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ON-LINE MONITORING AND FAULT DIAGNOSIS OF INDUCTION MACHINES - STATE-OF-THE-ART -

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Abstract: On-line condition monitoring and fault diagnosing of induction machines has received considerable attention both from industry and research community. The recent trend is toward sensorless methods that use more and more sophisticated mathematical models in order to avoid false alarms. In this paper a short survey of model-based methods for condition monitoring and detecting of commonly occurring faults in induction motors are presented. Critical comments regarding some of new achievements are also included.

Keywords: *induction machines, condition monitoring, model-based fault detection*.

1. INTRODUCTION

Supervisory control, condition monitoring and fault diagnosis of electrical machines are of great interest for electrical engineers who work in power systems and other applications related. In the last two decades, several research groups from the whole world invested significant efforts to develop principles, methods and procedures for supervising and diagnosing of different types of electrical machines [1]. Nowadays, important progress and outstanding industrial application results are reported.

The timely importance of the research topic is revealed by two facts as well. The first one: in 1991, on IFAC initiative has been started the series of IFAC Symposiums on Fault Detection, Supervision and Safety for Technical Processes (shortly „SAFEPROCESS"), which take place every three years. The last one was organised in 2003 in Washington, DC (USA). The second reality: it was 1997, when on IEEE initiative the first conference related specifically to the topic of the present paper was organised. The series of IEEE Symposiums on Diagnostics for Electrical Machines, Power Electronics and Drives (shortly „SDEMPED") is held from that time every second year. The last one, the fourth in the series, was organised in August 2003 in Atlanta, Georgia (USA).

Despite of the considerable scientific achievements and practical results, there is still a lot of work to do, the topic is still open for research and several unknown directions and new opportunities characterise it. These conclusions are supported by at least three main remarks: firstly, one may face a very high diversity and variety of electrical machines, both from the broad production offer side, and both from the uncountable number of their engineering applications. On the other side, the results of the research work in the fields like on-line monitoring of processes, as well as fault detection and diagnosis became recently known and introduced into the engineering practice. Last, but not least, there has to be mentioned the outstanding progress of the past few years in information and communication technology, that not only changed and enlarged the equipment at disposal, but also the set of possible principles, models and methods.

Digital instruments and measurements, as well as the computer-based, sophisticated dynamic modelling approaches have progressively and excludingly replaced the classical techniques using analogue measurements and steady-state characteristics. The modern technology has fully penetrated the field of electrical machines and drives. This opened new research areas in terms of time-domain and frequency-domain analysis, as well as new physical phenomena that have been neglected in the past were put into evidence, leading to new ways of thinking about monitoring and fault diagnosis.

All above-mentioned facts influenced substantially the design, manufacturing and practical use of electrical machines and drives, as well as their monitoring and fault diagnosis, and resulted in a completely new, modern reasoning about all these topics.

Nowadays, besides the on-line monitoring methods based on practical (computerized) measurements, the model-based - so called "sensorless" - methods are more and more used. These methods may replace the costly instrumentation and may combine the analytical methods with knowledge-based ones [2].

In the actual literature there is still no generally accepted or valid classification of the condition monitoring and diagnosing methods for electrical machines. Despite this shortage, the available techniques can be generally classified into two categories:

- measurement-based methods,
- model-based methods.

In the first case, along with the classical measurement of electrical quantities (currents, voltages) and eventually speed, additional sensors (for ex. temperature, flux, vibration, etc) are used for collecting the necessary information. Then, the condition of the electrical machine is determined by comparing the measurement results with the nominal, eventually reference values. In the second case, mathematical models of different appearance and complexity are delivering the necessary and useful information, based on only and exclusive measurements of electrical quantities (usually currents and rarely voltages, too) at the machine terminals. These letter methods are nominated in the literature as MCSA (Motor Current Signature Analysis) methods [3].

Usually, the developed (or to be developed) mathematical models are far away to be general; they are always oriented to detect a specific fault or faulty operation. Unfortunately, because of the approximations in the models, in most of the cases false alarms may occur due to influences of reasons and causes that differ from that of the real faults. It is well known that the signals carrying the faulty information have much lower level of energy than that of signals carrying the energy conversion in the machines. Therefore, in fault detection it is a demand to have an acceptable signal/noise ratio. This can be achieved by using suitable (and costly) instrumentation, but also by especially compensating the estimations carried out in the model-based approach.

Decreasing the sensibility of the monitoring and/or diagnosing system can partially reduce the undesired false alarms, but this solution has other drawbacks (for ex. missing of alarms in case of real faults) that may reduce the reliability of these systems. The better solution lies in developing of more accurate, detailed and complex models, with their more difficulties and inconveniencies. Despite all these, the primarily direction of the actual research shows towards the model-based, so called sensorless solutions.

Operating of induction motors coupled directly or through a drive to the mains, represent the most, over 80 per cent of industrial applications. It seems to be very common that in the past few years the research in condition monitoring and fault diagnosing was primarily directed to these applications. The present paper tries to put shortly together the related achievements and do a short survey with critical comments regarding the model-based methods and techniques used for condition monitoring and detecting of commonly occurring faults in induction motors.

2. PRINCIPLES OF MODEL-BASED FAULT DETECTION

The fault diagnosing systems can be basically grouped into three main categories [4]:

- syndrome (or symptom)-based diagnosis,
- model-based diagnosis,
- knowledge-based diagnosis.

In the first case, the eventual faults are detected and diagnosed using the time-domain or frequency-domain analysis of measured signals. Anomalies, discrepancies regarding to the reference signals are analysed and the faults are detected accordingly.

In the case of the second group of methods, the information and knowledge concerning faults are included into a mathematical model representing the normal (faulty free) operation of the considered system. A fault (or faulty operation) can be detected by evaluation of the difference(s) (in technical terms "residuals") between the behaviour of the real system at its model. In fact, generating of suitable residuals and their evaluation represent the basis of model-based fault detection and diagnosis.

In the third case, detecting and recognising of faults starts from their representation in the human knowledge and experience accumulated. Typically, knowledge intensive methods and decision systems are used in fulfilling this representation. Neural networks and fuzzy logic approaches are characteristic, however behind all applied knowledge-based methods one may in fact find mathematical modelling formalism.

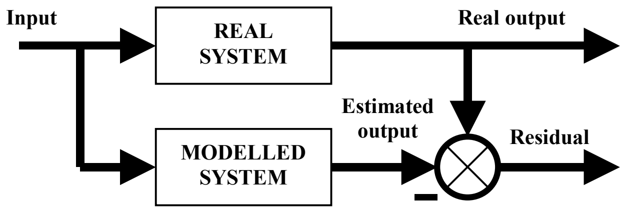

Figure 1. Basic principle of model-based fault detection [5].

Figure 1 presents the basic principle of model-based fault detection. The figure does not show the further evaluation of residuals, however, this is also possible by means of analytical modelling. It is obviously that the performance of model-based fault detection and diagnosing systems depend partially on the model accuracy, and partially on the authenticity of measurement of the process variables. The general scheme shown in the figure may detect theoretically any fault or any structural and/or parametric change that could be expressed in a mathematical model form.

3. THE ELECTRIC MOTOR AND ITS POSSIBLE FAULTS

This paper focuses only on faults that may occur in induction motors. The faults to be considered are the followings:

- stator inter-turn short circuit,
- broken rotor bars,
- thermal overload.

3.1. Detecting inter-turn short circuit in the stator windings

If a fault (typically inter-turn short circuit) occurs in one of the stator windings, it results in an unbalanced three-phase impedance that generates negative-sequence components in the line currents. Unfortunately, similar phenomena result as a consequence of the unbalanced supply or unbalanced measurement. Therefore, only in the steady absence of the letter cases it is possible to apply the fault detection by means of negative-sequence current measurement. Most of practical applications work with this assumption, or do not compensate the effects of the nominated error sources.

In order to improve reliability in the model-based inter-turn short circuit detection systems, in the actual literature indicates some tests with more or less success, that use trained neural networks or look-up tables to automatic compensation of unbalanced data [6], [7], [8]. The NNs are trained during the faulty-free operation, while look-up table solution allows faster search, and may include compensating data to avoid false alarms.

3.2. Detecting broken rotor bars

Frequently and usually it is the stator current frequency domain analysis used for detecting broken rotor bars in squirrel-cage induction motors. It is supplementary frequency component that appears in the current spectrum according to the magnetic asymmetry caused by the broken rotor bar. The frequency of this component is relatively low, according to the formula:

$$f_r = f_s(1-2s) ,$$

where f_s represents the frequency of the stator current supply, while s represents the slip, that may vary according to the load.

At the same time, there are high-frequency components as well in the stator current spectrum, which are due to the rotor slots. However, when using vector-controlled drives, these components are highly damped and compensated due to the relatively large frequency band in which the controller works. So, they are very difficult to be detected.

In the literature, one may also find numerous variants to detect broken rotor bars. In the simple, steady state model based on symmetrical components [9], this fault results in increased rotor resistance, which leads to the increase of the corresponding f_s component of the stator current frequency spectrum. Unfortunately, this approach has several drawbacks, coming both from the model simplicity and both from practical application. For example, if the load varies with a frequency twice the slip frequency (that may easily happen), the fault indicating f_s component is considerable damped depending on the load and reduced inertia.. Attempts to compensate these effects, there were neural network solutions proposed [10].

Application of special modelling techniques and parameter estimation methods could also be used to detect the increase of rotor resistance due to broken rotor bars [11], [12]. However, the results are very questionable, because of the various and unpredictable reasons that could lead to the increase of the rotor resistance (for ex. load variations). So, it can be concluded that it is a very difficult task to detect the process of breaking of the rotor bars, and nowadays, important research effort is directed toward this question.

3.3. Detecting motor overheating

There are numerous modelling methods enumerated for studying electrical motor overheating. Further, there are reviewed only those methods which are not based on the direct temperature sensing (with built-in and expensive temperature sensors). This means that the temperature is determined indirectly, by means of electrical quantities. So, developing of corresponding thermal models with sufficient accuracy is necessary. A model has also to be simple, that is not very complicated and not complex. This is the reason why most of the developed thermal models appear as their electrical circuitry equivalence. On the other hand, this approach needs very precise motor models combined with on-line parameter estimation, in order to determine as exactly as possible the energy losses (the supplied heat) both in stator windings and rotor.

In case of static models the model parameters are determined (by measurements) and fixed in advance. These models are usually simple, easy to use, but they cannot be applied in the case of changing of thermal characteristics, as for example in the case of malfunction of ventilation. Therefore development of dynamic models is a need.

Figure 3 presents such a dynamic model, where the electrical circuit symbols in fact represent thermal characteristics (thermal resistance, thermal capacity, thermal source). Each parameter value depends of the rotor thermal time constant, which is updated correspondingly by on-line estimation of the rotor resistance.

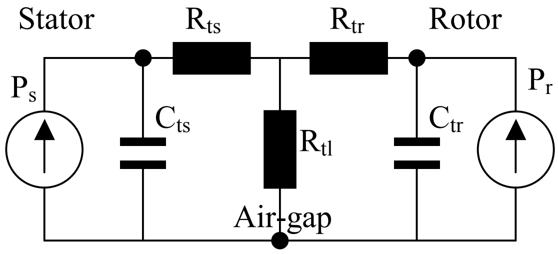

Figure 3. Thermal model of the induction motor [13].

The value of the rotor resistance is estimated from the results given by the rotor flux observer and the speed observer. The rotor flux can be estimated from writing in two different ways the motor model equations. These equations are: the voltage model equations for the stator in the stator-fixed reference frame, respectively the current model equations for the stator in the rotor-fixed (rotating) reference frame. The speed can be determined from the difference between the rotor fluxes, determined in the above-mentioned two different ways. At the same time the speed can be determined by MCSA, so the difference between the two estimates of the speed can be used to compensate (correct) the rotor resistance value, that is the rotor thermal time constant.

The presented approach was tested with quite good results. However, the method is not reliable in detecting overheating in cases of abnormal change in cooling conditions.

A good thermal model determines not only the heat developed in the rotor, but takes into consideration also the energy losses in the stator windings. That is why determining precisely the stator resistance is of great importance. The stator resistance can be computed most precisely by using DC measurement values. That is why in practice small DC offset is added to one of the stator phase voltages and then the DC current component is filtered out. Applying Ohm's law, the stator resistance value is determined simply and relative precisely. This method is very practical, because the determined value is neither influenced by the frequency, nor by other asymmetries. As drawback, the electromagnetic torque pulsates with amplitude that grows as the dc offset has higher value. On the other hand as higher is the offset value as precise is the determined stator resistance value. So, a reasonable compromise is necessary.

In case of inverter-fed motors, adding the DC offset voltage can be easily realised with corresponding control of the inverter. When the motor is supplied directly from the mains, the most efficient way to add the small DC offset is by connecting two anti-parallel diodes in series with one of the stator windings (Figure 4). The supplementary connected resistance R limits the amplitude of the DC current and adapts the amplitude to the desired compromise value for different types of motors and applications.

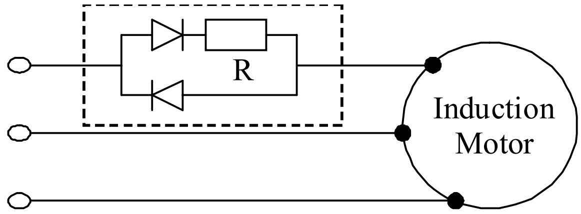

Figure 4. Adding a DC offset to one of the stator phase [14].

4. CONCLUSIONS

The present paper resumed shortly the most important and currently used principles, models and methods concerning on-line monitoring and fault detection of induction motors, namely stator inter-turn short circuit, broken rotor bars, and thermal overload. Problems and their actual solutions have been shortly presented. The research topic is very large and the interest for it is in steady evolution [15].

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