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Review

Improving squirrel cage induction motor efficiency: Technical review

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Studying and improving of Squirrel Cage Induction Motor (SCIM) efficiency is a continuous area of interest not only among the researchers but also the industry, manufacturer and government. However, until today there are still struggles to find the most holistic environment of the SCIM which achieve its efficiency at the most lowest cost and at the same time sustaining the performance of the motor. This paper will focus on the method on improving SCIM efficiency. The first discussion presented the main importance of efficient motors and its drive systems. These are partly conceptual, partly concerning circuit topology and current commutation technique. The second discussion ooptimization of SCIM efficiency using intelligent techniques which are of particular interest. The third discussion describes the energy efficiency of SCIM standards and most effect motor parameters on SCIM efficiency.

Key words: Induction motor, efficiency, maximization.

INTRODUCTION

As the Squirrel Cage Induction Motor (SCIM) drives have been the traditional alternating current (ac) workhorses in the industries, and their widespread acceptance makes this study very important not only for its evaluation but to provide comparison with other drive systems. The maximum efficiency point occurs when the SCIM magnetizing flux level is properly regulated according to the motor load. However, in some industrial sectors, most SCIM are operated under rated condition due to under load or the motor is over sized and as a result, the efficiency of the motors is low. The immediate effect of low efficiency is low power factor which then becomes the main cause of poor power factor in industrial installations. Therefore, to retain the maximum efficiency operation of SCIM while driving a partial load, the controller must search for the maximum efficiency operating point and then operates the SCIM at this point (Lingshun et al., 2009; Fernando and Anibal, 2008; Hasan et al., 1997).

Issues on controlling the speed and the torque of SCIM have drawn great attraction to the research since twenty years ago. It is the most preferable motor to be used in industries and tertiary sectors are responsible for approximately 32% of total electricity consumption in the EU (Nailen, 1989) and almost 2/3 of total electricity consumption in the US (Stroker, 2003). According to the latest survey, more than half of the electricity generated is consumed by the electric motors and since most of the power-generating systems produce ac, a majority of the motors used throughout the globe are designed to operate on ac, specifically SCIM (Ali, 2004; De Almeida et al., 1997; De Keulenaer et al., 2004). Therefore, study in increasing energy saving of SCIM is very important as a small percentage increase in efficiency, will save huge percentage amount of energy (Auinger, 2001; Gang, 2004). Results from research have been done, to improve the efficiency of SCIM drives: (1) the use of high-efficiency (premium efficiency) motors instead of standard motors, (2) replacement of constant speed mechanically controlled processes with variable or adjustable speed control, and (3) replacement of direct current (dc)-motor drives with induction motor adjustable speed drive (ASD) in industrial processes where the adjustable speed is necessary for the process, typically conveyors, textile and paper industry, and machine tool. The variable-speed drive system coupled with premium efficiency motor capable in matching the power consumed to the work completed.

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Therefore, maximizing the efficiency of motor and control systems is a continuous effort to achieve significant energy savings and substantially, bring up opportunities to improve plant efficiency, to reduce the use of fossil fuels, and to reduce greenhouse gas emissions. This paper will focus on contribute the following knowledge in the area of power electronic and electrical drive system. First, describe the methods in achieving maximum efficiency of SCIM drive. Second, the designed, simulation, looking for component shops, purchasing components, finding the appropriate components and studying the characteristics of all components, components matching, integrating software and fabric-cated hardware are the knowledge that could be gained.

The importance of efficient motors and drive systems

An ongoing research is required to further creating the most holistic environment of using electric motors especially SCIM to achieve efficiency, performance and cost reduction. The cost issue due to power consumption of using electric motor has regained substantial attention among the researchers, industry and manufacturer nowadays due to the current economic situation. From 1979 to the present, the electric power rates have continued to increase at an average annual rate of 6%/year. The annual electric power cost to operate a 10-hp motor 4000 h/year increased from $850 in 1972 to $1950 in 1980 and to over $2500 by 1989.

In the usage of SCIM, even small efficiency improvements will produce very significant energy savings. This is due to the fact that most electric motors are designed to run at 50-100% of rated load. Maximum efficiency particularly SCIM is usually near 75% of rated load. However, studies conducted by the Electric Power Research Institute reveal that over 60% of industrial motors are operating below 60% of their rated load capacity (Fernando and Anibal, 2008). In other word, 40% of industrial motors have continuously wasting the electrical energy for about 15%. Although, the motors are generally efficient, idling, cyclic, lightly loaded or oversized motors consume more power than required even when they are not working.

Squirrel cage induction motor (SCIM) efficiency and losses

Research on electric drive system efficiency is about to increase the ability and intelligence of an electric motor and its controller, to convert electrical energy into mechanical energy; that is, kilowatts of electric power are supplied to the motor at its electrical terminals, and the horsepower of mechanical energy is taken out of the motor at the rotating shaft. Therefore, the only power absorbed by the electric motor is the losses incurred in making the conversion from electrical to mechanical energy. Thus, the direct measurement method of motor efficiency (Agamloh, 2009) can be expressed as:

$$efficiency = \frac{mechanical\ energy\ out}{electrical\ energy\ in} \times 100\%$$

but,

Mechanical energy out = Electrical energy in – Motor losses

or

Electrical energy in = Mechanical energy out + Motor losses

Obviously, to increase the mechanical energy out for a given electrical energy in, the motor losses must be reduced and as a result, the electric drive system efficiency is increased. Therefore, often, the efficiency can also be determined by first determining the losses and using either the input power or the output power to calculate the efficiency. This is called indirect method or loss segregation method (Agamloh, 2009). Indirect method efficiency calculation required the knowledge of SCIM losses. The next section explained the component of energy loss in SCIM.

Component of energy loss in squirrel cage induction motor (SCIM)

Figure 1 (Hitoshi and Yuji, 2003) illustrates the components of energy loss in 3.74 kW SCIM. They include primary resistance losses in the copper rotor windings, secondary (stator) resistance losses or also called stator copper losses and rotor copper loss, respectively, magnetic energy dissipated in the motor's iron components or also called core losses, various mechanical losses and stray losses. Figure 2 (Bose, 2002) shows the characteristics of these losses.

Primary and secondary resistance loss or copper loss is due to flow of the electric current through the stator and rotor windings. Therefore, they can be calculated by current flow in wires and conductor bars and their resistances. For a single winding, it can be represented simply as

$$Pcl = I_{rms}^{2} \cdot R \qquad (1)$$

The resistance R in SCIM is composed of *N* turns of a conductor of electrical conductivity σ , of length l_w and a total cross-sectional area A_w within the slot, the winding resistance (which is proportional to the length of the wire in the winding and inversely proportional to its cross-sectional area) can be written as:

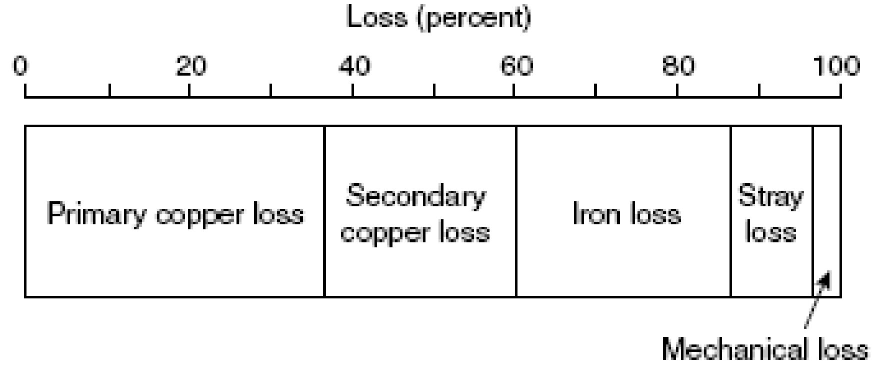

Figure 1. Component of energy loss in SCIM.

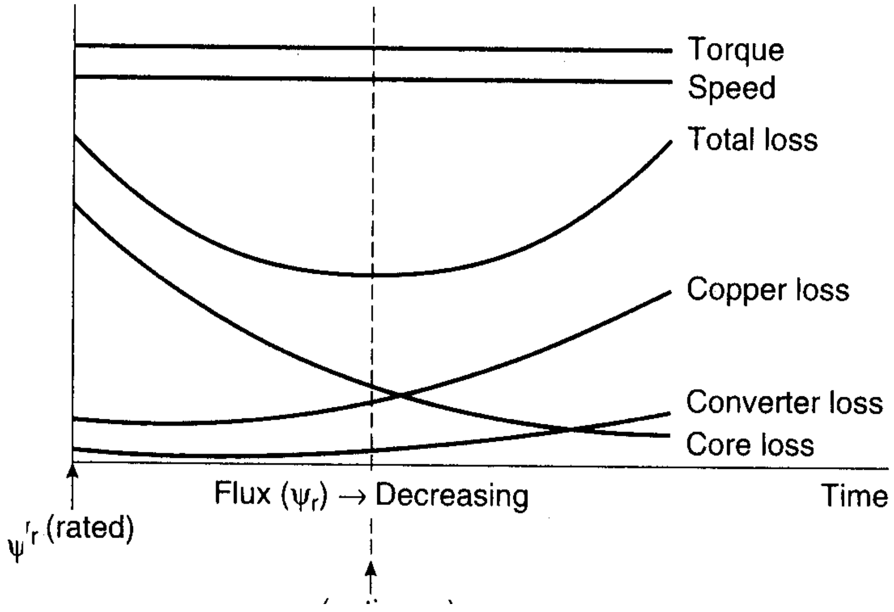

Figure 2. SCIM losses characteristics.

$$R = \frac{N \cdot l_w}{\sigma \cdot A_w / N} \tag{2}$$

Using Equation 1 in Equation 2, then copper losses can be written as:

$$P_{cl} = (N I_{rms})^2 \frac{l_w}{\sigma \cdot A_w} \tag{3}$$

Obviously from Equation 1, reductions in electrical resistance are the key to minimizing these losses and based on Equation 2, the reduction can be done by increasing the winding conductivity or by increasing the cross-sectional area (that is, get more conductor into the slot) or by reducing the winding length and coil end length.

The copper and core losses contribute 70% of the total losses and hence, are the critical factors which decide the motor efficiency while the sum of stray load losses and the mechanical loss do not exceed 30% of the total losses (Stefanski and Karys, 1996, Chandan and Yoichi, 2003). The values of them are different as the voltage and the load changes. The copper losses are less, whereas the majority of the total loss during light load is core losses.

Iron loss or core loss is the losses due to eddy currents and hysteresis. The core loss within a motor is determined by the choice of core material, the magnetic flux density at which the motor is operated and the operating frequency. From Figure 2, Bose (2002) describe that as the flux or operating frequency are reduced, the core loss also reduced, however, losses due to operating frequency variation gives more effect than the rotor flux (Sokola et al., 1996; Bose et al., 1997; Mannan et al., 2003). As the flux depends on the input voltage, the core loss is also affected by variation with the machine voltage (Zahedi, 2007). Thus, when the SCIM operates under normal condition (s << 1) the rotor iron losses can be neglected. In a more accurate consideration, when machine efficiency is concerned, the iron loss can be ignored (Cui, 2006).

The stray losses are mainly attributed to the rotor current (Kioskeridis and Margaris, 2005). Since the rotor current in SCIM cannot be measurable, stray losses are expressed as a function of the stator current. The estimation and experimental investigation of stray load losses in the machine poses one of the most difficult problems in the characterization of losses in a machine. This leads to the origin of empirical values for both stray no load and load losses of induction motors between 0.5-10% of the total losses, depending on the rating, for small machines (Boglietti et al., 1995).

Figure 2 is giving very important information in improving energy saving of SCIM. It can be described as when the power supply is connected to the motor the electromagnetic torque is produced. The electromagnetic torque is proportional to the vector product of rotor magnetic flux and rotor current. It is thus, possible to obtain the same torque with different combinations of flux and current values. For a given torque, the iron loss can be minimized by applying a minimum possible flux value (Ferreira et al., 2005). This also minimizes the stator copper loss component due to magnetizing current. On the other hand, torque creation with small flux value must be connected with increase in rotor current, and hence with increase in the stator current, which leads consequently to the increase of the total copper losses (Ferreira et al., 2005). Power loss minimization can be achieved by proper adjustment of the magnetic flux, an appropriate balance between copper and iron losses (Kirschen et al., 1985).

Maximize efficiency of squirrel cage induction motor (SCIM)

Conversional techniques

Based on previous researches, in order to obtain maximum efficiency, the losses are minimized by adjusting or determining the optimum flux (Stefanski and Karys, 1996; Radwan et al., 2008). The copper losses and the core losses are a majority of the total loss during light load. On the other situation, the lower voltage results in less core losses and current which results in less copper losses. It is well known that, for SCIM, as shown in Figure 2, the maximum efficiency is obtained when copper losses and core losses become equal at any given torque and speed condition (Sousa, 2000). Bose (1994) mentioned that for certain speed and torque at steady state condition, the flux is reduced to achieve optimum energy saving (that is, high efficiency). Other researchers (Cardoso et al., 1998; Pitis et al., 2008) also found the same observation. To achieve this goal, the system must adopt voltage-regulating scheme or air-gap flux-regulating scheme (Bose, 1994; Benbouzid et al., 2006). For voltage controlled SCIM drive, the power may feed through ac voltage regulator or controlled rectifier circuit and then the control circuit will regulate the supply to achieve the goal (Mohan, 1980). This is true only and limited to fix line frequency operation of SCIM. For ASD, the power to SCIM must be fed through an inverter and the control circuit will regulate the supply such that the motor excitation yields a balance magnetic flux and electric loading (Benbouzid et al., 2006). Table 1 shows the percentage of energy saving on flux-regulating scheme of SCIM.

Three approaches are identified to achieve the voltage-regulating scheme (Abrahamsen et al., 1997). The first approach is called simple state control which utilizes the fact that in operation with optimal efficiency, certain motor quantities are easily defined. The control circuit kept the identified quantity to it value throughout the operation regardless the load torque and speed. This method requires knowledge of both motor parameters and speed (Kim et al., 1984). The second approach is known as model-based control or also called loss model controller (LMC) (Kioskerisdis and Margaris, 1996). The method is based on the properly modeling the motor and the losses to derive an expression that associated with minimum losses or maximum efficiency. Then the controller is built based on this expression. The approach requires the knowledge of stator voltage, current and phase shift angle. The third approach is called search control (SC). The principle of SC is to keep the output power of the motor constant and finding the operating point where the input power is minimum (Kirschen et al., 1985; Ghozzi et al., 2004). The minimum power is found by exact measurement of the input power, and iteratively changing the flux level in small steps until the input minimum power is detected. The main advantage of SC is that the point of optimal efficiency is found without knowing the motor or converter parameters (Abrahamsen et al., 1997). The fourth approach called a look-up table method (Kim et al., 1984) where the table for slip values versus operating points table is established. Slip value is assumed to be optimal whenever it is corresponding to an operating condition and assumed to be constant. These assumptions cannot always be acceptable since the optimal slip value varies due to magnetic saturation and temperature variation. Moreover, a look-up table cannot store the slip values for the whole range of speed-torque combinations in real time.

Table 1. Efficiency improvement by flux program for 5 hp motor.

Speed (pu)	**0.25**		**0.5**		**0.75**	
Flux program	**Rated**	**Optimum**	**Rated**	**Optimum**	**Rated**	**Optimum**
Efficiency (%)	59.1	63.9	68.9	73.2	73.4	76.4
Efficiency different (%)	4.8		4.3		3	

Torque, 0.3 pu.

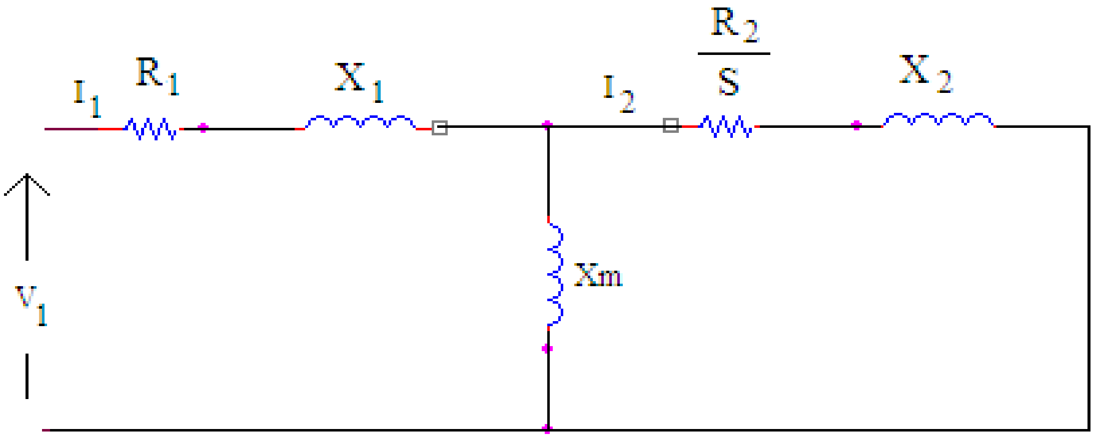

Figure 3. Per phase SCIM equivalent circuit.

From the literatures, many researchers work on maximizing efficiency as mentioned above are based on SCIM equivalent circuit as shown in Figure 3 (Lu et al., 2006; Holmquist et al., 2004). The Figure 3 consists of stator and rotor resistances, R_1 and R_2, stator and rotor inductances, X_1 and X_2, and magnetizing inductance, X_m. These parameters values can be obtained through dc, no-load, and Block-rotor tests and today they can be found through on-line parameters test (Zhang et al., 2007; Baburaj et al., 2007; Karanayil et al., 2007).

Intelligent techniques

The ANN has been successfully applied to identify and control the currents of an induction machine. There have been several applications of ANN in ac drive systems such as adaptive flux control (Pedro et al, 2004), current control, speed control, and field oriented control (FOC). It is expected that ANN as an artificial intelligence (AI) tool to guide to new modem techniques in power electronics and motion control systems. Several types of ANN and training algorithms are available in the market and one of them is Radial Based Function Neural Network (RBFNN) (Lin et al., 2003; Sing et al., 2003). As shown in Figure 4 (Bose, 2002), RBFNN architecture has three different layers, input, hidden and output layer. Different basis functions like spline, multiquadratic and Gaussian functions have been studied, but most widely used is the Gaussian type. In comparison to the other types of neural network which is used for pattern classification like back propagation feed forward networks, the RBF network requires less computation time for learning and has more compact topology (Alanzi et al., 2007). The Gaussian RBFNN is found suitable in generalizing a global mapping but also in refining local features without altering the existing learned mapping. RBFNN has been adopted in ac IM simple and well known reliability, Volt-Hertz (V/f) (Sompong et al., 2006) speed control (Hasan et al., 1997), accurate fault location (Alanzi et al., 2007) and etc. (Sarevska and Abdel, 2006; Ang et al., 2006; Mohammad et al., 2006). Previous researches on optimizing efficiency of SCIM using AI are discussed in next paragraph.

In Fuzzy-Indirect vector control scheme (Bose et al., 1994), there is an indirect vector-controlled induction motor drive which incorporates the fuzzy-logic-based efficiency controller. The fuzzy controller has the advantage of adaptive decrements the step size of the excitation current so that fast convergence is attained. In a new fuzzy logic based on on-line minimum input power search control strategy, which makes full use of the results of loss model control, the simulation verifies that it is very fast and highly precise, and should be widely used in the efficiency optimization control for IMs (Zhang et al., 2007). In a set of near-optimal power factor method, set

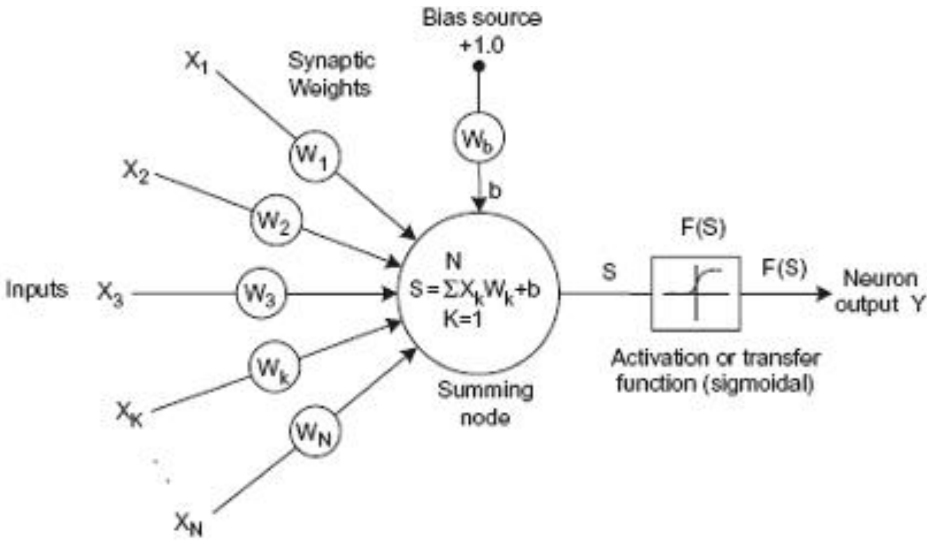

Figure 4. Model of artificial neuron.

of PF commands is generated by a fuzzy logic compensator in the commissioning of the motor drive. Then an on-line tuning controller is used to adjust the power factor command to its optimal value when the motor is at normal operations. A novel technique is found for energy efficient operation of voltage controlled induction motor drive using fuzzy logic principles. In the proposed method, the time required to converge to the best efficiency point of the drive is minimum and the machine is subjected only to one step change of voltage irrespective of load change (Sundareswaran and Palani, 1999). Beside fuzzy logic, another intelligent approach used in induction motor is a Neural Network-Based scheme which is used to optimize the energy efficiency of a vector-controlled voltage source inverter (VSI) induction machine drive. The idea is to use an artificial neural network to represent the nonlinear relationship between the optimal rotor flux producing current and the machine torque-speed relationship under parameter uncertainty. Experimental results show a significant improvement in energy saving (Zhang and Hassan, 1999). In the latest study (Zhanyou et al., 2009), the efficiency optimization controller for a vector controlled induction motor has been explored. The optimum flux-producing current has been obtained by utilizing RBFNN. Comparing with the conventional neural network, the radial basis function neural network possesses characteristic of simple structure, fast convergence and strong generalization, Huang and Tang (2005) has studied the application of the general mapping regressor (GMR) neural network to the direct torque control of an induction motor in order to obtain the proper choice of commands to be given to the power devices of the converter. GMR was experimentally verified and manages to substitute the optimal switch table.

Technology in AI in the area of power electronics semi-conductor, microprocessor etc keep changing and this changing will give a new environment in controlling the SCIM (Dan et al., 2005; Jong and Chin, 2007). Therefore, the research on SCIM and drive system will never come to end since high efficient motors are able to save more energy (Faiz et al., 2005; Li et al., 2006; Jingli et al., 2008; Shumei et al., 2008; Tsambouris, 2009). Thus, another new aspect that needs to be considered is maximizing the energy saving among SCIM drive system (Huang and Tang, 2005).

Energy efficiency of squirrel cage induction motor (SCIM) standards

Studying and improving standard for motor efficiency is a continuous area of interest not only among the researchers but also the industry. However, until today there is no single and acceptable standard method of measuring motor’s efficiency used throughout the industry (Renier et al., 1999). For example, in the area of electric motors, cost was considered as a parameter to define the standard, particularly those in the 1-250 hp range. Whereas, in other standard, the performance of the motor was treated as the important parameter of the standard where the amount of active material, that is, lamination steel, copper or aluminium or magnet wire, and rotor aluminium was selected as the minimum levels required which is expected to increase the performance of the motor (Peter et al., 2007; Tessarolo et al., 2009). Another standard focused on the efficiency where the efficiency is maintained at optimum levels to manage and control the temperature requirements of the particular motor (Khalifa et al., 2009).

Table 2. Motor testing standards.

Country	Institute	Standard name
United States	Institute of Electric and Electronic Engineering	IEEE 112
United States	ANSI (American National Standard Institute)	C50.20 (based on IEEE 112)
United States	NEMA (National Electrical Manufacturer Association)	MG1-12.58.1 (based on IEEE 112)
Canada	Canadian Standards Association	C-390-M1985
International	International Electrotechnical Commission	IEC-34-2
Japan	Japanese Electrotechnical Committee	JEC-37
Great Britain	British Standard	BS-269

The exploration and improvement of the study of those standards found that efficiency is the first and most important parameter since efficiency will create holistic environment which combines and balance the motor efficiency, cost and performance. The research has derived several holistic standards accepted by the industry and are used as the current and common reference (Cummings et al., 1981; Boglietti et al., 2003; Finley et al., 2004; Holmquist et al., 2004). Among the common standards are shown in Table 2.

The IEEE 112 standard recognizes three main methods for determining motor efficiency, namely (1) Method A, simple input-output (2) The IEEE 112 Standard Method B, input-output with loss segregation (or separation) and (3) The IEEE 112 Standard Method F, equivalent circuit (model) calculation. The IEEE 112 Standard Method B estimates the efficiency by the direct method. The method also clearly defined the procedure and requires testing at full operating temperature or making corrections for temperature differences.

The IEC 34-2 Standard provides several methods and procedures for the efficiency measurements in accordance with the type and sizes of machine, with the wanted accuracy, etc. These methods can be subdivided in two categories: (1) the “direct” method: the absorbed and provided power at the motor shaft is directly measured; and (2) the “indirect” method: the motor losses are measured by suitable tests and the efficiency is measured by measuring the motor adsorbed power. The method also provides guidelines for efficiency measurement for the motor operating under condition of partial-load, temperature changes and voltage variation.

The CSA C390 Method 1 test standard is equivalent to IEEE 112 Method B test standard and it is commonly used in Canada.

JEC 37 is a Japanese standard which can be considered as an indirect method; neglecting the SLL and no thermal correction of the losses resulting generally higher efficiency values.

As a summary, IEEE 112, IEC 34-2 and JEC 37 are the most popular standards accepted globally focused for the induction motor efficiency evaluation. However, due to no single standard of motor efficiency measurement, the electric motor efficiency around the world has different values which depend on the standard according to which the efficiency is determined (Renier et al., 1999; El- Ibiary et al., 2003; Lu et al., 2006; Cui et al., 2008; Agamloh, 2009). To reduce the uniformity issues, most industries use IEEE 112-B test method which they consider the most suitable standard for the stray losses measurement and as a consequences it is used as the best motor efficiency evaluation.

Having the above standards, not all users are able to understand and use the standard easily. Further research to simplify the use of standard was done and as a result, an establishment of motor efficiency reference table was found to be useful to assist users including manufacturer, industry and government to easily categorize the motor by just referring to the established efficiency table. The establishment of the motor efficiency reference table is found to be very important to for two main reasons: (1) categorizing the efficiency class of the motors, and (2) promoting the development high efficiency motor program. However, the issue of establishing a uniform reference table of motor efficiency is again a struggle since several entities are interested due to their roles, requirements and level of importance especially manufacturer and government.

The government is considered to play the best role in managing standards since it can protect all the users including manufacturers, industry and public users. As a result, the efficiency tables endorsed by the government agency are the most important and mostly referred. For example, in the US, The Energy Policy and Conversation Act (EPAct) of 1992 has established efficiency reference values for limited range of motors. The policy has set that motors having efficiencies equal to or higher than EPAct are designated as Energy Efficient and consider as standard. In further development, NEMA has issued an efficiency reference table of higher efficiency than efficiency table provided by EPAct and thus, defining the minimum nominal efficiency for the NEMA Premium^{TM} Efficiency Motor Program (Rooks, 2000; Agamloh, 2009). Table 3 shows the difference between two NEMA standards of induction motors, standard efficiency and premium efficiency. Figure 5 shows three difference efficiency standards of induction motor. Obviously from Table 2, using standard motor will improve energy

Table 3. NEMA efficiency standards for induction motor.

Horsepower	Standard efficiency	Premium efficiency
1	78.0	82.5
2	78.5	84.0
5	84.0	89.6
10	84.0	91.1
15	87.5	91.7
25	90.2	93.0
50	91.7	94.1
100	91.7	95.0
250	94.1	95.8

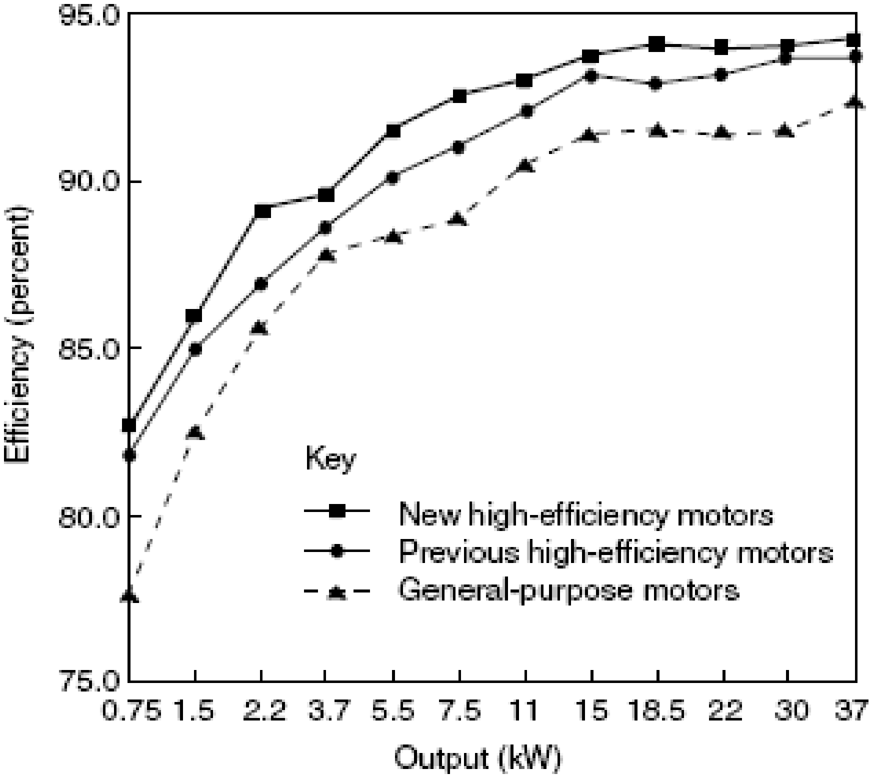

Figure 5. Efficiency comparison for Mitsubishi Electric 4-pole, 200V, and 50Hz motors.

consumption, however, using premium efficiency motors will have better efficiency improvement. From both table.1 and table.3, it shows that larger motors are having higher efficiency compared to small motor (< 10 kW).

As mentioned earlier that the efficiency of a variable speed induction motor drive can be optimized by adaption of the motor flux level to the load torque. In small drives (<10 kW), this can be done without considering the relatively small converter losses, but for medium-size drives (10-1000 kW) the losses cannot be disregarded without further analysis (Abrahamsen et al., 2000; Geng et al., 2004). Based on the experiments with a 90 kW drive, it is found that, it is not critical if the converter losses are neglected in the control, except that the robustness towards load disturbances may unnecessarily be reduced.

Advanced volts/hertz (V/f) control of SCIM drive

V/f control is among the simplest and cheapest control schemes for induction motor drives system. The control is

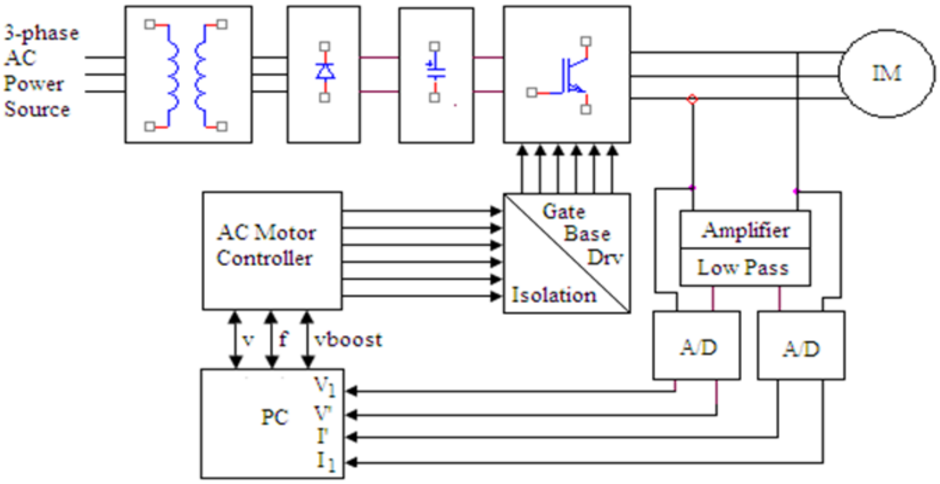

Figure 6. Model for modified or advanced V/f IM drive system.

an open-loop scheme and does not use any feedback loops. Although the V/f strategy can provide speed variation, it is unable to provide reliable control under transient conditions. Furthermore, the performance of the V/f drive is very poor at low frequency as the air gap flux decreases when more voltage drops across stator resistance (Bose, 2004). Another problem with open loop control strategies is that they are only suitable when the motor can be operated at steady torque without speed regulation. The idea in V/f drive is to keep stator flux constant at rated value so that the motor can develop rated torque/ampere ratio over its entire speed range. At low frequencies, the supply voltage is also low, thus the voltage drop caused by the stator resistance cannot be neglected. Therefore, at lower speeds, an extra boost voltage is applied to compensate the resistive drop. Although it has been superseded, open loop V/f control is still widely used in applications that do not require precise speed control such as fans for Heating Ventilation and Air Condition (HVAC) (Bose, 2004).

There are many performance-improving schemes have been proposed for the basic V/f control. Boys and Walton (1988) introduced a new scalar algorithm for effective control strategy for ac drives. The algorithm operates the motor at a continually varying flux level, thereby completely eliminating the boost voltage problem. Wu et al (2009) improve the performance of V/f SCIM control in low speed range by introduce closed-loop V/f with proportional-integral (PI) controller integrated with genetic algorithm (GA). Kumar et al. (2007) uses micro-processor to implement the closed-loop V/f SCIM control system and gain the following advantages: (1) improved reliability and increased flexibility, (2) simplicity of implementation in variable speed drives, (3) low cast, high accuracy and (4) possible to change torque speed characteristics of drive by software modification. Ramdan (2008), with the model shown in Figure 6, uses micro-controller and through the master mode, operates SCIM at closed-loop V/f control and obtained the following advantages (David, 2005): (1) DSP filtering which enhanced speed stability in noise environment, (2) high precision calculation which up to 32-bit resolution, (3) selectable base speed, (4) speed control from 1-128 Hz, and (5) independent control of the voltage waveform with respect to the motor frequency. This is important feature especially for lightly loaded motor at full frequency, where the voltage can be reduced for better efficiency. Recently, the embedded DSP-based compact fuzzy system for SCIM V/f speed control has been implemented. The control system optimized the speed error in keeping the voltage –frequency ratio constant. It can be concluded that research on V/f drive systems are still attractive and significant field especially in improving the performance at low speed range. The opened-loop V/f drives require feedback circuits and must be the first step toward improving their performance. The general model for the modified or advance V/f is shown in Figure 6. The voltage, current and other parameters can be sensed and used for further development in enhancing the performance such as speed accuracy, maximizing efficiency and low speed performance.

The effect of motor parameters on SCIM efficiency

Speed sensorless for SCIM

Close loop speed or position control in both vector- and scalar-controlled drives requires the speed, torque and motor parameters. A speed signal is also required in indirect vector control in whole speed range, and in direct vector control for low-speed range, including the zero speed start-up operation. A traditional way of getting speed and torque information is using sensors. In recent years, various speed and position (Hu and Hu, 1998; Bensalem and Abdelkrim, 2009) control scheme have been developed for variable-speed ac drives. The main reasons for the development of these “sensorless” drives are reduction of hardware complexity and cost; increased mechanical robustness and overall ruggedness; operation in hostile environments; higher reliability; decreased maintenance requirements; increased noise immunity; unaffected machine inertia; improvement of the vibration behavior, elimination of sensor cable etc (Inanc, 2000; Holtz, 2002). The terminology “sensorless” refers to the fact that no conventional speed or positions monitoring (for example, tachometer based speed sensors, optical incremental sensors or electro-mechanical resolvers) are used in these drives (Gang, 2004). In “sensorless” drives, the speed and/or the position signal is obtained by using monitored voltages and/or currents signals from the drive system, through the carrier frequency signal injection, creating saliency by changing the machine rotor structure and by utilizing mathematical models or artificial-intelligent-based system (Hui et al., 2006).

Temperature effect on SCIM

When an induction motor is fed by a PWM inverter power supply, its stator winding is subjected to high-voltage stresses caused by the train of wave fronts in the PWM voltage waveforms (Bian et al., 2005). In addition, switching supplies produce an increment of losses in the magnetic material due to the high variation rate of the applied voltage and losses in an induction motor are dissipated as heat from the winding and core (Puchstein, 2006). The losses in the iron and copper to be dissipated vary roughly, as the volume of the material. As the size of the induction motor is increased, the ratio of heat generation volume to surface for dissipation becomes large. The heat may cause the temperature to reach to unsafe zone if special cooling means are not provided. Heat also will cause a stator and rotor resistances change their values at every 4°C increase in temperature, which result in poor performance of the drives (Zhi et al., 2005; Khluabwannarat et al., 2007; Weili et al., 2007). In SCIM, the stator flux can be estimated by taking the integral of the difference between the input voltage and the voltage drop across the stator resistance. At high speeds, the stator resistance drop I_sR_s is too small to be neglected. However, at low speeds, this drop becomes dominant compared to the input stator voltage. As a result, errors are introduced in estimating of stator flux and consequently of the electric torque and the stator flux position (Ganesh at el., 2003). The variation of stator resistor during the operation of SCIM makes the controller as a dependent stator resistance such as DTC which has a difficultly to operate at low speed. Also, the characteristics of the vector control employing stator voltages and currents usually deteriorate as the speed gets lower because the calculated rotor flux depends on the stator resistance. A simulation to obtain the relationship between the stator current and stator resistance have shown that their relationship is highly nonlinear. Therefore, to overcome the change in resistor value, proper stator resistor compensation according to the change of the stator resistor value over time in the controller must be designed carefully.

As the temperature of the rotor increases due to the operating temperature, R_2 increases in value, the slope of the torque-speed curve decreases, and the operating point shifts such that it result in lower value of efficiency (Famouri and Cathey, 1991; Cisz et al., 2009). Furthermore, in indirect vector control, increase in R_2 will change the rotor circuit time constant which can cause significant performance deterioration if no means for compensation or identification is applied (Zhang and Hassan, 1999). Therefore, the rotor-flux estimator must be improved so as to reduce the stator-resistance influence and to make it possible to calculate the rotor flux at standstill (Ohtani et al., 1992).

Obviously, since there is a significance negative impact to the drives influenced by temperature, the improvement of thermal design methodology of induction motor should not be lag behind. Furthermore, the uncertainties in the characterization of the composite materials, in defining the various thermal constants, and in lack on loss density distribution puts the demand for better thermal design strategy and this requirement is as important as the need for better performance in terms of efficiency and power density.

CONCLUSION, RECOMMENDATION AND FUTURE RESEARCH

Through the above literature study, it can be concluded that there are still a lot of limitations of SCIM. Among the major ones is that the efficiency problems of SCIMs when it operates in environment other than rated load. In addition, many research works have been focused on maximizing efficiency where voltage and current supply strategies, flux-program scheme and their mathematical expression based on per phase equivalent circuit were derived and introduced. To further improve and optimize the SCIM performance, various research works have been done in integrating AI in SCIM drive system. Since the research trends shows a rapid development of SCIM performance improvement, the issues are always significant and continuously evolved.

The following recommendations are proposed to be considered by induction motor controller manufacturers and users:

The study proposes to the motor manufacturers to consider the V/I maximum efficiency software control to be embedded in their motor controller to increase the motor efficiency, thus increase the energy saving.

The study proposes to the motor manufacturers to consider the integration of MAC3PAC advance closed loop v/f controller software with the current motor for easy management of the motor due to the GUI and advance features of the software.

The study proposes to the users to consider the usage of neural network to speed up the existing motor controller due to the intelligence of the technique.

Three areas were identified where follow-up research based on this study could be conducted. The following describes the areas for future research:

Study on integration of VI_RBFNN and V/I maximum efficiency control software**:** The existing study on V/I maximum efficiency control software and VI_RBFNN is done separately. For the real-life implementation, both software should be integrated into a single software and reside in a single chip for easy usage and management. The future work should focus on the best integration strategy to produce the laboratory and industry prototypes.

Study on other Artificial Intelligent Techniques to improve V/I Maximum Efficiency Model: Even though RBFNN is proven to be performance improvement factor for V/I maximum efficiency, some other artificial intelligent techniques such as genetic algorithm, rules based and fuzzy logic should be further investigate to further improve the intelligence, thus improve the efficiency.

Study on application of V/I Maximum Efficiency Model in achieving Maximum Toque of SCIM.

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