical mechanical

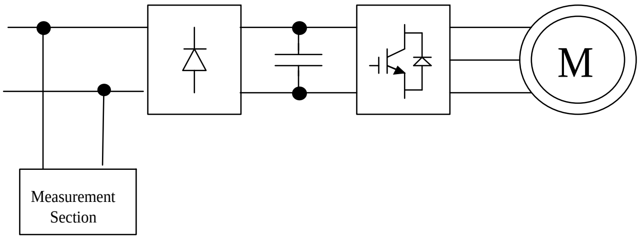

Fig. 1: scheme of the system under consideration

and thermal features, the simulation would provide insight of the phenomenon and of the consequences of the fault.

The study of the faulty behaviour for implementation purpose and the availability of a complete simulation, provides insight about the amount of information related to the fault that is reflected at the AC side. This knowledge may have consequences on the design of a monitoring and diagnostic system for an induction motor drive. This knowledge can constitute a guideline for a trade off between the complexity (and cost) of the monitoring system and the capability to identify faults. Among the variety of faults that may occur, the author selected, for this introductory part of the study, the case of variable stator phase resistance.

The simulation setup provide data to identify the information content of the AC side current concerning an open or nearly-open stator phase. The same setup will be tested on an actual system for validation purpose.

The method used in this work to perform a comparison for validation purpose relies on the comparison between the wavelet decomposition coefficients. In first place the comparison is performed between the wavelet coefficient of the current in healthy conditions and in faulty conditions, for the identification of the fault related information carried by the wavelet coefficients. Then the comparison will be performed between the wavelet coefficients of the actual and simulated system. Wavelet decompositions have the capability to identify the signature of a signal. In this particular case, a variation of resistance in one stator phase is reflected as a distortion of the current waveform at the AC side. This distortion can be detected through the wavelet decomposition of the current when compared to a standard healthy case.

Preliminary results in case of total loss of one of the stator or rotor phases are presented in literature [13]. The reported results refer to a dramatic fault case. The wavelet decomposition is used for fault identification. In the present work a more refined fault case is considered. The capability of the presented approach to distinguish much lighter faults is here investigated.

The conclusions drawn from the proposed study present therefore a double advantage. If the decomposition is able to point out the fault information reflected at the AC side then the wavelet decomposition is also a convenient domain within which to perform diagnostics tasks. In addition the wavelet decomposition is a convenient domain within which to perform validation of simulated systems.

III. THE SIMULATION ENVIRONMENT

All the considerations introduced above concerning the need for strong integration between simulation and design and between different characteristics of the same system, i.e. electrical, mechanical, chemical, suggest the desirability of a new high-level interface that allows many types of users to be comfortable with the virtual prototyping tool. A significant contribution towards the development of such a tool has been underway at the University of South Carolina for several years now under the program named Virtual Test Bed (VTB), [5][6].

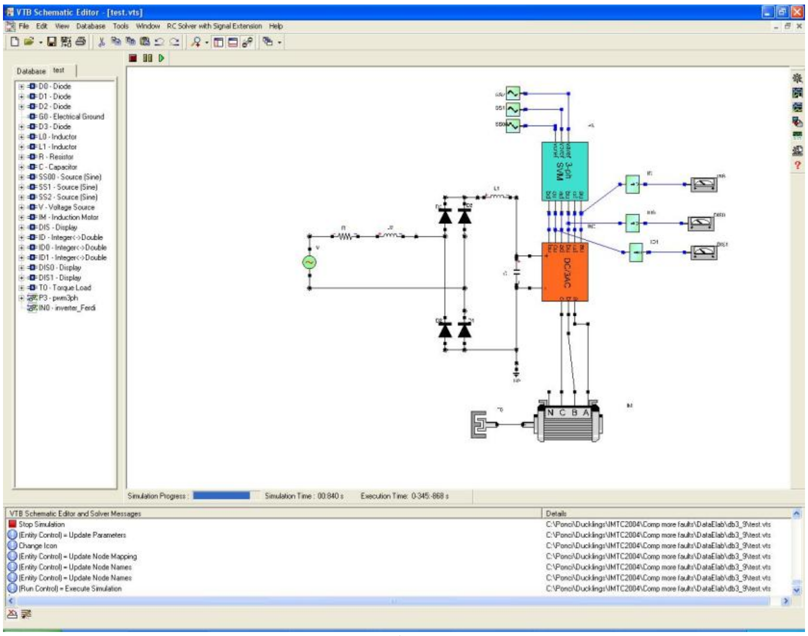

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Fig. 2: VTB schematic of the induction motor drive

The VTB approach solves the traditional dichotomy in modeling that universally plagues designers, allowing them now to use a proper instrument for each part of the system design problem. In contrast, classical simulators, where a single specification language is available to the users, really limit the analysis of such systems.

The VTB schematic of the drive used in simulation is reported in Fig. 2~~Fig. 2~~.

The model of the induction motor allows the modification of the values of stator resistance for every phase. The simulations was performed using the nominal value of Rs=0.531Ω, same value for every phase, for the normal operating condition. Then the resistance of one phase of the stator was modified and the following values were assigned time by time: Rs=0.7Ω, Rs=1Ω, Rs=4Ω, Rs=9Ω. The system was simulated from startup to 1s. The steady-state part of the signal was then isolated by inspection and decomposed in wavelet coefficients within a Matlab environment.

The fault case here considered is a change in stator phase resistance, as it may represent an incipient loss of connection. This fault case is trivial but it constitutes an interesting case study. A closed-form analysis to study the effect of resistance change is extremely difficult for the described system. If more complex systems and more sophisticated kind of faults are considered, a closed form analysis is not realistically achievable.

The variable chosen for analysis in this work is the current at the AC side of the drive. Satisfactory results have been obtained in the past following this path. Still the authors are considering the option of power signature analysis, reported in literature in [15].

For the purpose of analyzing the effects of a variable stator phase resistance on the AC current, the collected data are decomposed into a set of wavelet coefficients. The effects of this processing are to summarize the features of the signal in a set of significant coefficients and to provide with a flexible tool for time-frequency analysis. The Daubechies wavelets (6 coefficients) are chosen, being the corresponding wavelet decomposition easy to implement.

IV. THE WAVELET DOMAIN ANALYSIS

The AC side current signals of the actual system and of the simulated system are compared based on the wavelet decomposition coefficients.

Wavelets are particular functions whose energy is concentrated both in time and frequency [8], [9]. They come in structured families where each member of the family allows the analysis of the signal within a given range of frequencies and within a given interval of time .The narrower wavelets of the family, for example, allow a great time resolution analysis. The wavelet analysis leads to the representation of the signal at different detail level, both in terms of time and frequency. Among the potentialities of this representation, a major one is the possibility to choose independently the most convenient time-frequency resolution. The time resolution can be different at different frequencies (always in the limits of the Heisenberg principle). For example, a family can be chosen so that the time resolution is particularly fine at high frequencies, allowing the precise time identification of glitches or sudden very high frequency contents. On the other hand, the frequency resolution could be particularly good at lower frequencies, allowing the monitoring of the stability of the fundamental component. A wide variety of combinations of time-frequency resolution is possible and custom solution are made available by wavelet packets.

The approach proposed here involves the analysis of the signal through wavelet series decomposition. The decomposition results in a set of coefficients each carrying local time-frequency information. An orthogonal basis function is chosen, thus avoiding redundancy of information and allowing easy computation.

The computation of the wavelet series coefficients can be efficiently performed with the Mallat algorithm. The coefficients are computed processing the samples of the signal with a filter bank. The coefficients of the filters are peculiar of the family of wavelets used as expansion basis. This algorithm is fully discrete.

In this work the Daubechies3 wavelets (6 coefficient filter) are used. The levels of resolution are limited by the number of samples. Considering that the samples themselves can be considered as the highest possible resolution level, the decomposition is performed from this level of detail up to coarser levels. Consider the case in which 5 levels of wavelet decomposition are used: the decomposition results in 5 sets of wavelet coefficients plus the remaining summarized by the coefficients of the scaling function.

For the purpose of investigating the common patterns of AC side current in healthy and faulty conditions at the different resolution levels, the correlation between the wavelet coefficients was computed. From this comparison it is possible to identify at what time-frequency resolution level the main changes due to the incipient faults are concentrated.

In **Error! Reference source not found.**~~Fig. 3~~and **Error! Reference source not found.**~~Fig. 4~~ the correlation between wavelet coefficients of healthy and faulty conditions at different

levels are reported. It can be noticed that the heavier fault affects significantly all the orders while a light fault predominantly affects the coefficients at finer detail.

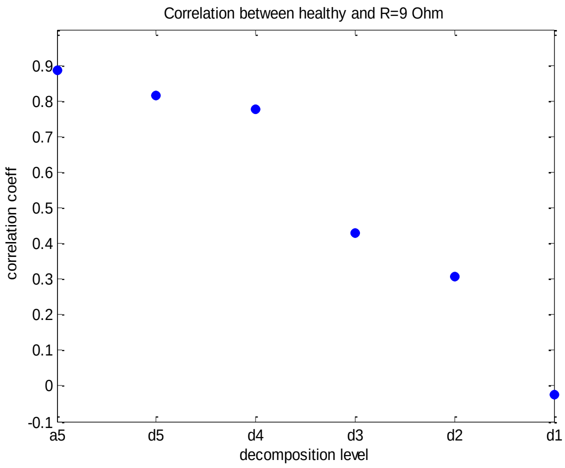

Fig. 3: correlation between wavelet coefficients in healthy condition and in incipient fault condition with R=9Ω

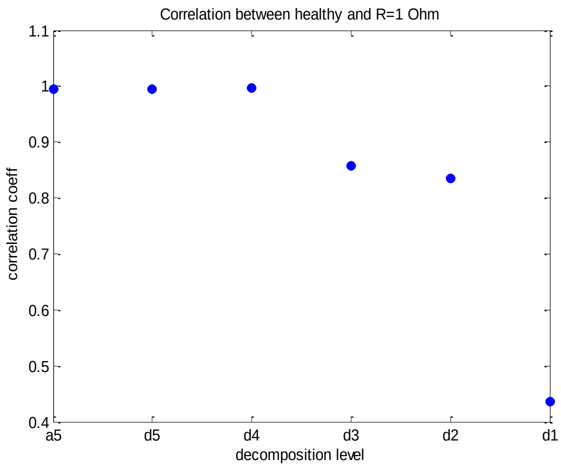

Fig. 4: correlation between wavelet coefficients in healthy condition and in incipient fault condition with R=1Ω

The direct comparison between the pattern of the coefficients at different decomposition levels is reported in Fig. 5. For any faulty condition, the correlation between the wavelet coefficients of healthy and faulty conditions is computed. For every faulty condition (on the x axis), one correlation coefficient for every level of resolution is computed (may be superimposed therefore non separately visible in some cases, e.g. d5 and d4 are correlated in the same way with the healthy case). It can be noticed, for example, that the correlation between healthy and faulty wavelet coefficients at level 4 is practically equal to one when the fault consist in stator phase resistance equal to 0.7Ω (~35% more than normal condition) and equal to 1Ω (~100% more than normal condition). This can be interpreted as non significant effect of the fault on the AC current at that scale. The autocorrelation healthy-healthy is reported for completeness and is equal to one at any level.

The same analysis presented above was performed using a more extensive decomposition. In particular 9 levels were examined. With 9 levels the wider wavelet has a width that is much larger that the period of the examined signal. With this analysis it is therefore possible to identify very low frequency oscillations.

The results are reported in **Error! Reference source not found.**~~Fig. 6~~. It is to be pointed out that the coefficients at certain level carry the information about the change in shape of the current at the AC side more than others.

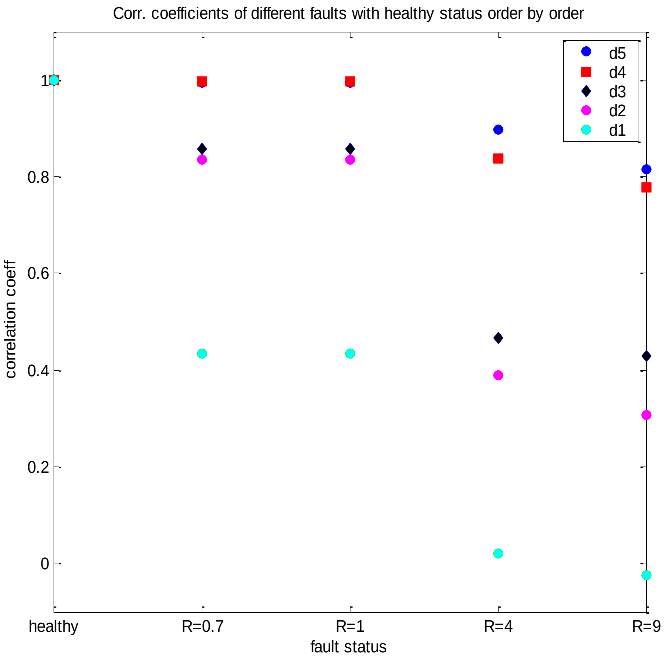

Fig. 5: comparison of correlation between healthy and faulty condition at different decomposition levels

The experimental set-up is already in place. An experimental set-up has been implemented to verify the proposed theory. A DSP-based system acquires the field signals and performs the diagnostic algorithms.

The line voltage – not used for wavelet decomposition - and current are acquired by an Analog-to-Digital conversion board (ADC), 8 input channels with simultaneous sampling up to 500 kHz sampling rate on a single channel, 10V range, 12-bit resolution and offset, gain and non-linearity error in the range ±½ LSB.

Voltage and current transducers have been specially realized in order to ensure an adequate insulation level between channels and between the supply and measuring devices over a wide band.

According to the input signal

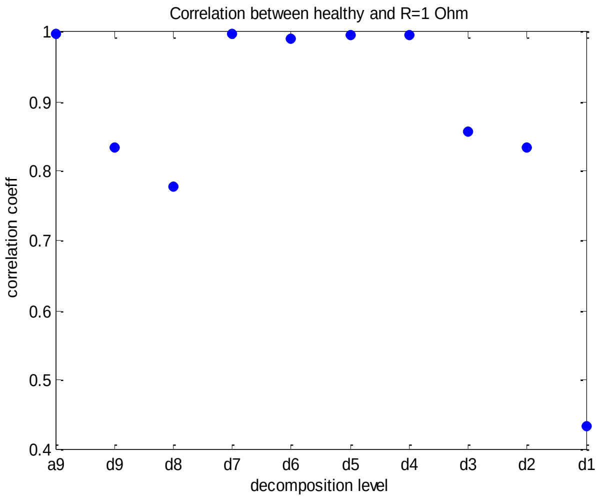

Fig. 6: correlation between healthy and faulty (R=1Ω) condition using 9 decomposition levels

range (230 V rms for the voltages and up to 20 A rms for the currents) a non-inductive, resistive voltage divider followed by an isolation amplifier was used as voltage transducer, and a closed-loop Hall effect transducers was used as current transducer.

The voltage transducers show a relative standard uncertainty on the gain of 0.02% and the current transducers show a relative standard uncertainty on the gain of 0.03% up to 5 kHz. The time delay at 50 Hz between the voltage and current channels is 20 µs and is constant up to 5 kHz.

Voltage and current are sampled at a 12.8 kHz sampling rate, so that 256 sampled/period are acquired for a fundamental frequency of 50 Hz. The measurements performed on the actual system will be compared to the variables computed in simulation and the results will be presented in the final paper.

V. CONCLUSIONS

The single-phase AC side current of an induction motor drive was analyzed for the purpose of identifying the effects of incipient stator phase fault on the shape of the current. The incipient fault was modeled as a change in stator phase resistance. A variety of cases was simulated and the steady-state current in each case was considered. The steady-state current was decomposed in wavelet coefficients and the change of wavelet coefficients in healthy and faulty condition was examined. The correlation between the coefficients was computed, a small value of the correlation coefficient is considered as a symptom of significant different in pattern. The analysis thus performed allowed the identification of specific resolution levels whose wavelet coefficients carry the most significant part of the information about the operating conditions. This analysis opens the way to simplified analysis for stator open-phase fault identification. Assuming to train a intelligent algorithm for fault recognition, the attention in training and operation can be focused on a specific set of wavelet coefficients.

The authors are also considering the extension of the approach herein introduced to the analysis of instant power signature for fault identification, as presented in [15].

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