2.1 INTRODUCTION

Failure surveys (IEEE Survey 1985, Thorson and Dalva 1997, Bonnet and Soukup 1992) have reported that percentage failure by components in induction motors is typically

i) Stator related : 38%

ii) Rotor related : 10%

iii) Bearing related : 40%

iv) Others : 12%

During the past 15 years, there has been a substantial amount of research into the development of new condition monitoring techniques for induction motors. Excellent examples of typical failures in random wound, low voltage induction motor are shown in Bonnet and Soukup (1992). Pre-warning of motor failure such as in Bonnet and Soukup (1992), Thomson (1984) can only be achieved if shorted turns within a coil can be initially diagnosed via on-line diagnostic techniques. This requires continuous on-line monitoring to diagnose the faults stated in IEEE Survey (1985), Thomson and Dalva (1997) for low voltage induction motors.
In order to assess the efficiency and effectiveness of the manner in which induction motors are used in industry, the U.S. Department of Energy and the Bonneville Power Administration (BPA) investigated a three-phase study into the estimation of the efficiency of in-service induction motors in 1994. Phase one of the study was conducted by the Oak Ridge National Laboratory (ORNL) and the results of the ORNL study are available, in Hsu et al (1995) and Kueck et al (1996). Phase two of the BPA program has been undertaken by Washington State Cooperative Extension Energy Program and the Motor Systems Resource Facility (MSRF) at Oregon State University. Phase three of the program considered the above two studies that appear most appropriate, following laboratory testing and apply them in industry (Wallace et al 1997).

Following the macro review of IEEE and ERPI on potential motor troubles, effects and the resultant failure categories, (IEEE Motor Reliability working group 1985 and 1987, Hobson 1965, Bonnet 1978) the majority of motor troubles is categorized into four groups:

i) Unbalance Voltage Effects
ii) Single phasing effects
iii) Overloading Effects
iv) Environmental and Maintenance Effects

The knowledge about fault mode behavior of an induction motor drive system is extremely important from the stand point of improved system design, protection and fault tolerant control. Mohammed et al (2000) had taken the initial step to investigate the efficiency of current monitoring for diagnostic purposes.
2.2 MODELLING, SIMULATION AND FAULT ANALYSIS

Zhongning Ye and Bin Wa (2001) presented the simulation of three-phase induction motor drive system with emphasis on the electrical faults of the induction motor. Using the basic components of MATLAB/ SIMULINK tool boxes, the drive system is modeled. It is shown that the stator current can be used for detection of the electrical faults in the induction motor.


The study of induction motor fault detection and identification has been of increasing interest during the last 20 years and a great amount of research has been done on the topic. For example, Benbouzid (1999), lists 365 books, papers and articles related to induction motor fault diagnosis. A great number of induction motors are used in industrial plants and factories. If a motor is broken down in a production line, the line is obliged to be stopped. Much time may be required for recovery of the line, resulting in huge economical loss. Under such circumstances, establishment of fault diagnosis method of motors is strongly required to assure their operation with high reliability (Scheon et al 1995, Benbouzid et al 1999).

Toliyat and Lipo (1995) have shown through both modeling and experimentation that faults result in asymmetry in the machine impedance causing the machine to draw unbalance phase currents. This is the result of negative sequence currents flowing in the line. However, negative sequence currents can also be caused by voltage unbalance, machine saturation, etc.,
Klima et al (1996) model these unbalances which also includes instrument asymmetries. Detection of stator voltage unbalance and single phasing effects using advanced signal processing techniques have been described in Benbouzid et al (1999).


In most aforementioned studies (ANSI/IEEE Standard 141-1993, Natarajan 1989, ANSI / IEEE C37- 96 1988) the method of evaluating the level of voltage unbalance is either the percent voltage unbalance (PVU) defined by NEMA (National Electrical Manufacturers Association) or the voltage unbalance factor (VUF) defined by IEC (International Electrotechnical Commission). Operation of polyphase induction motors on unbalanced voltage can cause serious ill effect such as over heating and reduction in output torque. The magnitude of these ill effects is directly related to the degree of voltage unbalance. Section 14.34 of NEMA Standard MGI (1987) gives some excellent generalities and guidelines on this topic. Woll (1975) provides more detailed information on unbalanced voltage operation together with specifics on understanding and calculating its effects.

the application of a pattern recognition approach to detect electrical faults in an induction motor. Pragasen Pillay and Peter Hofmann (2002) examined the proper application of induction machines when supplied by unbalanced voltages in the presence of over and under voltages. Differences in the definition of voltage unbalance are also examined. The approach adopted is to use NEMA derating for unbalanced voltages as a basis to include the effects of under voltages through motor loss calculations.

Pragasen Pillay and Marubini Manyage (2006) estimate motor life when a motor is supplied with a combination of over or under voltages with unbalanced voltages. The motor life is predicted by estimating the stator winding insulation life of squirrel cage motors using Arrhenius’ equations. The operation of three phase induction motors when supplied by unbalanced voltages has been of major interest (Williams 1954, Gafford et al 1959). NEMA defines voltage unbalance as the maximum deviation from the average line voltage over the average line voltage. IEC defines voltage unbalance as the ratio of the negative sequence voltage to the positive sequence voltage (Muljadi et al 1959, Berrdt and Schmikz 1963).

Ching – Yin Lee (1999) uses a real load test to investigate the effects of an unbalanced voltage supply on an induction motor’s performance. The importance of the positive sequence voltage in the motor’s apparent performance and of the negative sequence voltage in the hidden damage is pointed out. The British standard BS-4999 “General Requirements for Rotating Electrical Machines” states that motor deliver their rated horsepower when fed continuously from a supply with a VUF of 2 percent or less. NEMA standard MGI 1245-(1987), state that operation of a motor above 5 percent voltage unbalance is not recommended. They do not specify the type of unbalance condition. In fact, some unbalance cases may have a lower PVU and a lower efficiency.
Generally speaking, each unbalance condition would lead to a different degree of extra temperature rise, and an induction motor would be damaged in a long-term or even short-term operation. However, only one temperature rise curve is provided for one value of PVU in most of the related documentation (Gafford et al. 1959). Besides, the output limit of an induction motor depends mainly on heating and the life span of the motor will be shortened by over heating. A derating factor was recommended by NEMA (1987). It gives factors only as a function of the percent VUF. William H. Kersting (2005) describes three different ways in which an induction motor will operate in a single phase condition.

Brighton and Ranade (1982) indicate that a 1.15 service factor motor operating at 115% motor loading will have a considerable shorter insulation life than a 1.0 service factor motor operating at 100% motor loading. IEEE standard 242 (1975) and Woodruff (1984) states the following: “Many motors, especially in the higher horsepower rating can be seriously damaged by negative-sequence current heating, even though the stator currents are low enough to go undetected by overload (over current) protection”. Therefore, phase unbalance protection is desirable for all motors, where its cost be of importance.

Supplying a three phase induction motor with unbalanced voltages has many negative effects on its performance. The influences of unbalance on the efficiency, temperature rise and life reduction, derating in the machine, increase of losses and the negative effects on the insulation life as well as the performance of the protective relays in motors operated with unbalanced voltage are some contributions in the area (Reed and Koopam 1936, Williams 1954). In many cases, only general qualitative results were presented and precise numerical values and characteristics have not been given. An additional drawback of these studies is that the definition of unbalanced
voltage and the resulting motor characteristics have not received attention. That is the prime focus of Jawad Faiz et al (2004). The extent of these effects depends directly in the magnitude of the unbalanced voltage at the motor terminals.

Yaw-Juen Wang (2000) presents an analytical study into the steady state performance of a three-phase induction motor powered by unbalanced supply voltage. The majority of the methods developed for detecting insulation failures are based on the negative sequence component of the motor currents. Because power supply unbalance can also cause the appearance of negative sequence current, modifications to the negative sequence currents approach have been performed to compensate for the impact of unbalanced machine operation (Sottile and Kohler 1993, Kliman et al 1996). Recently, by using an equivalent motor circuit model for shorted turns (Kliman et al 1996) developed the injected negative sequence current which is not affected from an unbalanced supply voltage but it appears sensitive to load variations.

To detect stator winding faults, several other techniques have been proposed. Statistical process control techniques have been applied (Dister and Schiferl 1996). The detection of stator voltage unbalance and single phasing effects using advanced signal processing techniques has also been presented by Benbouzid (1999). Also, recently the IEEE transactions on industrial electronics published a special section on motor fault detection and diagnosis, including two survey papers of tutorial nature regarding induction motor fault diagnosis (Benbouzid 2000, Filippatti et al 2000).

James H.Dymond and Nick Stranges (2007) discuss the instrumentation and testing of a four pole, 1120 kW induction motor that was tested at three different levels of unbalanced voltage. Results were presented on the stator and rotor heating, the speed-torque and locked rotor performance, as well as noise, vibration and shaft voltage.
According to a report on fault analysis of high voltage induction motor (Thorsen and Dalva 1999), stator winding is the component where an electric fault is observed most frequently, while mechanical one is often occurred in bearings or in rotor bars. Sharma and Arya (2007) describe a consideration in designing an induction motor, which gives desired and acceptable performance at different supply voltage even when operated without protection.

2.3 ON LINE MONITORING AND PROTECTION OF INDUCTION MOTOR

The condition monitoring of induction machines has received considerable attention in recent years. The diagnostics based on vibrations produced by these motors can form valuable data for preventive maintenance of these machines. Maruthi and Pandurange Vittal (2005), propose a technique of detecting abnormal electrical operating conditions in three phase induction motor such as single phasing, voltage unbalance by employing spectrum analysis of vibrations measured through MEMS accelerometer.

Some fault detection methods using Park Vector and torque in airgap have been proposed and studied by (Hsu 1995 and Cruz and Cardeso 2001). These physical quantities are rather difficult to be treated and it is desirable to find an alternative method which enables on-line monitoring easily. Rodriguez et al (2006) presented a method for determining the signatures of electrical faults in the air gap force and vibration pattern of induction machines. The monitoring of faults is achieved through measurement of vibrations in the stator frame. Berndt (1963) presented a method for calculating reduced motor rating. In the last decade, research in this field has mostly focused on the protection strategies.
Ehaled Schemata et al (2004) present design and implementation of two current relay prototypes. The first one is based on FPGA and the second one is based on Microcontroller. A complete summary of techniques for monitoring and protecting each major component of a low voltage, line connected induction motor is given in by Habetler (2002). A novel protecting method for motor’s over current is introduced by Dai Jun et al (2003). Venkataraman (2005) discusses the fundamentals of a motor thermal model and its mathematical interpretation and physics for the different stage of motor operation (Overload, locked rotor, too frequent or prolonged acceleration, duty cycling application).

A protection scheme was designed by Fahrudin Mekic et al (2005) so that all fault types and abnormal operating conditions are properly detected and declared. Vector control provides high performance to drives, but does not achieve a good transient response, a high electrical torque is required and it means high currents flowing in the machine. Apart from the achievement of decoupled and optimal control, it is also necessary to protect the motor against over currents (Mario J. Duean et al 2006).

According to an IEEE sponsored survey, three quarter of all motor failure can be prevented with early diagnosis by employing appropriate prevention or prediction technique. Digital techniques and more recently the advent of the microprocessor have brought further steps in the same direction. Abdul Kadir et al (2006) discuss types of fault and their detection methods. Lacroix and Clegi (1989) optimize the quality of the protection without any appreciable increase in cost.

Herbert Cheung et al (1993) illustrate the generalized protection and communication capabilities provided by a commonly used motor protection relay and to see how close we are achieving the goal of complete motor protection for large ac induction motors with one microprocessor based

The manufactures and users of electrical machines initially relied on simple protections such as over current, over voltage, earth fault, etc., to ensure safe and reliable operation. However, as the tasks performed by these machines grew increasingly complex, improvements were also sought in the field of fault diagnosis (Subhasis Nandhil and Toliyat 1999). It has now become very important to diagnose faults at their very inception; an unscheduled machine downtime can upset deadlines and cause heavy financial losses.

Early detection and diagnosis of incipient faults is desirable for online condition assessment, product quality assurance and improved operational efficiency of induction motors. Kyusung Kim et al (2003) developed a speed sensor less fault diagnosis system for induction motors using recurrent dynamic neural networks and multi resolution or Fourier based signal processing for transient or quasi steady state operation respectively.

Cummings et al (1985) have introduced a new protection concept, the VUF to integrate stator and motor losses for purposes of evaluating the effectiveness of protective devices, based on a half life concept of motor insulation subjected to unusual service conditions. Thermal limit curves for induction machines are defined by IEEE Std. 620-119 (1996). Dymond (1993) generated a broader understanding of the definitions, the methods of calculation and the thermal effects of stalling, accelerating and repeated starting of medium and large fabricated squirrel cage induction machines.
2.4 SUMMARY

Induction motors are ideal for many industrial processes because they are cost effective and robust in the sense of performance. Because of the potential savings offered by fault diagnosis systems, a lot of research has been carried out for the study and development of fault detection and diagnosis methods for electric machines. While many types of motor fault detection methods have been proposed, practical detection techniques for three-phase induction motors are generally provided by some combination of mechanical and electrical monitoring techniques.

Among the various strategies that can be followed to assess operating conditions of induction motors, condition monitoring based on noninvasive detection of signals is the emergent one. Regular inspection and processing of input voltages and currents allow one to predict possible deterioration and to schedule the motor shut down if a prefixed rate is exceeded (Kliman et al 1997, Burstein et al 1996, Kliman et al 1998, Benbouzid 1998, Benbouzid et al 1999). Based on the above, current transformers (CTs) and potential transformers (PTs) are utilized to measure the currents and voltages from the motor terminals and are used for on-line monitoring, fault detection and protection purposes.


The main drawback of the NEMA definition is that knowing the percentage voltage unbalance does not define the terminal voltages. In other
words, for any percentage unbalance, there are an infinite number of terminal voltages of the machine and each having a different influence on the performance of the motor. Thus, in the analysis of a three phase induction motor under a given percentage of unbalance, it is not sufficient to choose only one case of the terminal voltage and investigate the performance of the motor under such voltage unbalance.

Some reports on the effects of voltage unbalance on the performance of the motor have used the above mentioned procedure and extended the obtained results. To further limit the amplitude of the terminal voltage variation, some researchers specify the percentage voltage unbalance and assume that the average terminal voltage of the motor is equal to the rated voltage of the motor, which is not a requirement with the NEMA definition. In this thesis, to overcome the above drawbacks, many combinations of voltages (single phase, two phase and three phases of under voltage and over voltage unbalances) are chosen for a particular percentage voltage unbalance and the performance of induction motor is analyzed in detail.

There have been numerous papers addressing the harmful effects of unbalanced voltages and the associated unbalance currents (Postingl 1982, Cummings et al 1985). When the voltages are unbalanced, a much higher current is induced in the rotor because it has much lower impedance to the negative sequence voltage component. For a 3% voltage unbalance, the current unbalance might be 18 to 24% (Hobson 1965). The increase in stator current is usually small and therefore the overload relays do not trip in time to prevent damage from the high induced rotor current (Bennet 1978). This additional rotor heat can exist for a considerable time period and since the rotor and shaft are continuous metallic structure, the heat transfer to the shaft ends can reduce bearing life (Hobson 1965).
Whereas much has been written concerning the effects of unbalance voltages, little or no documentation was found identifying the specific cause of additional motor failures as a direct result of persistent unbalanced voltages. Taking this into consideration, this thesis analyses the effect of unbalance and other electrical faults by measuring rotor currents, stator and rotor d-q currents, speed and torque in addition to stator voltages and currents.

The PIC series had the advantage of the C compiler that was reasonable in price, free updates of the complier, a free development environment and a single supplier of software and hardware. Although embedded C programming has the disadvantage of not knowing the real time nature of the code it is producing, it was implemented and proved to be effective and efficient (Ganssle 2000). In this thesis, PIC16F877 microcontroller is used to implement the integrated motor protection scheme considering the above advantages.