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A General Scheme for Induction Motor Condition Monitoring

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Abstract - This work proposes a general scheme to detect induction motor faults by monitoring the motor current. The scheme is based on signal processing (predictive filters), soft computing techniques (fuzzy logic), the analytical studies of induction motor under fault conditions and the analysis of data generated by Finite Element Method (FEM). The predictive filter is used in order to separate the fundamental component from the harmonic components. Fuzzy logic is used to identify the motor state and FEM is utilized to generate virtual data. A simple and reliable method for the detection of stator failures based on the phase current amplitudes is implemented and tested. The layout has been proved in MATLAB/SIMULINK, with both data from FEM motor simulation program and real measurements. The proposed method is simple and has the ability to work with variable speed drives. This work, on one hand, shows the feasibility of spotting broken bars and inter-turn short-circuit by monitoring the motor currents. On the other hand, it shows that the detection of eccentricity and bearing fault by monitoring the motor current is a difficult task.

I. INTRODUCTION

Three-phase induction motors are the most widely used machines. They are robust and have high reliability. However, owing to the thermal, electrical and mechanical stresses, mechanical failures are unavoidable in induction motors. Early detection of abnormalities in the motor will help to avoid expensive failures. Operators of electric drive systems are under continual pressure to reduce maintenance costs and prevent unscheduled downtimes that result in lost production and lost of financial income.

The task of the diagnostic system presented in this work is to detect an upcoming machine fault as early as possible, in order to save expensive manufacturing processes or to replace faulty parts. The failure monitoring system can monitor a variety of motor failures. This work focuses on the application of motor current signature analysis (MCSA) to diagnose faults in three phase induction motor drives, establishing a general scheme that permits to spot failures in variable frequency. MCSA utilizes results of spectral analysis of the supply current of an induction motor to detect an existing or incipient failure of the motor in the drive system. The motor current amplitudes are also used in order to spot failures in the stator. Motor current amplitudes contain potential fault information and constitute the most suitable indicator for diagnosing stator fault, in term of easy

accessibility, reliability and sensitivity. Fuzzy logic approach is used to make decisions about the motor condition. Fuzzy logic can describe the characteristics of an industrial process with linguistic terms. The motor condition identification task requires the interpretation of data and makes a decision from this data. Fuzzy logic was chosen in this work because the motor condition constitutes a fuzzy set. In practice, the users are concerned about condition of the motor in terms of a linguistic variable that can be expressed as “good”, “damaged” or “seriously damaged”.

The modern industry has widely used reliability based maintenance and condition-based maintenance strategies to reduce unexpected failures and downtime. These techniques can increase the time between planned shutdown for standard maintenance and reduce maintenance and operational costs. The operation of the machine in unsafe condition must also be avoided. Nevertheless, the failures are unavoidable and failure statistics [1] has reported that the percentage of failures in induction motor components is as follow:

1. Bearing related: 40%
2. Stator related: 38%
3. Rotor related: 10%
4. Others: 12%

II. MOTOR CURRENT SIGNATURE ANALYSIS

MCSA is a non-invasive, on line monitoring technique to diagnose problems in electrical machines. A large amount of research has been directed toward using the stator current spectrum to sense motor faults. The monitored spectral components can result from a number of sources, including those related to normal operating condition. It is necessary to use some degree of expertise in order to distinguish a normal operating condition from a potential failure mode.

This requirement is even more acute when analyzing the current spectrum of an induction motor since a multitude of harmonics exist due to both the design and the load condition. In fact, MCSA utilizes results of spectral analysis of the stator current, precisely the supply current of an induction motor to spot an existing or incipient failure of the motor or the drive system [1],[2]. Each induction motor fault has its own effect in the stator current. A symmetrical three-phase stator winding fed from a symmetrical supply will produce a resultant forward rotating magnetic field at

synchronous speed, and if an exact symmetry exists there will not be a backward rotating field. Any asymmetry of the supply or stator winding impedance will cause a resultant backward rotating field from the stator winding. Reference [3] made a reviewed of the frequency components given by motor faults. Table 1 shows the components of interest by every fault.

Table 1. Frequencies associated with faults.

Fault	Components of interest
Bearing fault	$f_{\text{bng}} = f_1 \pm m f_{i,o} \quad (1)$ $f_{i,o} = \frac{n_b}{2} f_r \left[1 \pm \frac{D_b}{D_p} \cos \alpha \right] \quad (2)$
Rotor fault	$f_{\text{brb}} = f_1 \left[k \frac{(1-s)}{p} \pm s \right] \quad (3)$
Eccentricity fault	$f_{\text{ec}} = f_1 \left[(kR \pm n_d) \left(\frac{1-s}{p} \right) \pm n_w \right] \quad (4)$

- f_{bng} components generated by bearing faults
 f_1 supply frequency
 $m = 1, 2, 3, \dots$
 $f_{i,o}$ characteristics race frequencies
 n_b number of bearing balls
 D_b ball diameter
 D_p bearing pitch diameter
 α contact angle of the ball on the races
 f_{brb} components generated by broken rotor faults
 $k = 1, 2, 3, \dots$
 p number of pole-pairs
 s per-unit slip
 f_{ec} components associated with eccentricity
 n_d rotating eccentricity order
 n_w stator MMF harmonic order
 R number of rotor slots

Theoretically, by monitoring the frequencies given in Table 1, it is possible to identify faults from bearing, eccentricity and broken rotor bars. On the other hand, stator faults are difficult to identify from the current spectrum. Reference [4] showed that from the nature of the cage induction motor, all flux density waves from the stator side will be reflected, and occur only at the following frequencies in the stator spectrum

$$f_{\text{rf}} = f_1 \left(1 \pm \frac{kn}{p} (1-s) \right) \quad (5)$$

f_{rf} components reflected from the stator side.

Reference [4] arrived to the conclusion that under stator short circuit there are magneto-motive (MMF) and flux density waves at all number of pole pairs and in both directions of rotation. Therefore no new frequency components appear in the stator current spectrum as a result of fault in the stator winding, only a rise in the rotor slot harmonics can be expected. Reference [4] showed that these components can not be used as specific sign of the occurrence of inter-turn short circuit in the stator winding.

An important fact also is that any stator short circuit produces a negative sequence component in the input currents. When a short circuit occurs, the phase winding has less impedance, less turns and therefore less MMF. This gives the possibility of diagnosing stator short circuit by monitoring only the amplitude of the phase current [5].

III. THE PROPOSED DETECTION SYSTEM

The scheme of the system can be seen in Fig. 1. The system consists of two main blocks. The left-hand block to spot faults from the bearing, rotor and eccentricity is based on MCSA. And the right one to spot faults from the stator is based on monitoring the amplitudes of the motor currents. The proposed detection system in this work is a consequence of the analytical results.

The left-hand block has a new idea with respect to the traditional scheme given by [3], in order to make the system able to work in variable frequency. After the A/D block, a predictive filter of third generation is used to remove the fundamental component. The third generation predictive filter was chosen because this filter overcomes the main drawback of the first two generations. The first and second generation predictive filters are not able to work in variable frequency.

The role of this filter is very important. Firstly, the current measurements are made in a noisy environment and this filter has the ability to cancel all notches, filtering the wide band noise and the high frequency noise. Secondly, this filter does not produce delay between the incoming signal and the filtered signal [6].

This feature is useful for detecting harmonic components by subtracting the input signal from the output of the filtered signal without delay. Yielding a measurement of the harmonic components rather than the fundamental sinusoidal. Fig. 2 shows a corrupted input signal and the filtered signal as an example of the filter performance in steady state at 50 Hz. The filter is able to work in variable frequency, only by changing some control parameters correspondingly [6]. The frequency range is limited only by the Nyquist frequency of the discrete time system. Another advantage from the use of the predictive filter is that digital processing offer higher accuracy than analog processing.

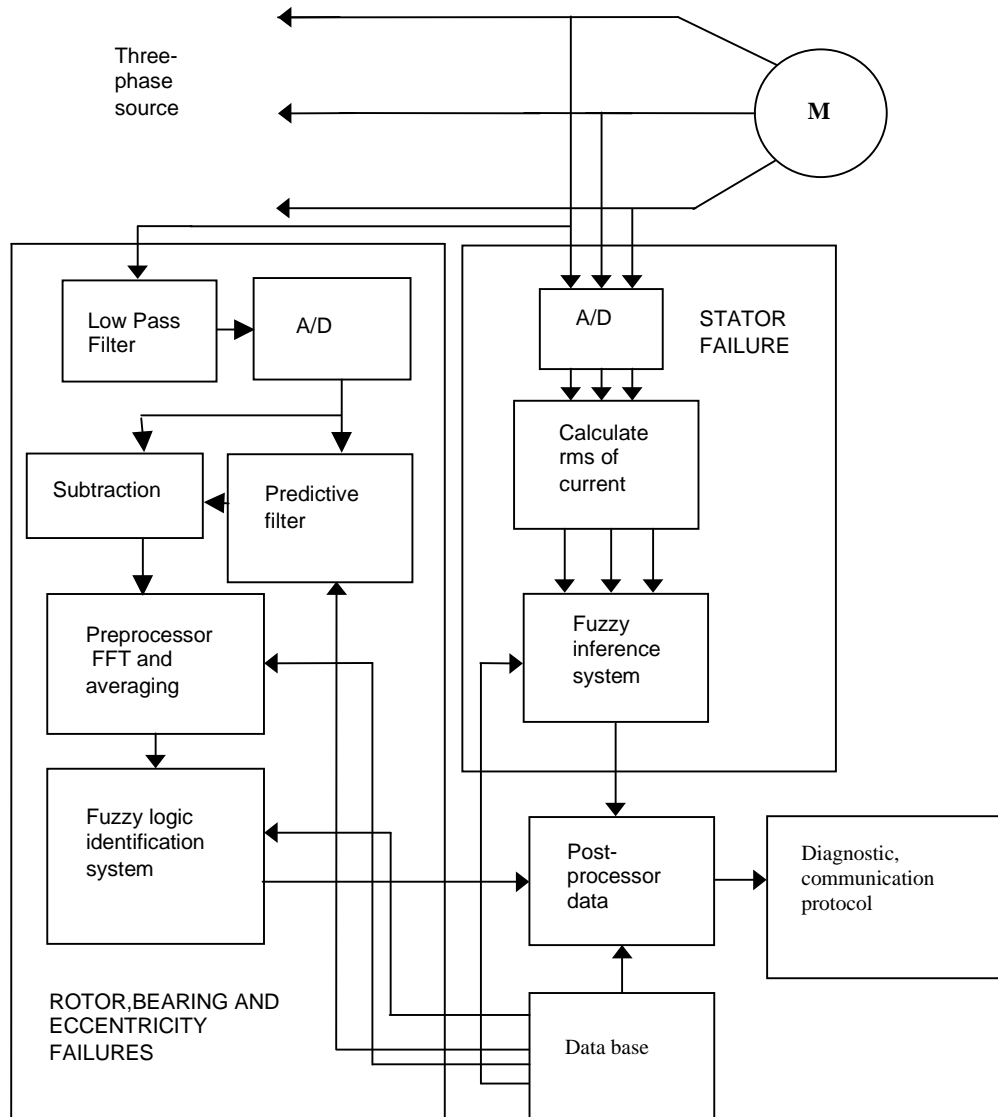


Fig. 1. Block diagram of the proposed motor protection system.

The filter was tested at 50, 60 and 100 Hz with current data from FEM motor simulation program. Fig. 3 shows the motor current, when the motor was working with two broken rotor bars at half load and 100 Hz. The harmonic components due to broken rotor bars can be seen from the current spectrum. Fig. 4 shows the subtraction result of the filtered signal from the input signal. Just the harmonics components can be seen, as the subtraction has removed the main component. In Fig. 1, after the subtraction, the harmonic components are obtained. The next step is to execute a FFT algorithm in order to get the frequency domain signal. It is necessary to take into account that the signatures of the current spectrum depend on the machine slip and the physical characteristics of the machine such as: number of rotor bars, number of stator slots, stator connection and

number of poles. The slip can be the maximum slip permitted for the machine or either it can be calculated. The necessary data is introduced from the data base block to the rule based frequency filter. The study made with different data from the FEM simulation program showed that the best choice is to carry out the investigation of the signatures of the harmonics of order one and three given from formula (3), in the case of broken rotor bars. They can be seen in Fig. 4. The identification task is executed by a fuzzy logic system. The inputs of the fuzzy system are the signature frequency and the data from the motor.

The fuzzy system allows the transformation of heuristics and linguistics terms into numerical values via fuzzy rules and membership functions and it is able to approximate the complex relationship related with the identification task.

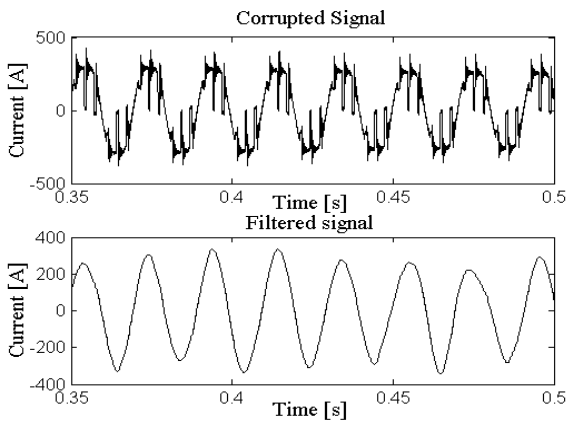


Fig. 2. Corrupted and filtered signal

The system for monitoring the stator failure is shown in Fig. 1, right hand block. This block is monitoring the amplitude of the motor currents. The root mean square of each phase current is calculated over a period of time. In this layout, the stator currents are considered as input variables of the fuzzy system and stator condition (SC) is chosen as output variable. These variables are vague information. The digital output from the A/D converter is converted in suitable linguistic values. The linguistic values are represented for four categories that allow us to classify the amplitude of the currents. These categories are “very small”, “small”, “medium” and “large”. In order to define these categories, specific information data of the motor is needed. The term (SC), interpreting the stator condition, as a linguistic variable could be “Good”, “Damaged” and “Seriously damaged”. Good might be interpreted as a stator with no faults, damaged as a stator with voltage unbalance, and seriously damaged as a stator with an open phase or coil short circuit. This method is described by [5] with 14 rules in the fuzzy filter but we have included a new rule that takes into account the amplitude variance, in order to improve the system sensitivity.

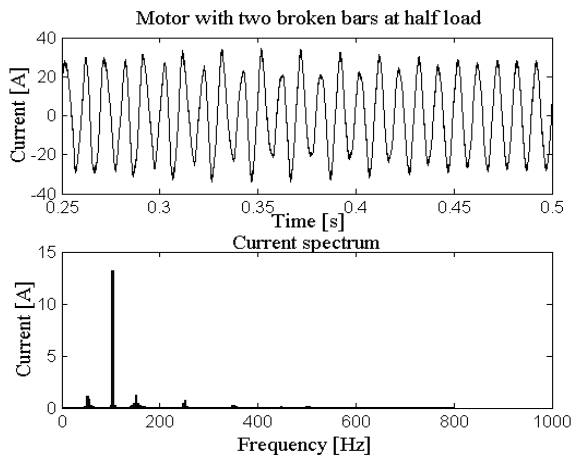


Fig. 3. Stator current and its spectrum. Motor working with two broken bars at half load. Simulated data.

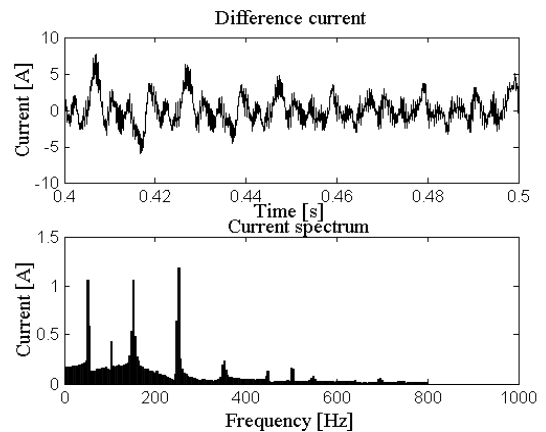


Fig. 4. Current after subtracting the fundamental component and its harmonic contents.

IV. SIMULATION RESULTS

Details about the FEM program can be found in [7]. The rated parameters of the motors are given in Appendix I. The FEM program was run under different motor conditions, healthy, coil short-circuited, inter-turn short circuit, one, two, three and five broken rotor bars, 33 % of static and dynamic eccentricity and healthy condition, details about fault implementation can be found in [8]. The sampling frequency in the FEM simulation program was 40 kHz and number of samples was 20 000. The data were introduced from MATLAB workspace, in such a way that the model is working on-line with the data. The data were collected under three load conditions, no load, half load and full load. Two MATLAB/ SIMULINK models were implemented to test the proposed identification system shown in Fig. 1. The models were adjusted and tested with the collected data.

A first model was implemented to detect stator condition. The simulation model was able to identify the fault with excellent accuracy. For every data set, the fuzzy filter executes 25 validations of the stator condition. The duration time of every data set was 0,5 seconds. In order to prove the performance of the SIMULINK model under noisy condition, a source of noise was added to each phase. Table 2 shows the performance of the model under noise conditions.

A second MATLAB/SIMULINK model was implemented in order to identify broken rotor bars, eccentricity and bearing failures, simulating the left-hand side of Fig. 1. The model was tested with data from the FEM simulation program.

Table 2. Correct detection of stator condition under noise.

Motor condition	Data sets	Accuracy
Healthy motor	3	96%
Open phase	9	100%
Inter-turn short	3	92%
Coil short circuited	3	100%

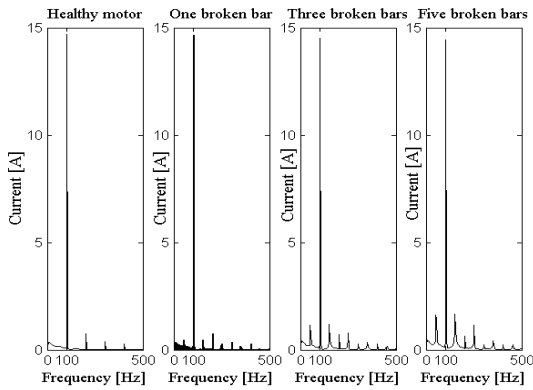


Fig. 5. Current spectrum. Motor working at half load. Simulated data.

Fig. 5 shows the current spectrum for different rotor conditions with the same load. The model was able to identify the rotor condition in all the data sets corresponding with broken bars and the case of dynamic eccentricity. However, for the case of static eccentricity, the amplitude of the harmonic components given by formula (4) did not appear in the simulated data. Therefore, the system was not able to detect this type of fault even with a high degree of static eccentricity (33%). Fig. 6 shows the current for the case of dynamic eccentricity with sinusoidal supply at 100 Hz.

V. MEASUREMENT RESULTS

A measuring setup was arranged to get data from a working motor. It is shown in Appendix II. The motor used in the measurements was the same used in the FEM simulation. The data was recorded through a transient recorder. The sampling frequency used was 40 kHz. The tests were carried out with the motor in healthy condition, a real inter-turn short circuit, from one to five broken rotor bars, a static eccentricity of around 40 % and a bearing failure (a passing whole in the outer ring). Data were collected at 50, 60 and 100 Hz in three load conditions.

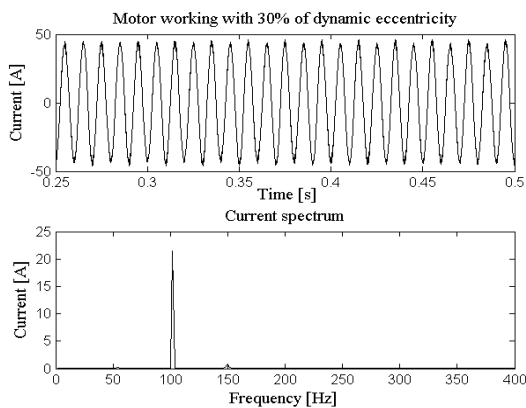


Fig. 6. Motor current and its spectrum. Simulated data with sinusoidal supply.

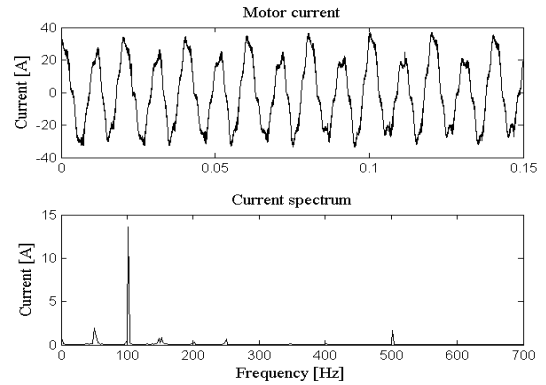


Fig. 7. Motor current and its spectrum. Motor working with four broken bars at half load. Measured data.

The measured data were used to test the implemented models. Firstly, the model designed to detect rotor, eccentricity and bearing faults. For these cases, the model was not able to identify the faulty motor with neither one broken rotor bar, nor the static eccentricity nor the bearing failure. However it was able to identify two, three, four and five broken rotor bars with high accuracy. Fig. 7 shows the measured motor current when the motor was working with four broken bars, half load, inverter supply at 100 Hz.

The SIMULINK model for the identification of the stator condition was fed with motor data in healthy condition and with the real inter-turn short circuit. Data were collected at four different supply frequencies. The model was able to identify the stator condition with an accuracy of 96%.

VI. DISCUSSION

The main objective of this work was to establish a layout capable of detecting the motor condition by monitoring the motor currents. The data analysis from FEM motor simulation program showed the same features in the motor current as were predicted in the analytical study for the case of broken rotor bars and dynamic eccentricity. On the other hand, the harmonic components related with static eccentricity and bearing fault were not relevant enough to detect these fault conditions. For the case of stator fault, as was expected from the analytical results, no new prominent current harmonics are generated when the motor is working with this failure.

It is important to note that in the case of static eccentricity there are solely space flux harmonics, hence, no new current harmonic must be induced in the current spectrum. In agreement with the conclusion given by [9] the static eccentricity does not produce any noticeable change in the current spectrum. This is corroborated by our work from FEM calculation and measurements.

From the analytical and simulation results, a novel fuzzy logic and predictive filter layout was designed. In this layout, a predictive filter to cancel the main harmonic component was introduced. The filter was tested at different frequencies

with simulation and measured data. It showed good performance and it was able to work with both sinusoidal and inverter supplies. In this layout, fuzzy logic was used to analyze the data and make decisions. It was able to identify the motor condition with high accuracy for the cases of broken bars and stator faults

MATLAB/SIMULINK models were implemented to simulate the proposed system. The first SIMULINK model was able to identify the stator condition with simulation and real data. The model was able to identify the stator condition with good accuracy even under noisy condition. The model was fed with measured data at different supply frequencies, with both inverter supply and sinusoidal supply. In both cases, it was able to identify the stator condition. Two conditions were tested with measured data: healthy condition and inter-turn short circuit. The model showed that comparing the rms current of the phases reveals changes in the internal electrical balance of the machine. It was sensitive enough to reveal one shorted turn in the stator winding, where there were 11 turns by coil. The model implemented to detect the rotor condition, eccentricity and bearing faults showed good performance in the accuracy detection rate using the simulation and real data measurements for the detection of broken bars. However, it was not able to detect static eccentricity and bearing faults. This is due to the fact that the harmonic components related with eccentricity and bearing fault were no relevant enough to be detected.

VII. CONCLUSION

This work showed on one hand the feasibility of spotting stator faults and broken rotor bars by monitoring the motor current with appropriate use of the existing techniques for signal processing and soft computing. On the other hand, it showed that eccentricity and bearing faults are highly difficult to detect from the current spectrum. Another important conclusion is that a pure static eccentricity does not produce new harmonics in the current spectrum.

REFERENCES

- [1] Thomson W. T. and Fenger M., "Current Signature Analysis to Detect Induction Motor Faults," IEEE Transactions on Industrial Applications, July/August 2001, pp. 26-34.
- [2] Benbouzid M.E.H, Viera M. and Theys C., "Induction Motor's Fault Detection and Localisation Using Stator Current Advanced Signal Processing Techniques," IEEE Transactions on Power Electronics, Vol. 14, No. 1, January 1999, pp. 14-22.

- [3] Benbouzid M. E. H., "A Review of Induction Motors Signature Analysis as a Medium for Faults Detection," IEEE Transactions on Industrial Electronics, Vol. 47, No. 5, October 2000, pp. 984-993.
- [4] Joksimovic G.M. and Penman J., "The Detection of Inter-Turn Short Circuits in the Stator Winding of Operating Motors", IEEE Transactions on Industrial Applications, Vol. 47, No. 5, October 2000, pp. 1078-1084.
- [5] Benbouzid M. E. H., "A Simple Fuzzy Logic Approach for induction Motor Stator Condition Monitoring," IEMDC 2001. IEEE International, January 2001, pp. 634-639.
- [6] Vainio O. and Ovaska S., "Multistage Adaptive Filters for In-Phase Processing of Line Frequency Signal," IEEE Transactions on Industrial Electronics, Vol. 44, No. 2, April 1997, pp. 258-264.
- [7] Arkkio A., "Analysis of induction motor based on numerical solution of the magnetic field and circuits equations", Acta Polytechnica Scandinavica, Electrical Engineering Series No. 59, ISBN 951-666-250-1, 97, available on web at <http://lib.hut.fi/Diss/list.html#1980>.
- [8] Pöyhönen S., Negrea M., Jover P., Arkkio A., Hyötyniemi H., "Numerical Magnetic Field Analysis and Signal Processing for Fault Diagnostics of Electrical Machines", COMPEL, The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 22, No. 4, pp. 969-981, 2003.
- [9] Cameron, J. R., Thomson W. T., Dow A. B., "Vibration and current monitoring for detecting airgap eccentricity in large induction motors", IEE Proceedings, pp. 155-163, Vol. 133, Pt. B, May 1986.

APPENDIX I. RATE PARAMETERS OF THE MOTOR

Start connection		
Power	35	kW
Rate current	64	A
Number of rotor slots	40	
Number of poles pairs	2	
Number of stator slots	48	
Voltage	400	V
Rated frequency	100	Hz

APPENDIX II. MEASUREMENTS SETUP

