International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 4, Number 7 (2011), pp. 787-806

http://www.irphouse.com

Condition Monitoring and Protection of Induction Motor using Wavelet Indicator

Khalaf Salloum Gaeid and Hew Wooi Ping

Department of Electrical Engineering,
University of Malaya, 50603 Kuala Lumpur, Malaysia
E-mail: salimhazim2010@gmail.com

Abstract

In this paper a novel protection and monitoring algorithm utilizing wavelet is implemented for many faults in a vector controlled induction motor. The stator current is introduced first to the wavelet circuit to calculate the energy of all the decomposing levels, the highest one being used. The energy of the original phase current is calculated to obtain the wavelet index. AC current protection, above voltage, under voltage protection, above DC voltage, short stator winding, broken rotor bar and damaged induction motor are introduced in this paper. More than 13 trips can be monitored along with the time of the fault occurrence. The trip status analysis by wavelet is used to enable a protection circuit to stop the motor. Additionally, a summary of the wavelet types (continuous and discrete) are given.

Keywords: Wavelet, induction motor, fault diagnosis, protection, monitoring, vector control.

Introduction

The induction motor is crucial in the industry for a variety of reasons, including its simple construction, low maintenance requirement, rigidity and high reliability. It is commonly used in compressors, pumps and fans.

Condition monitoring (CM) is an important industrial tool that involves monitoring a parameter of condition in induction motors, such that any change in the system performance or the parameters will be indicated as a machine fault or failure. It improves machine efficiency, reduces unscheduled shutdowns and minimizes damage.

The induction motor current contains harmonics that are used as fault indicators. Squirrel cage motors are especially important because their functionality is not severely affected until the fault becomes considerably high [1].Besides; they are relative cheap and have high reliability [2].

The mathematical equations used to separate a given continuous-time signal into several scale components is called wavelet. A lot of work has been done to identify faults like stator short, broken rotor bars, stator open winding, DC short buses and bearing in the field of condition monitoring with wavelets.

Condition monitoring can be off-line or on-line. Alternatively, it can also be classified as continuous or periodical [3]. Continuous monitoring allows the detection of damages as soon as they appear, even if they are sudden and humanly inaccessible. Trends can be formed automatically, thus minimizing the labor. Periodical monitoring has its share of advantages too. Mechanical damages, loosened fastening and leaking seals are easily discernible with this method. Also, when measurement is carried out, the motors can be cleaned. Periodical monitoring is also a cheaper option than continuous monitoring.

Condition monitoring using wavelets has been investigated for a variety of scenarios. Condition monitoring performed for an induction motor with a broken rotor bar and end ring faults as in [4]. CM to sensor signals in induction motor has been tested by [5]. CM to medium voltage induction motor operation has been performed by [6]. The difference wavelet function was used by [7], who also employed the Quadratic Discriminated Classifier (QDC) and the Linear Discriminated Classifier (LDC) for CM. [8] used the MCSA method for the CM to monitor the fault frequencies using both FFT and wavelets. This method has been shown to perform health monitoring with noninvasiveness and high reliability [9]. The condition monitoring of induction machines follows the sequence of fig.1.

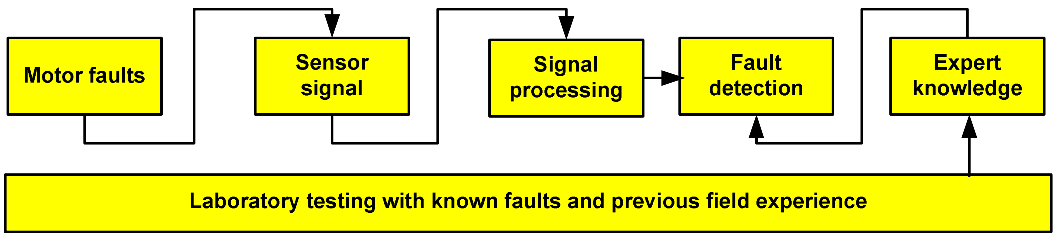

Figure 1: Condition monitoring procedure.

While previous research has focused exclusively on either monitoring, detection or protection circuits for induction motors, in this paper, wavelets have been used to synchronize the three processes. Additionally, circuits have been developed to provide the time and location of occurrence of faults.

A key requirement of the monitoring system is the ability to make the distinction between machine faults and supply conditions [10]. Improving over traditional statistical methods, The Robust Condition Monitoring technique takes into consideration both the presence of anomalous feature measurements in Phase I of the Quality Control process and the different motor performance characteristics.

The paper is organized as follows: Section 1 gives an introduction about monitoring and protection. Section 2 describes condition monitoring for stator current and voltage, induction motor speed, DC voltage, stator short winding, stator open winding and broken rotor bars. Section 3 outlines the proposed methodology. Section 4 presents the protection against the faults. Section 5 contains a case study of 1 broken rotor bar and AC voltage unbalance with under speed. Section 6 presents simulation results. Finally, future possibilities are mentioned in conclusions.

Condition monitoring

Stator Current

The stator phase current is a useful quantity for condition monitoring as it is easy measure. Faults affect the spectrum of the current signal while the induction machine is sufficiently loaded and extracted [11].Fig.2 shows the protection circuit against the stator phase current exceeding or dropping below the standard requirement. This circuit is mainly composed of current measurement which depends on the negative sequence analysis of stator current per phase. Negative-sequence currents arise in this system due to construction asymmetry, faults, transducer-gain difference, voltage and load unbalance at the terminals [12], according to the following relationship:

$$I_1 = \frac{1}{3}(I_a + \alpha I_b + \alpha^2 I_c) \tag{1}$$

$$I_2 = \frac{1}{3}(I_a + \alpha^2 I_b + \alpha I_c) \tag{2}$$

$$I_o = \frac{1}{3}(I_a + I_b + I_c) \tag{3}$$

$$\alpha = \exp(2\pi/3) = 1\angle 120 \tag{4}$$

The instantaneous AC over current fault will occur when the maximum value of stator phase current exceeds 1% of the rated current (I.7 Amps), that is when |max $(I_{a,b,c})$|>1.7*1.01 yields logic 1 to enable the decoding unit and the fault and time are shown.

Maximum allowable AC current ($|I_1|$) occurs when it exceeds the rated current by 10%. The decoding-encoding circuit is then enabled by logic 1 to show this fault with time as can be seen in Fig.2.

Max AC current unbalance fault will occur when the condition I_2/I_1 > 40%*I_{rated} holds true.

The decoding circuit will be enabled to show this fault and its time as can be seen in the monitoring circuit of Fig.2.

For the condition monitoring program to be truly effective, it should allow the determination of a procedure for extracting different features from the current signal, so that a distinction can be made between various machine conditions. This will allow the classification of faulty models from normal models [13].

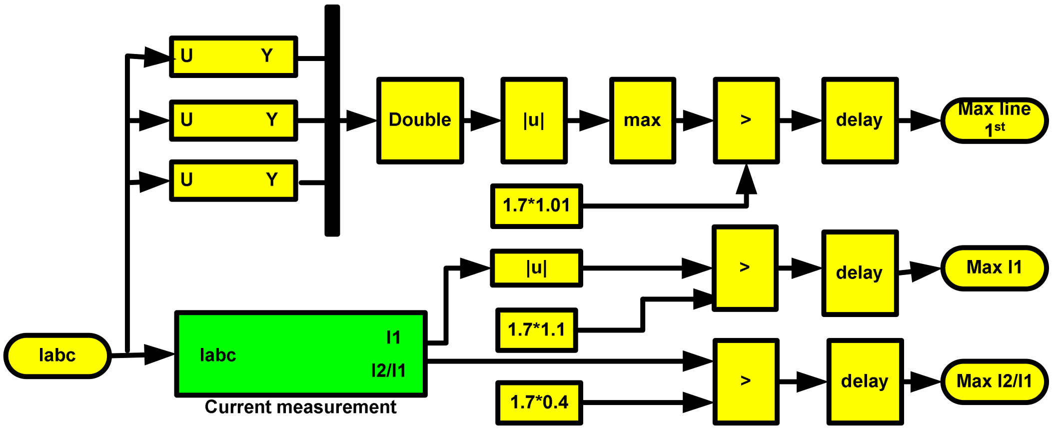

Figure 2: Current motor protection against excess and drop.

Stator Voltage

The stator voltage is another important quantity that proves useful in condition monitoring of the induction motor.

$$V_1 = \frac{1}{3}(V_a + \alpha V_b + \alpha^2 V_c) \tag{5}$$

$$V_2 = \frac{1}{3}(V_a + \alpha^2 V_b + \alpha\ V_c) \tag{6}$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{7}$$

α as in (4).

The circuit to detect AC under voltage is shown in Fig.3. The condition 'Min V_1' refers to AC under voltage, when the voltage V_1 falls below 90% of the nominal stator voltage. 'Max V_1' refers to AC over voltage, when V_1 exceeds 110% of the nominal stator voltage, as shown in Fig.4. Max voltage unbalance or negative sequence occurs when the ratio of V_2 to V_1 exceeds 10% of the stator voltage. Max voltage unbalance (zero sequence) occurs when the ratio V_0 to V_1 exceeds 10% of the stator voltage. At the occurrence of either condition, the decoding circuit is enabled to indicate the fault and the time of occurrence.

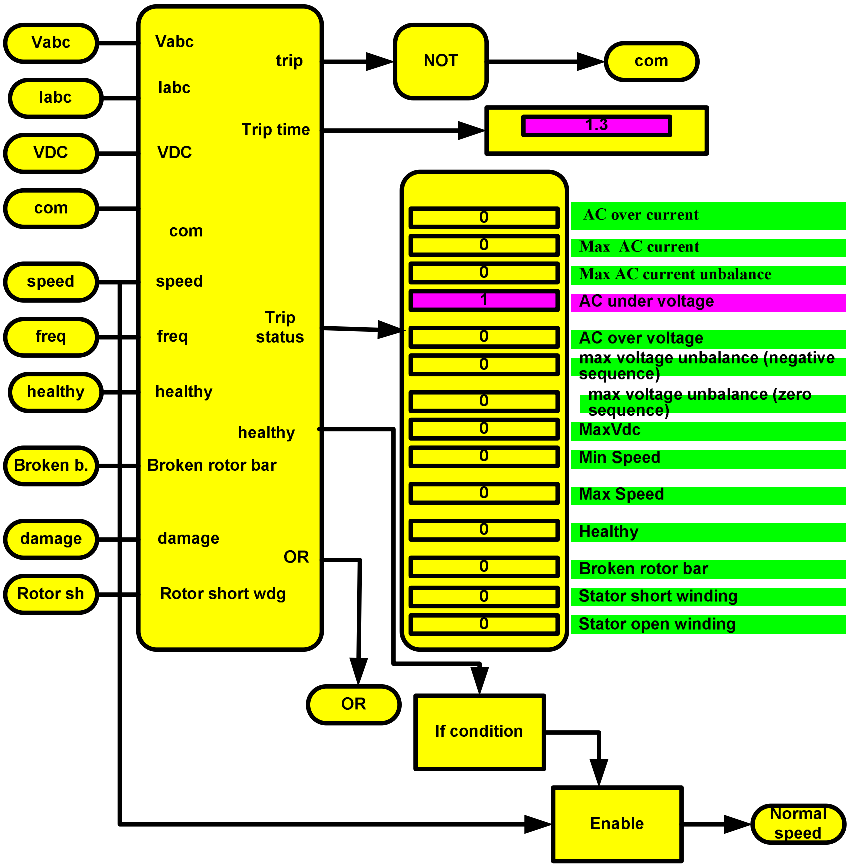

Figure 3: AC under voltage monitoring.

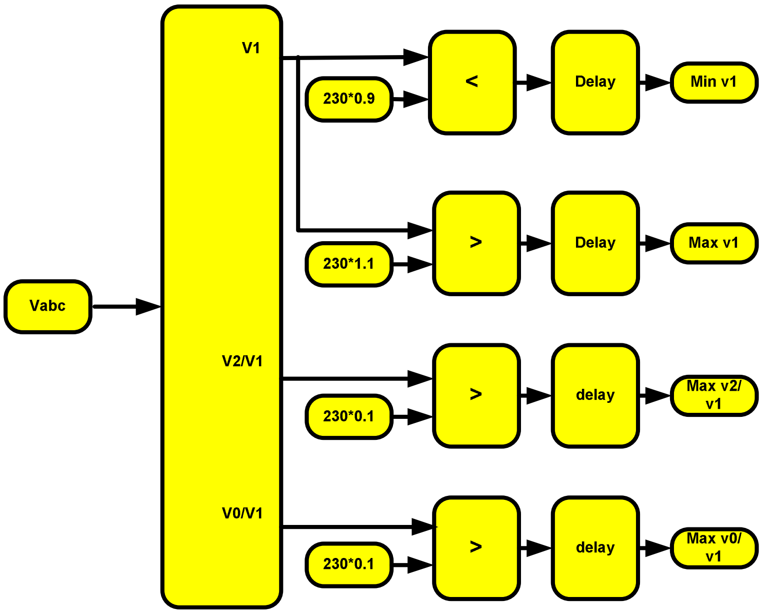

Figure 4: Voltage motor protection circuit.

The voltage unbalance at the terminals of an induction machine leads to increased heating losses and requires de-rating. Therefore, the unbalance is normally restricted to below 5 % as can be seen in Table1.

SIEBER LS71 induction motor parameters are listed in Table2.

Table 1: Observation of induction motor according to IEEE standard.

Induction motor faults observation		
Faults	Acceptable values	Value limits
AC over current	2 times rated	1.5 rated
AC current unbalance	Up to 45%	Up to 40%
AC under voltage	5-25%PNDA & PNDI	0.25-20%
AC over voltage	± 10%	± 10%
AC voltage unbalance	1-5% IEEE stand	1-3%
DC over voltage	V_{DC}	V_{DC}
Over speed	+ 25%	+10%
Under speed	-25%	-10%
Rotor broken bar	20% less than 2 m.for 2 pole	20% less than 2 m.for 2 pole
Short stator winding	10% less than 2m for 2p	10% less than 2m for 2p
damage	Not permitted	Not permitted

Table 2: SIEBER LS71 induction motor parameters.

Motor spec	Unit	Value
power	kw	0.5
Current	ampere	1.7
Voltage (delta)	volt	230
Rated speed	RPM	2800
No. of pole		2
Moment of inertia	Kgm^2	3.5e-4
Stator resist.	ohm	24.6
Rotor resist.	ohm	16.1
Stator induct.	henry	40e-3
Rotor induct.	henry	40e-3

DC Voltage

When the DC voltage V_{DC} exceeds 300 V, the 'Max V_{dc}' condition is enabled as in the circuit of Fig.5. The on delay in all units is to ensure the voltage change is genuine and not just momentary.

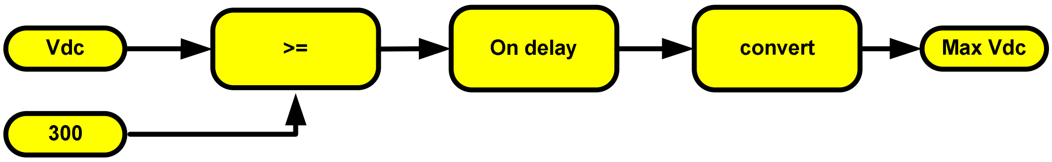

Figure 5: Protection circuit against excess DC voltage.

Speed Monitoring

The actual speed of the induction motor is considered one of the most important characteristics. Operating speed of the motor can be monitored by using the encoder as input to the circuit shown in Fig.6.

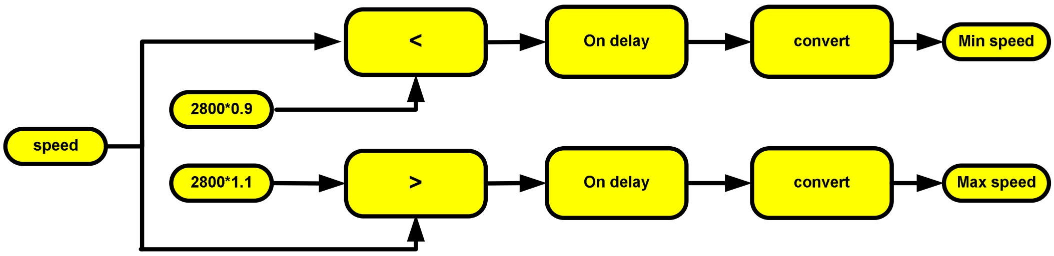

Figure 6: Protection circuit against excess or drop in speed.

Speed below 90% or over 10% of the 2800 rpm reference speed are taken as faults. Either condition enables the decoder circuit or the fault is indicated along with its time of occurrence. The on delay of 0.2 seconds is to ensure that the system is in steady state and that the speed change is not momentary.

Broken Rotor bar

The induction motor faults can be divided into two main groups: stator fault and rotor faults as is shown Fig.7.

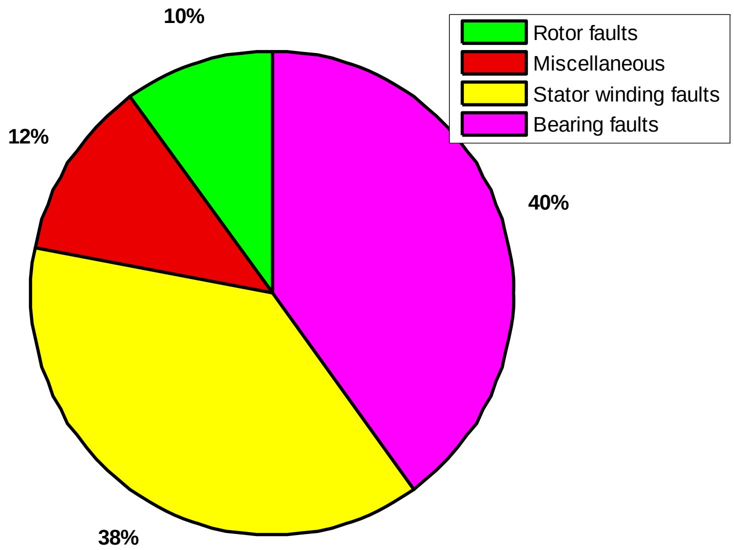

Figure 7: Induction motors faults percentages.

For more than 3 decades, fault detection of rotor bars has received attention in the context of induction motor fault diagnosis. A variety of diagnosis techniques have been developed to identify rotor bar faults. The use of effective signal processing techniques with condition monitoring ensures the early detection of faults [14].The prominent ones are machine current signature analysis, Fast Fourier Transform (FFT), estimation of rotor resistance approach, Short-Time Fourier Transform and Wavelet Transform. The Discrete Wavelet Transform (DWT) possesses a compression property that serves to keep the original signal in the desired frequency band [15].

The energy contained in the signal is a useful tool for the fault detection of induction motors. The energy is calculated for the details and for the approximation [16]. To determine the wavelet index for detection of the induction motor faults, the maximum energy serves as the most effective detailed information. In this paper, stator current is used as the input to the DWT. The variation in stator current waveform is defined as the instant at which a sudden increase, decrease or transient is observed in the magnitude of the current [17]. The construction of DWT is followed by implementing the criterion of fault detection for induction motors. The criteria used to detect the induction motor faults depend on the relationship between maximum detail energy (d6) and the original stator current (Ia) as can be shown in (8) and Fig.8.

$$W_{indx} = abs(energy(d6)) / average(energy(Ia)) \tag{8}$$

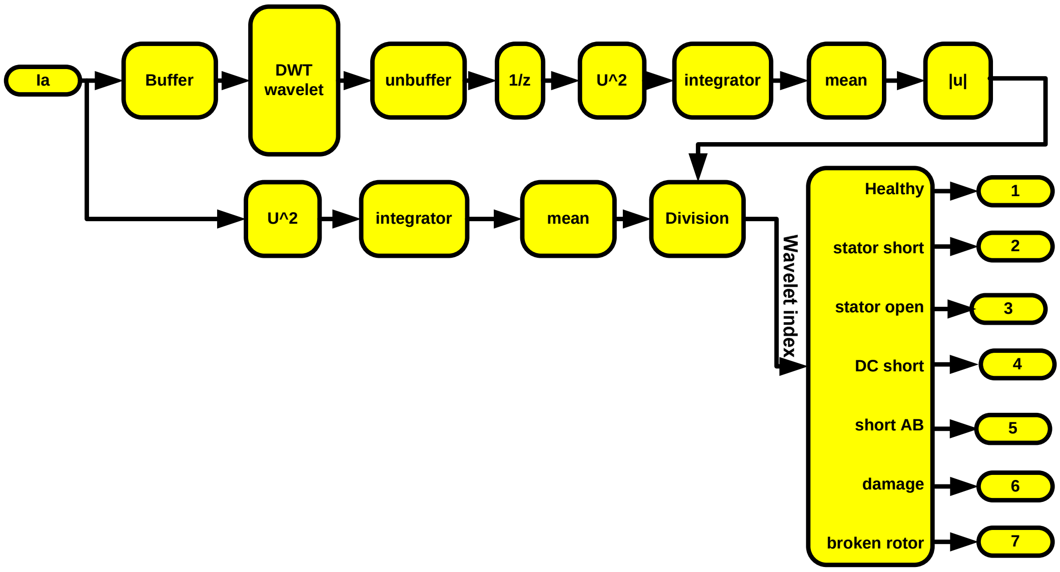

Figure 8: Fault detection according to the wavelet index.

The response of standard deviation of wavelet index for different load percentages is interpreted as in Fig.9.

The chief aim of this work is to detect the fault at the incipient stage and identify its source.

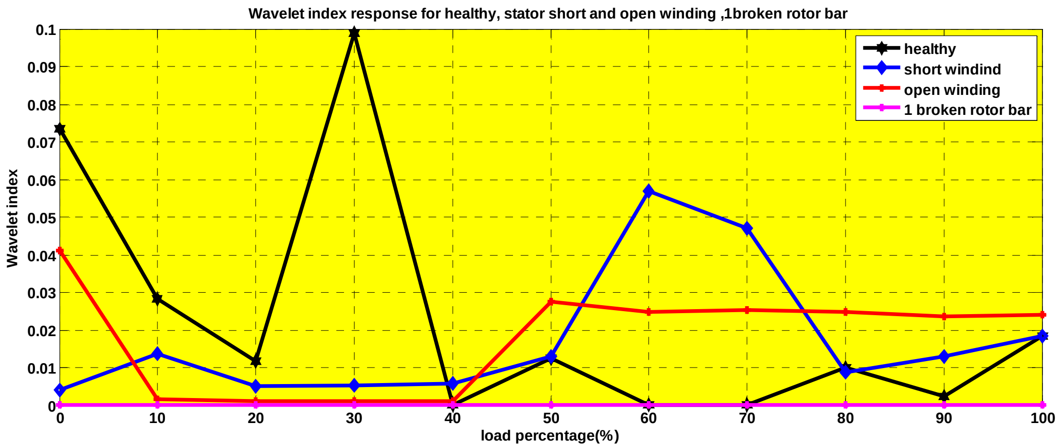

Figure 9: Standard deviation of wavelet index for different faults.

In the detection process, DWT was implemented using Daubenchies 10 (db10) function as the "mother" wavelet and decomposition level 6. Table 3 illustrates the measurements of both approximation and detailed coefficients for the reconstructed signal.

Table 3: Approximation and detail coefficients measurements.

level	Approximation			detail		
	mean	median	Std dv	mean	median	Std dv
1	-0.041	0.00156	1.306	6.36e-8	2.49e-8	0.00044
2	-0.041	0.00156	1.306	-1.89e-7	5e-9	0.0035
3	-0.041	0.00156	1.306	6.38e-7	2.58e-8	0.0072
4	-0.041	0.0026	1.306	-7.18e-7	5.69e-8	0.014
5	-0.041	0.0040	1.304	-4.91e-5	-2.46e-7	0.057
6	-0.041	0.0024	1.300	-0.00023	-0.00043	0.101

Shorted stator Winding

The presence of turn faults in the stator winding of an induction motor creates an asymmetry between the three phases. A negative sequence component thus appears in the line currents [18], the stator winding faults can be classified as follows [19]:

1. Turn to turn shorts within a coil.
2. Short between coils of the same phase.
3. Phase to phase short.
4. Phase to earth short.
5. Open circuit in one phase.

The majority of these faults are caused because of a combination of various stresses acting on the stator, which can be classified into thermal, electrical, mechanical, and environmental stresses [20].

Proposed methodology

The proposed methodology for multiple fault detection, monitoring and protection in induction motors involves obtaining the three phase stator current, three phase voltage and DC voltage fault monitoring and protection for one part of the proposed circuit as well as one phase current as input to the discrete wavelet transform to detect and monitor the broken rotor bars, short stator winding and open stator winding and many other faults, as is shown in Fig.10.

DWT analysis to precisely determine the motor condition adheres to the following procedure:

1. Current, voltage, DC voltage signals acquisition.
2. Processing the broken rotor bar, short stator winding and open stator winding interval test to be processed using the discrete wavelet transform as can be seen in Fig.10.

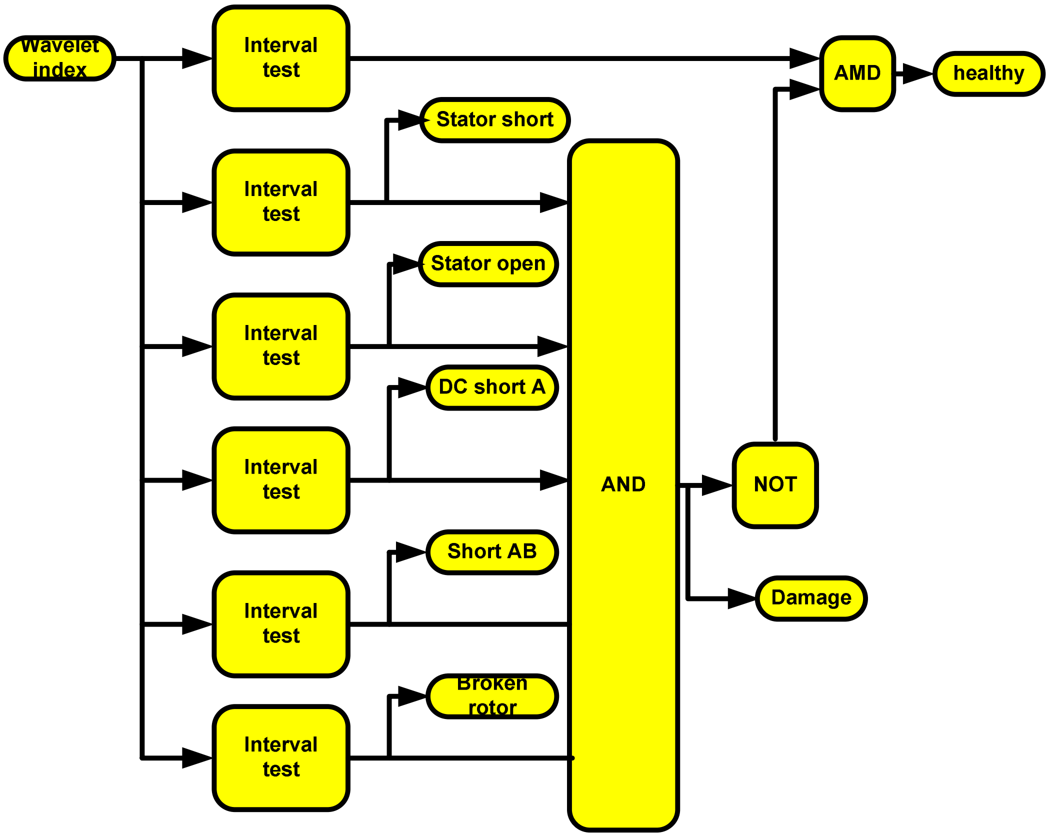

Figure 10: Fault detection interval test of wavelet index.

3. With these analyses determine the wavelet index to determine the stator, rotor bar status.
4. Analyze stator current and voltage using negative sequence to determine both AC current and voltage over, under and unbalance.
5. Analyze the induction motor speed to determine the under and over speeds.
6. The output of each stage is sent to an OR gate and encoding circuit to give indication of fault (0 or 1) and trip status respectively.
7. The output of the OR gate is considered as a monitoring unit to show both the trip and the time of the trip as can be seen in Fig.12.
8. The output of the encoding is part of the monitoring unit to show the trip status.
9. If the faults of the induction motor are high, the operation is halted. This is considered the protection unit.

The proposed circuit for detection and monitoring is shown in Fig.11.

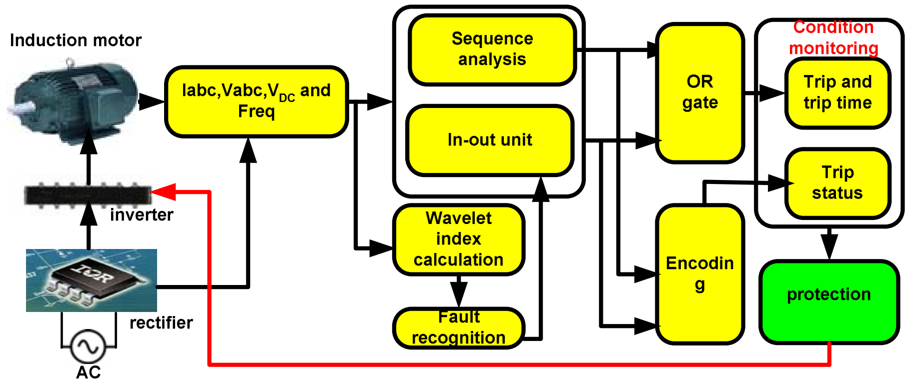

Figure 11: Procedure of monitoring and protection.

The internal connections of both detection and monitoring induction motor units are shown in Fig.12.

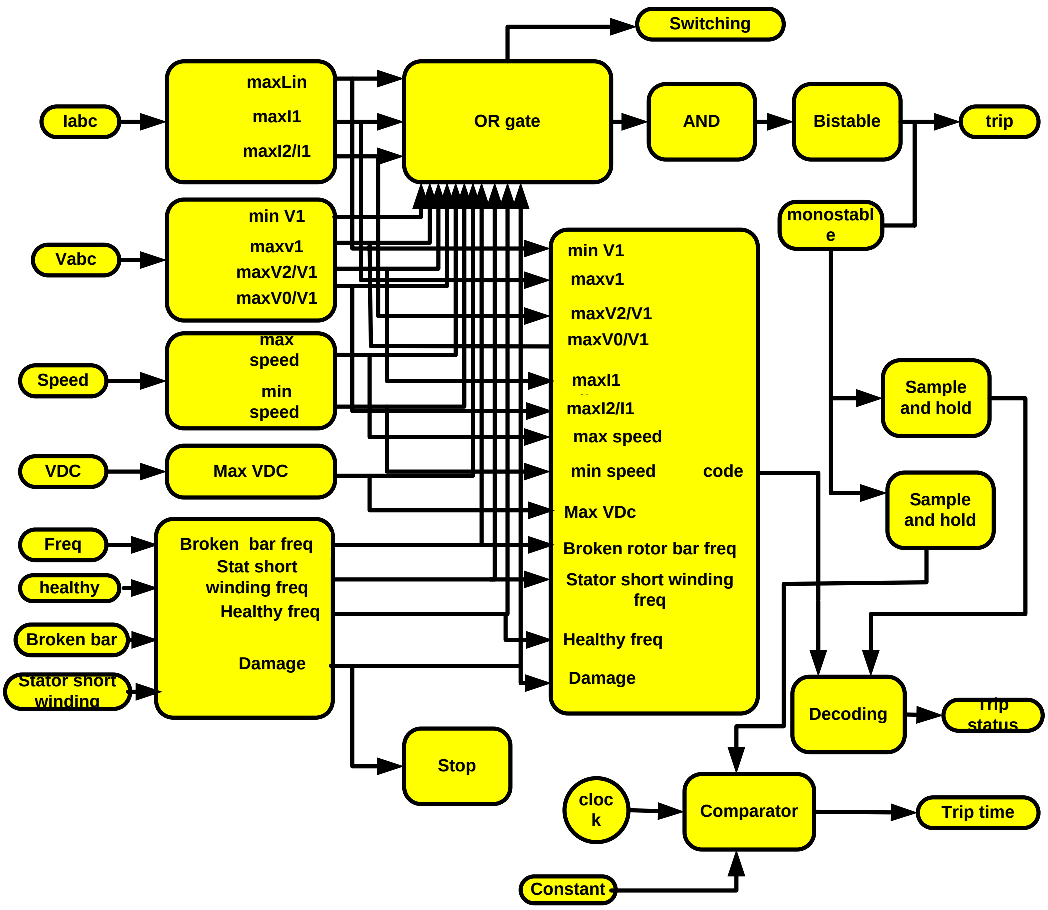

Figure 12: Internal connections of both detection and monitoring units.

Protection

To complete the system performance, a protection unit is added to be more efficient. The protection circuit is a novel technique to halt the faulty induction motor without any circuit breaker by setting the space vector modulation (SVM) pulses to zero through the switching mechanism. This behavior depends on the severity of the faults as can be seen in Fig.13.

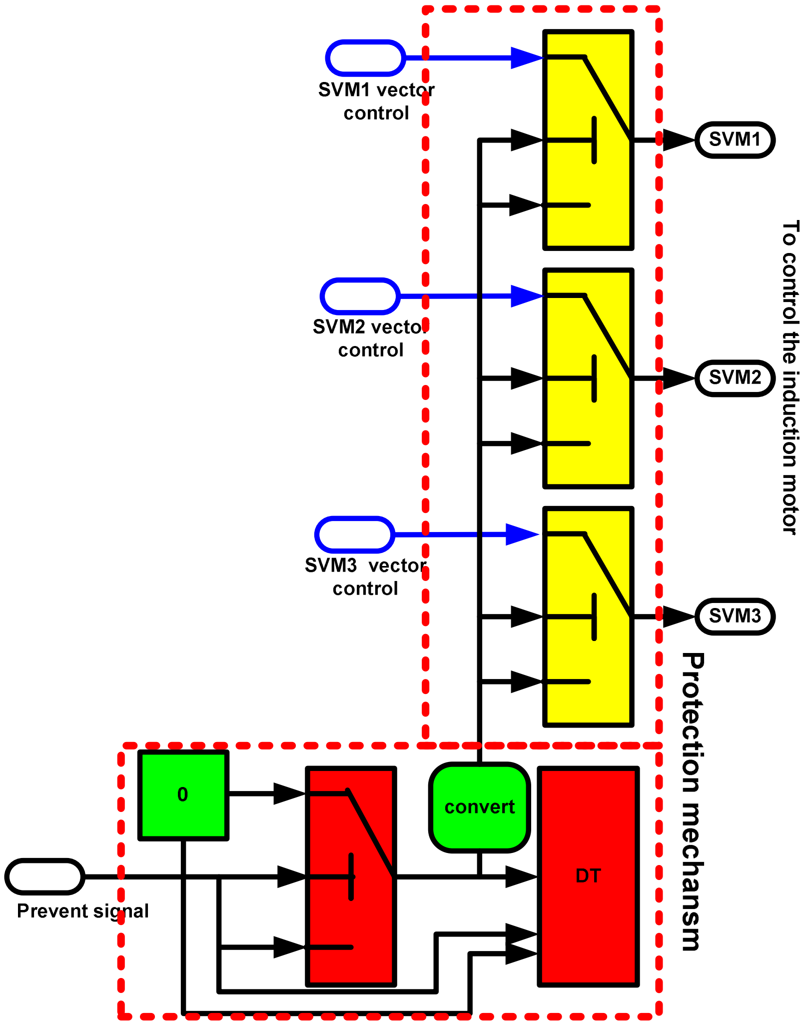

Figure 13: Protection unit mechanism.

The output of the detection unit in the healthy operation is logic 0. This output will be logic 1 in the faulty case to enable the switching mechanism to set the SVM generated by vector control to zero, hence stopping the induction motor.

To check the effectiveness of the proposed methodology, against multiple faults, three case studies are performed:

Case study

Healthy case

The healthy induction motor is tested first under normal operation conditions. The space vector pulse and the trip status are plotted in Fig.14. The comparison between the actual and reference speed is shown in Fig.15.

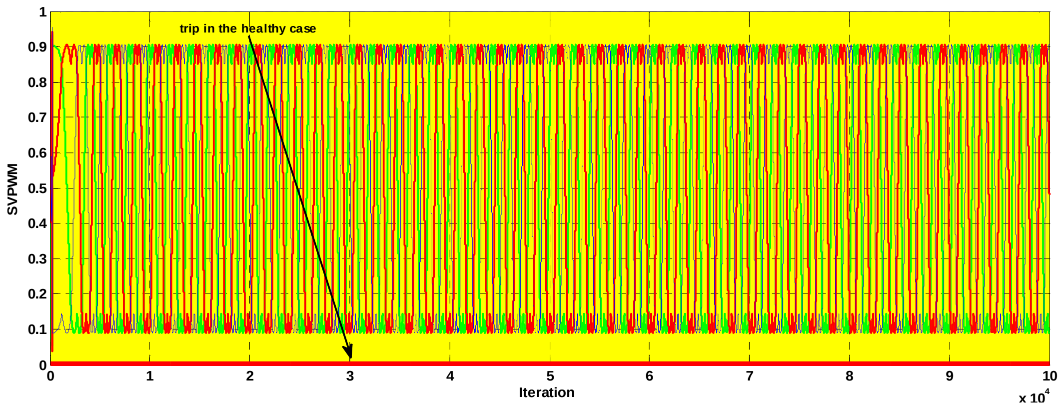

Figure 14: SVPWM with trip in healthy case.

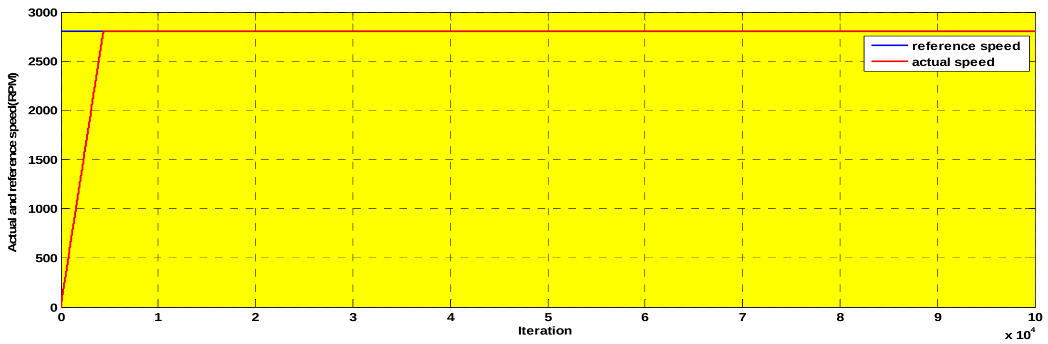

Figure 15: Actual and reference speeds in healthy case.

The monitoring of both trip time and status of the trips is shown in Fig.16.

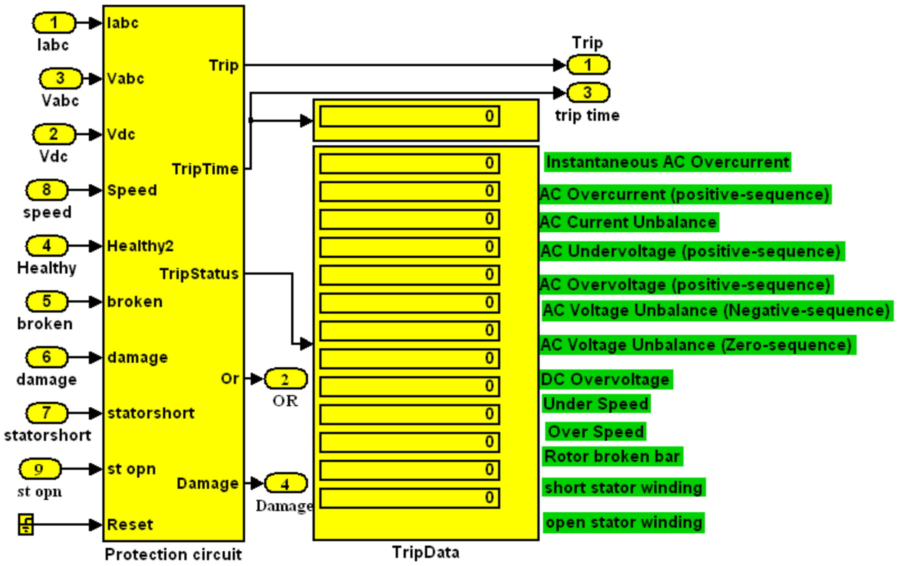

Figure 16: Simulink monitoring circuit for the healthy case study.

High severity case study

In this case study, multiple faults are subjected to the induction motor at the beginning of operation. These faults are AC under voltage, unbalance in one of the three line voltages as well as the speed sensor. The monitoring unit effectively shows all the trips and the time of the first fault is recorded as shown in Fig.17.

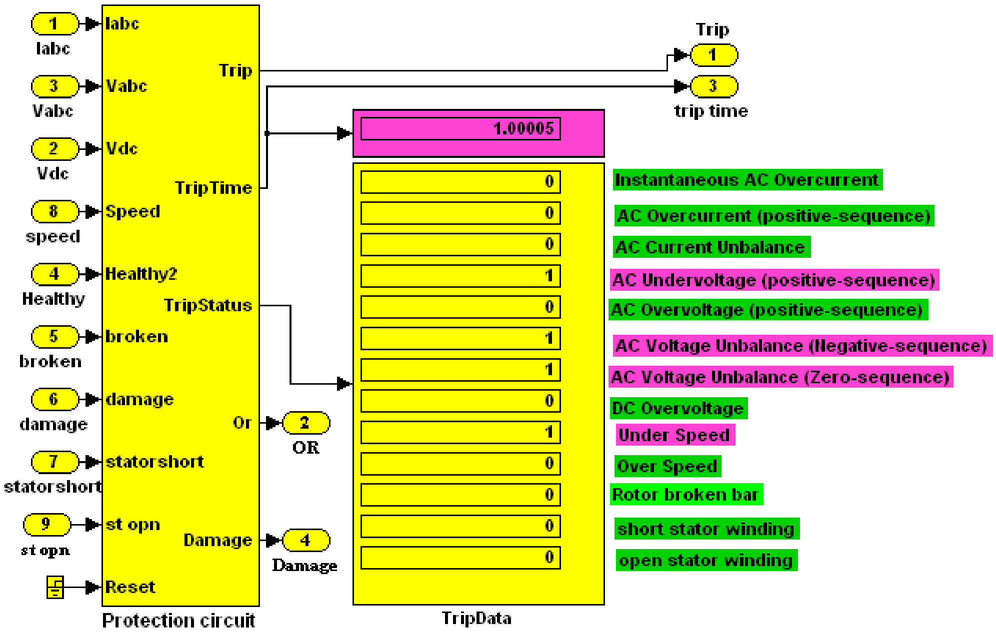

Figure 17: Simulink monitoring circuit for the first case study.

As mentioned earlier the output of the detection unit is 1 in the case of faulty machine as can be seen in the blue line in the Fig.18.

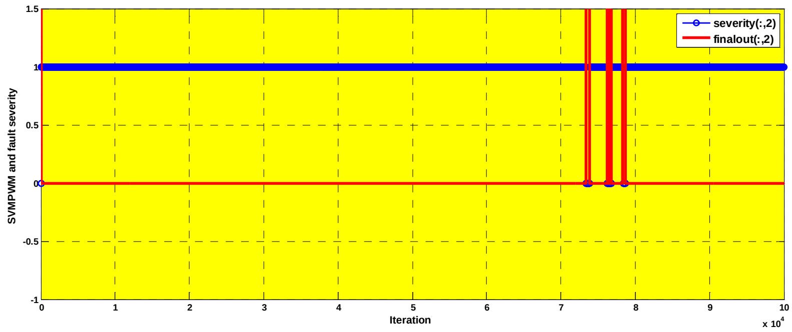

Figure 18: SVM (red) with trip (high severity fault).

Low severity case study

In this case study, one broken rotor bar with minimum speed is considered. Key reasons for a broken rotor bar are [21]:

1. Direct on line starting which leads to excessive heating and mechanical problems.
2. Variable mechanical load.
3. Unsatisfactory rotor cage manufacturing.

Broken rotor bar faults can be simulated by connecting three resistances with the rotor resistance so that by increasing one of the rotor phase resistances, the broken rotor bar equivalent resistance can be computed as in (9).

$$R_{brk} \cong (0.33/4) R_r z_{nb} / N^2_s \qquad (9)$$

The external added resistances are changed in 0.0833 Ω steps, which represent the difference between the reference rotor resistance and the original rotor resistance for one broken rotor bar. Reference rotor resistance depends on the number of broken bars and the total number of rotor bars [22]. The resistance of the induction motor rotor bar is assumed to be high.

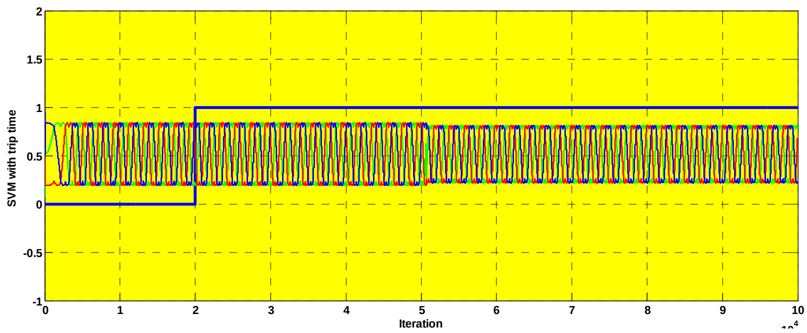

Figure 19: SVM duty cycle with trip (low severity fault).

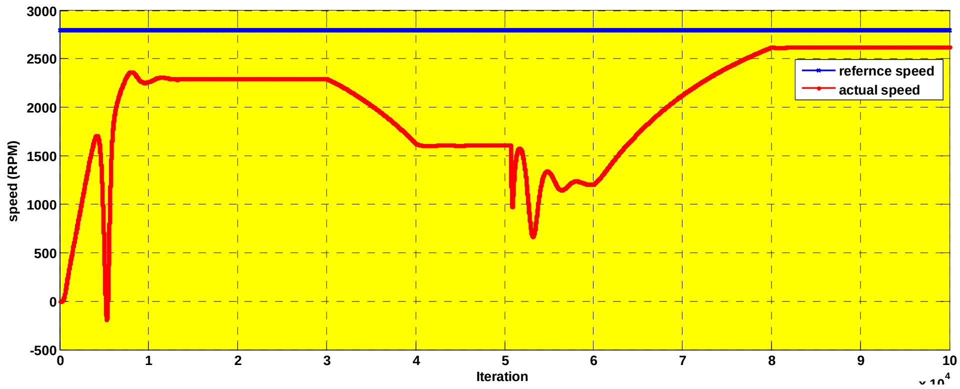

Figure 20: Speed response of both actual and reference.

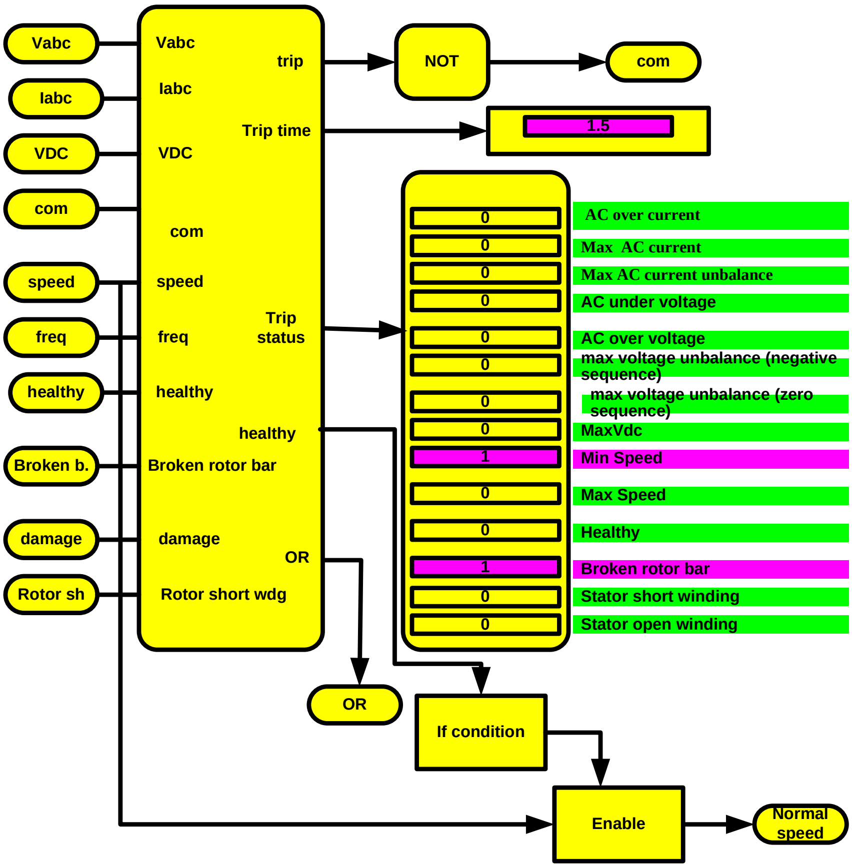

Figure 21: monitoring unit in the broken rotor bar.

Simulation results

Computer simulations using Matlab/Simulink have been performed for assessment of the operating features of the proposed scheme. The simulation involved a startup of a

0.5Hp, 230V, 50 Hz induction motor as is shown in Table 2. One phase of stator current is used as the input to the wavelet circuit. A higher order of wavelet (db10) is used to introduce better signal accuracy. As is clear from Fig.9, the standard deviation of wavelet index for different faults is an effective differentiating factor between healthy and faulty states of the induction motor.

Fig.14 shows the SVM duty cycle of the healthy case as well as the trip status which is always zero (red line). Fig.15 shows the actual and reference speeds, which completely coincide. Fig16 shows the trip status of the healthy case which is zero for all trips. Fig.17 and Fig.18 show both the trip existence and space vector modulation of the second case study. In the beginning of the operation, there is a high severity of faults so the output is zero to control the operation of motor. After that, we remove the fault for a short period so that there is an SVM pulse. Fig.19, Fig.20 and Fig.21 show low SVM with trip, actual and reference speeds and monitoring graphs respectively for low severity faults with one broken rotor bar. The fault time is 1.5 sec and the degradation of speed performance lasts for 1 sec after which the system behaves in a satisfactory manner. The duty cycle varies between 20% and 80 %. The figure does not start from zero because there is a 1 sec delay. Fig.22 shows the flowchart of the proposed monitoring and protection according to the wavelet index.

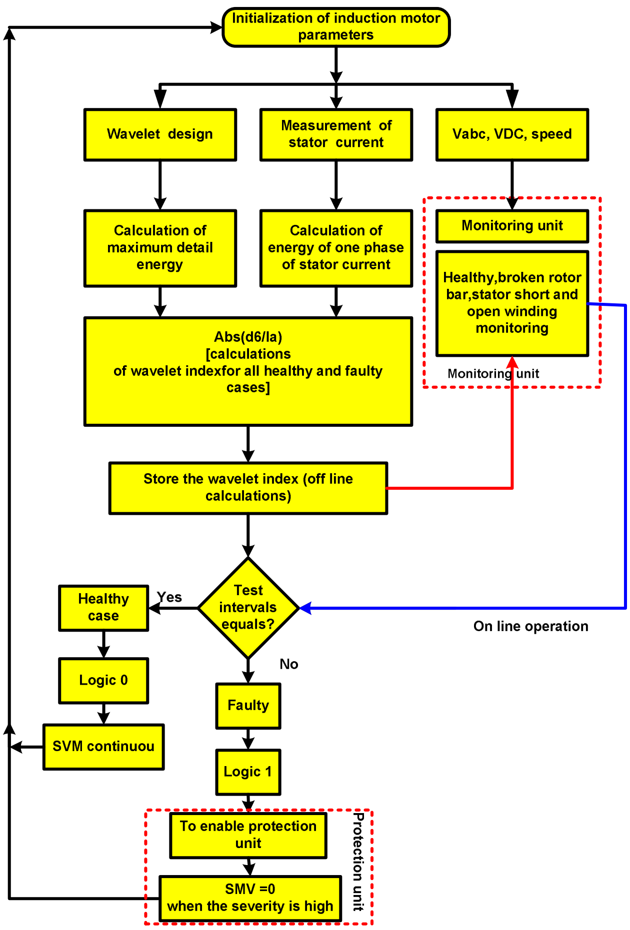

Figure 22: flowchart of the monitoring and protection circuit.

Conclusion

A number of conclusions can be derived from this work:

- The proposed method is effective in identifying a wide range of machine faults, as is evident from the simulation results.
- Condition monitoring with wavelet transform is a practical method to monitor electrical or mechanical faults.
- The monitoring method was able to identify the changes in running conditions and the protection technique was successfully implemented subsequently.
- The wavelet index was shown to properly differentiate between faulty and healthy states of an induction motor.

References

[1] Gaeid, Khalaf Salloum, Hew Wooi Ping, and Haider A.F.Mohamed. "Diagnosis and Fault Tolerant Control of the Induction Motors Techniques: A review." Australian Journal of Basic and Applied Sciences 4, no. 2 (2010): 227-246.

[2] Bodkhe, S. B., and M. V.Aware. "Speed-sensorless, adjustable-speed induction motor drive based on dc link measurement." International Journal of Physical Sciences 4, no. 4 (2009): 221–232.

[3] Lindh, Tuomo. "On the Condition Monitoring on induction machines." Thesis for the degree of Doctor of Science (Technology). Lappeenranta University of Technology, 2003.

[4] Georgakopoulos, I.P., E.D. Mitronikas, and A.N. Safacas. "Condition monitoring of an inverter-driven induction motor using Wavelets." 8th International Symposium on Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, ELECTROMOTION.. 2009. 1-5.

[5] Zhu, Kunpeng, Yoke San Wonga Hong, and Geok Soon. "Wavelet analysis of sensor signals for tool condition monitoring: A review and some new results." International Journal of Machine Tools and Manufacture 49, no. 7-8 (2009): 537-553.

[6] Zhang, Pinjia, Yi Du, and Thomas G. Habetler and Bin Lu. "A Survey of Condition Monitoring and Protection." IEEE Transactions on Industrial Applications 47, no. 1 (2011): 34-46.

[7] Basaran, Dogan Gokhan Ece and Murat. "Condition monitoring of speed controlled induction motors using wavelet packets and discriminant analysis." Expert Systems with Applications, 2011: Article in Press.

[8] Mehala, Neelam, and Ratna Dahiya. "Rotor Faults Detection in Induction Motor by Wavelet Analysis." International Journal of Engineering Science and Technology 1, no. 3 (2009): 90-99.

[9] Thomson, W.T., and M Fenger. "Current signature analysis to detect induction motor faults." IEEE Industry Applications Magazine 7, no. 4 (2001): 26-34.

[10] Singh, G.K., and Sa'ad Ahmed Saleh Al Kazzaz. "Induction machine drive condition monitoring and diagnostic research-a survey." Electric Power Systems Research 64 (2003): 145-158.

[11] Menacer, Arezki, Mohamed Said, Nait Said, /Hamid Benakch, and Said Drid. "Stator Current Analysis of Incipient Fault Into Asynchronous Motor Rotor Bars Using Fourier Fast Transform" Journal of Electrical Engineering 55, no. 5-6 (2004): 122-130.

[12] Zafar, Jawwad, and Johan Gyselinck. "CUSUM based Fault Detection of Stator Winding Short Circuits in Doubly-Fed Induction Generator based Wind Energy Conversion Systems." International Conference on Renewable Energies and Power Quality. 2010. 1-4.

[13] Luis A. Garcia-Escudero, Oscar Duque-Perez,Daniel Morinigo-Sotelo Marcelo Perez-Alonso. "Robust condition monitoring for early detection of broken rotor bars in induction motors." Expert Systems with Applications 38 (2011): 2653–2660.

[14] Mehrjou, Mohammad Rezazadeh, Norman Mariun, Mohammad Hamiruce Marhaban, and Norhisam Misron. "Evaluation of Fourier and wavelet analysis for efficient recognition of broken rotor bar in squirrel-cage induction machine." 2010 IEEE International Conference on Power and Energy,PECon. 2010. 740-743.

[15] Ordaz Moreno, A. de Jesus Romero-Troncoso, R. Vite-Frias. "Automatic Online Diagnosis Algorithm for Broken-Bar Detection on Induction Motors Based on Discrete WaveletTransform for FPGA Implementation." IEEE Transactions on Industrial Electronics 55, no. 5 (2008): 2193 –2202.

[16] Biju K, Jagadanand G, and Saly George. "Fault Detection of Induction Motor using Energy and Wavelets." Proc. of Int. Conf. on Control, Communication and Power Engineering. 2010. 210-214.

[17] Mamat-Ibrahimm, M.R., M.R. Tamjis, and T. Lachman. "Condition monitoring algorithm for induction motor drive." IEEE Region 10 Conference TENCON. 2004. 9-12.

[18] Habetler, T.G., R.G. Harley, R.M. Tallam, Sang-Bin Lee, R. Obaid, and J. Stack. "Complete current-based induction motor condition monitoring: stator, rotor, bearings, and load." IEEE International Power Electronics Congress,Technical Proceedings. CIEP. 2002. 3-8.

[19] Chetwani, S. H., M. K. Shah, and M. Ramamoorty. "Online Condition Monitoring of Induction Motors through Signal Processing." Proceedings of the Eighth International Conference on Electrical Machines and Systems,ICEMS. 2005. 2175-2179.

[20] Siddique, Arfat, G. S. Yadava, and and Bhim Singh. "A Review of Stator Fault Monitoring." IEEE transaction on energy convertion 20, no. 1 (2005): 106-113.

[21] Ahmed Y. Ben Sasi, Fengshou Gu, Yuhua Li and Andrew D. Ball. "A validated model for the prediction of rotor bar failure in squirrel-cage motors using instantaneous angular speed." Mechanical Systems and Signal Processing 20, no. 7 (2006): 1572-1589.

[22] akır, Hakan C¸ alıs¸ Abd ulkadir C¸. "Rotor bar fault diagnosis in three phase induction motors by monitoring fluctuations of motor current zero crossing instants." Electric Power Systems Research 77 (2007): 385–392.