2005 WSEAS Int. Conf. on DYNAMICAL SYSTEMS and CONTROL, Venice, Italy, November 2-4, 2005 (pp517-522)

Embedded Control and Diagnostics Algorithm with Fault Prediction and Analysis of AC Induction Machines

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Abstract:—Fault diagnostics of induction machines have been widely researched however, an integrated motor control with automated fault detection, prevention and condition monitoring is still missing. Condition monitoring can reduce the downtime of the processes and increase the maximum interval between failures, thus minimizing the number and cost of unscheduled maintenances, which is highly beneficial. Also an integrated approach can reduce the cost of the system and enhance its integrity. A new algorithm is introduced for control with embedded systems fault prediction and analysis of AC induction machines. The embedded control and diagnostics algorithm is implemented using the Analog Devices Blackfin™ ADSP-BF531 digital signal processor (DSP) which mainly controls the AC induction machine, and communicates to a Windows XP™ PC through the USB to monitor and display the electrical parameters of the inverter and the Motor. The algorithm employs various techniques to detect and predict different faults of the AC drive system. In this paper the Inverter fault prediction and diagnosis are covered.

Key-Words:-Blackfin ADSP-BF531, DSP, Motor Control, Condition Monitoring, Induction Motors, IGBT Fault.

1 Introduction

The squirrel cage Induction Machines are the main workhorse of the industry due to its ruggedness versatility and low manufacturing cost. They are used in many industrial processes, converting electrical energy to mechanical energy. The Voltage Source PWM Inverter too has become the most common of inverts to be coupled with this motor due to its simplicity and ease of use.

Most commonly many motor drive systems are coupled to form a single industrial process; hence, a malfunction in a single motor can often lead to the failure of the entire plant or process. Reducing the downtime and the maintenance interval of these processes is highly desired. Therefore, condition monitoring can aid in evaluating the economical condition of the systems to help commission its repair. According to an IEEE, sponsored survey [1] three quarter of all motor failure can be prevented with early diagnosis by employing appropriate prevention or prediction technique.

Types of fault and their detection methods are discussed in section 2. Section 3 discusses the current fault prevention techniques employed. In section 4 an overview of the experimental test system is presented. Section 5 presents automatic detection of the power IGBT condition monitoring and deterioration. Section 6 presents the conclusions.

2 Faults in Motor Drive System

Faults in induction motors can occur in any of the three main components of the motor:

- Stator
- Rotor
- Bearings.

While in the inverter several possibilities ranging from:

- DC link capacitor
- Power transistor
- Inductive elements.
- Diodes.
- Solder joints.

These can account for most faults. Traditionally fault detection and prediction have been an independent process aimed mainly in the motor, used to detect broken rotor bars, stator windings inter-turn, phase-to-phase or phase-to-ground short circuits, bearing failures, air-gap eccentricity, etc, these have been well documented [2]-[5]. Modern inverters have fault protection system built in but systems that can reasonably prevent a total drive breakdown with system monitoring the control algorithm through to the motor is still missing.

Faults in the drive can be classified into three different groups:

- Growing faults with only small effects on the operation.
- Partial non catastrophic faults with emergency operation possible.
- Catastrophic faults with total drive breakdown.

The causes of faults can be categorized in to two groups: Mechanical and Electrical [6].

Mechanical causes of failure

- Misalignment
- Mechanical unbalance
- Soft foot (all four corners of motor base do not rest smoothly on the mounting frame)
- Bearing fatigue
- Fractured rotor bars or end rings
- Overheating
- Loss of cooling
- Improper lubrication

Electrical causes of failure

- Poor power quality
- Resistance / Impedance and Inductance unbalance
- Insulation failure
- Excessive loading/current

3 Fault Prevention Techniques

A great deal of effort has been put into induction machine fault detection and prevention techniques, they have been based on current / voltage spectrum analysis, vibration spectrum analysis, resistance / impedance measurements, three phase electrical imbalance detection and parameter estimation, are a few to mention.

Of the mechanical causes of faults misalignments, unbalances and soft foot are most common and easy to diagnose and correct, these will not be investigated.

Bearing fatigue and Fractures in the rotor bars or end rings have been well researched and documented [7] they produce amplitude and phase angle modulation of the supply current, producing sidebands around the fundamental supply frequency (fs) at $(1\pm2S)\,fs$.
Where $S = (fs - fr) / fs$ and is defined as the non-dimensional slip ratio, fr is defined as the rotor frequency. Therefore S lies between zero and one, standstill to synchronous speed respectively but in reality zero is not attainable, hence a slip of 1-10% will exist.

Using spectrum analysis the amplitude ratio of these sidebands to the line frequency component are analysed to predict the health of the motor. Vibration analysis is also often used to determine rotor health, broken rotor bars or end rings which produces pole pass frequency sidebands at ($\pm fp$) around the rotor mechanical speed (fr) which is defined as number of poles (P) times the slip frequency ($fslip$,) i.e.,
$fp = P*fslip$

Vibration analysis is less reliable than current analysis due to presence of resonance from mechanical unbalance and faults. However they can be combined to complement each other for a more reliable result.

Overheating can destroy the bearing and the windings of the motor. Excess heat causes materials to melt into the lubricant leaving craters. Since the oil field strength is 10^6 v/m and a typical mineral oil film is 0.2 microns thick with two in series therefore the bearing threshold voltage becomes 0.4 volts. The ball, lubricant and race acts like a capacitor and charges via the shaft voltage causing high impulse currents (nanosecond) , on occasions this exceeds the threshold thus eroding the bearings over time. This is commonly referred to as fluting or Electric Discharge Machining (EDM).

Overheating of the insulation in the stator windings can lead to winding shorts or breakdown of insulation to ground [7]. The causes of these are usually:
Voltage unbalance, Overloading or Contamination in the windings.

Voltage unbalances causes unbalances in the currents resulting in overheating, they are easily detectable and if remedied early enough can prevent far serious faults.
Contamination in the winding may be restored by

cleaning, dipping and baking the stator if detected in time.

Temperature can be monitored using sensors placed on the coils or Infrared Thermography based on the principle that all objects having temperature above absolute zero emit energy or radiation, are good method of fault detection.

The power supply quality monitoring is another good method for motor predictive maintenance, giving good indication to motor health [8]. This involves monitoring the deviation of the Voltage level, frequency, voltage unbalance, power factor and harmonics.
The Typical allowed variations are [6]:

Voltage level = <10%.
Voltage unbalance = <3%.
Frequency variation = <5%.
Voltage harmonics = <5% THD (Total Harmonic Distortion) [9].
Current harmonics = <3% THD [9].

And the optimal power factor is 1 however, in most systems a power factor of 0.85 is considered OK.

Resistance / Impedance unbalance monitoring is the most convenient form of detection method for predicting faults over time [10]. This method is best for resistance, impedance and inductance. While resistance values are effected by temperature, the relative difference between the phases is constant, impedance and inductance are not significantly impacted by temperature. Winding faults usually develop gradually, with the resistive and capacitive values of the insulation changing at the point of fault, thus the power losses at this point increases gradually due to higher currents and increasing temperature, eventually causing the insulation at this point to carbonize rapidly. Finally, the insulation breaks down, often in an explosive rupture due to the high energy within this point.

4 Experimental System Overview

The Analog Devices Blackfin™ ADSP-BF531 is the heart of the system, chosen for its internal peripherals, its versatility to communicate with external peripherals, and its low cost high processing ability. A simplified overview of this system is shown in Fig. 1 below.

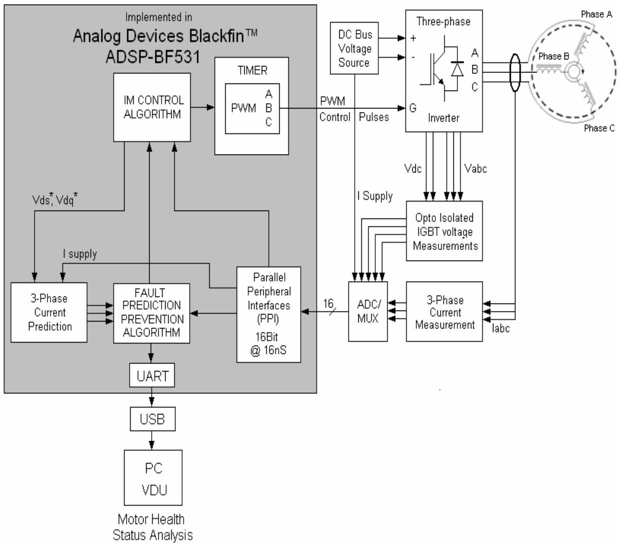

Fig. 1. The Experimental System

The motor controller is the primary algorithm, which is executed by the Blackfin DSP, the ADSP-BF531. The DSP incorporates 3 timer units that are switched to PWM mode, generating the motor control pulses that are needed to drive the inverter. This mode of use is possible due to most modern inverters having their own fault prevention circuitry incorporated in their design, which include automatic dead time insertion that ensures against IGBT shoot through and false turn on. However, the ADSP-BF531 has only 3 PWM outputs thus we need additional circuitry to generate 6 PWM signals required by the inverter therefore, these outputs are inverted to produce their complement to feed the high and the low side signals to the inverter, as shown in Fig. 2 below.

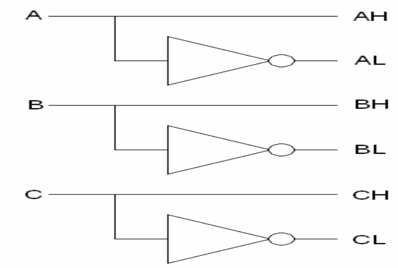

Fig. 2. Inverted complementary PWM signals

Feedback to the ADSP-BF531 is via its parallel peripheral interface (PPI) that can connect directly to parallel A/D and D/A converters. The PPI is 16 bits wide supporting a maximum speed of 15nS or 66 Mega samples per second (MSPS), which is more than adequate for any motor control application.

The fault prediction system is made-up of a number of sensors ranging from low pass filters (LPF), Hall Effect current sensors to opto-isolated op-amps. LPF are used to detect DSP failure at the PWM output, under noisy environments the DSP running the control system program can be effected by electrical noise causing the control system program to crash, leaving the DSP useless. Hall Effect current sensors are utilised to measure the 3-phase current drawn by the induction motor and the supply current drawn by the inverter. As the currents drawn by the 3-phases of the motor are dependent on the condition of the coils and the motor, analysing these currents can give a good indication on the condition using an appropriate diagnostics algorithm a catastrophic fault can be prevented. However faults can develop anywhere in the system, to gain more information on the condition of the complete system we have to take into consideration the Inverter and its power source. Therefore, opto-isolated op amps are used to measure voltages around the inverter IGBT and the power source, giving information on the health of the IGBT, the quality of the power source and the condition of the inverter. These are then multiplexed into a fast A/D converter and fed to the DSP via the PPI.

5 IGBT Condition Monitoring

Experimental data was collected with a simulated fault in one of the IGBT using a resistor placed between its source and drain as shown in Fig. 3 below.

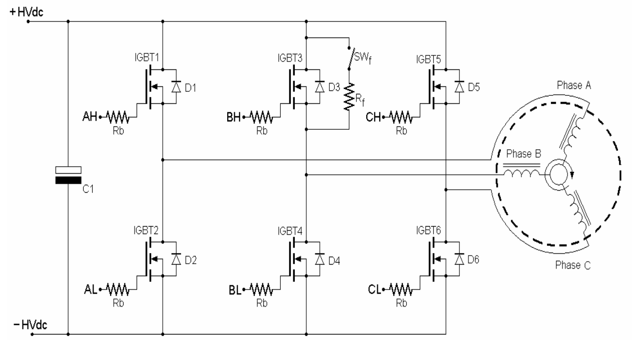

Fig. 3. IGBT power inverter with leakage resistor (Rf)

The inclusion of resistor Rf in Fig. 3 is simulating component ageing and drift causing a small leakage current to flow through to one of the coils of the motor. The stator phase currents of the motor under healthy and fault condition (with and without resistor Rf) are shown in Figs. 4 and 5, respectively.

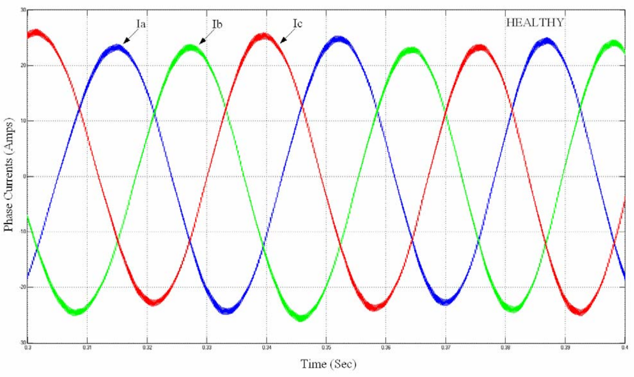

Fig. 4. Stator phase currents under healthy conditions.

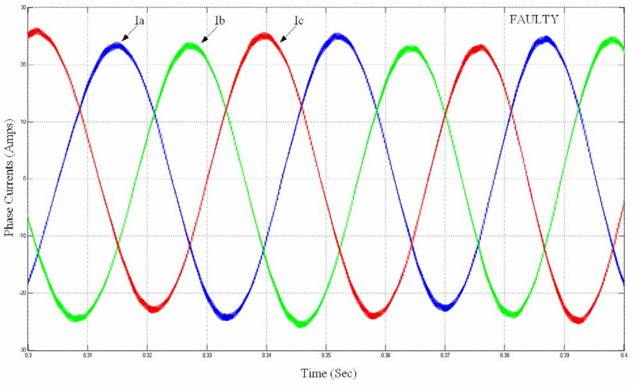

Fig. 5. Stator phase currents with IGBT 3 faulty.

From Fig. 5 we can see that the motor currents look normal and no fault exists, the motor also runs normally, however we know that IGBT 3 is leaking a small current. Using a new method, we project the current and compare with measured currents to identify the faulty component.

Projected Currents:

$$I_a^* = \left[\left(\int I_{dcbus}\right) \times \sin\left(\angle u_s + \frac{\pi}{3}\right)\right] \quad (1)$$

$$I_b^* = \left[\left(\int I_{dcbus}\right) \times \sin\left(\angle u_s - \frac{\pi}{3}\right)\right] \quad (2)$$

$$I_c^* = \left[\left(\int I_{dcbus}\right) \times \sin\left(\angle u_s - \frac{2\pi}{3}\right)\right] \quad (3)$$

$\angle u_s$ is the stator voltage angle, I_{dcbus} is the dc current supply bus of the IGBT's, and I_a^*, I_b^*, I_c^* are the projected stator currents of each phase.

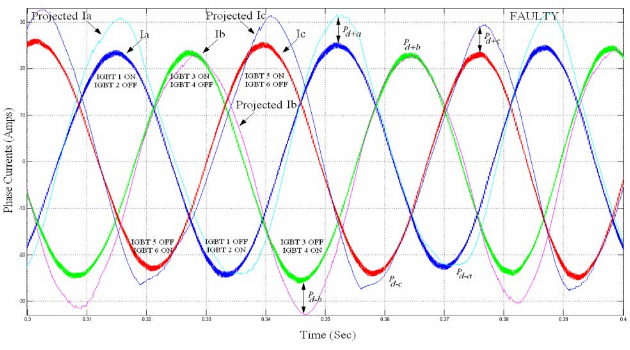

Fig. 6. Stator phase currents and projected phase currents with one faulty IGBT.

Fig. 6, plots the measured phase currents against the projected phase currents, which clearly shows the projected Ib current having the largest negative peak than the rest. This is due to IGBT 3 on the high side of phase B leaking current that is then shorted to ground by IGBT 4 when it is turned on. This small leak does not effect the performance of the motor, but it can be a strain on the power source with increased current demand, and it also generates more heat which lead to a complete failure of the IGBT and/or power supply.

A table can be drawn that identifies which IGBT is like to be faulty with this type of fault.

Ia (Error)		*Ib* (Error)		*Ic* (Error)		Diagnosis
Pos	Neg	Pos	Neg	Pos	Neg	
0	0	0	0	0	0	OK
0	1	1	0	1	0	IGBT 1
1	0	0	1	0	1	IGBT 2
1	0	0	1	1	0	IGBT 3
0	1	1	0	0	1	IGBT 4
1	0	1	0	0	1	IGBT 5
0	1	0	1	1	0	IGBT 6

Fig. 7. Fault diagnosis table A.

The table in Fig. 7 helps to identify the faulty IGBT under current leak conditions. A '0' represents less than 10% (or a predefined threshold) difference between the projected and the measured positive (Pos) and negative (Neg) current peak cycle of the phases, while a '1' represents a difference of greater than 10% (the predefined threshold).

A method for detecting IGBT current leak within one complete PWM cycle has been successfully presented. IGBT's have a low On-state resistance in the order of a few mili-Ohms, giving a low saturation voltage therefore the on-state losses are low. But the On-state resistance can drift with age and temperature causing voltage unbalance, which cause overheating of the coil and IGBT eventually leading to a complete failure. Fig. 8 below shows the phase currents of the motor with IGBT 3 incorporating a high on state resistance of 0.5 Ohms appose to the normal 0.001 Ohms.

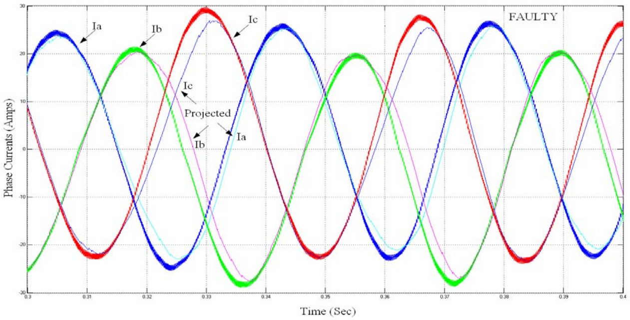

Fig. 8. Phase currents with high on state resistance fault on IGBT 3.

In Fig. 8, all three-phase currents show a slight DC offset, with I_b showing the most. This unbalance of currents can cause severe damage to the motor if not remedied in time. This can be automatically detected using a suitable algorithm as the one developed and shown in Fig. 9 below, the behaviour of the DC offset can be used to detect the faulty component.

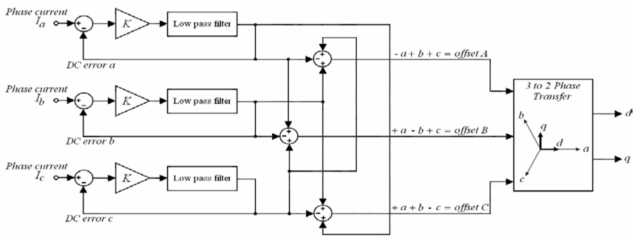

Fig. 9. Algorithm to extract three-phase DC error.

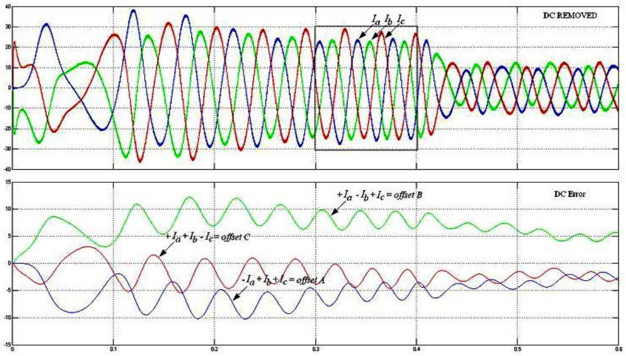

Fig. 10. Phase currents with DC components removed (top), 3 phase DC error (bottom).

The three-phase DC Error signals shows the signal *Offset A* and *Offset C* by both converging to half the DC offset of *Offset B*. If we observe the dq signals from Fig. 9 we obtain the plot shown in Fig. 11.

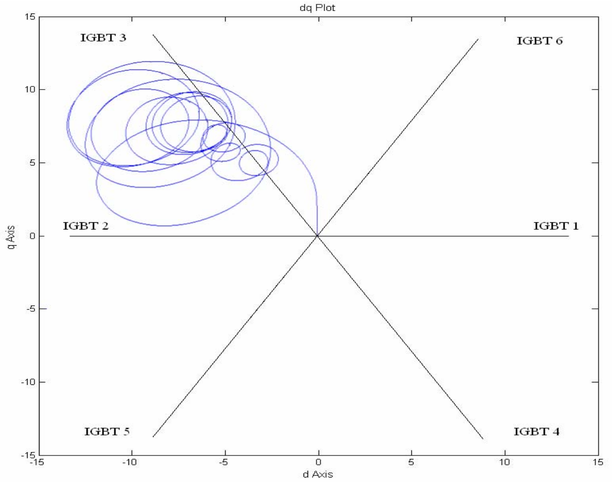

Fig. 11. dq Plot of DC offset error.

From this data we can characterise the faults to identify the faulty power switch in the three phase driver. The table in Fig. 11 below maps the signal offset error to the faulty component.

dq Offset	Fault
≈ 0	NONE
$< M_T\angle 0°$	IGBT 1
$< M_T\angle 180°$	IGBT 2
$< M_T\angle 120°$	IGBT 3
$< M_T\angle 300°$	IGBT 4
$< M_T\angle 240°$	IGBT 5
$< M_T\angle 60°$	IGBT 6

Fig. 11. Fault diagnosis table B.

M_T is the magnitude threshold which when exceeded an event can be triggered to indicate the corresponding IGBT fault.

6 Conclusions

A low cost high performance system for induction motor control with integrated diagnostics has been presented. For this paper the focus on the type of fault has been narrowed down to the IGBT. As the main current flow in the system is from the power supply to the motor via the inverter, monitoring the currents at certain stage of the current flow is the most logical technique for fault detection. Experimental results prove the algorithm is an adequate method for IGBT fault prevention and condition monitoring. It has demonstrated to allow correct identification of the faulty IGBT.

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