Journal of ELECTRICAL ENGINEERING, VOL. 60, NO. 4, 2009, 227–236

REVIEWS - LETTERS - REPORTS

REVIEW ON EFFICIENCY IMPROVEMENT IN SQUIRREL CAGE INDUCTION MOTOR BY USING DCR TECHNOLOGY

Subramanian Manoharan * — **Nanjundappan Devarajan** ** — **Subbarayan M. Deivasahayam** *** — **Gopalakrishnan Ranganathan**

Induction motors account for approximately 50 % of the overall electricity use in industrialized countries. In the agricultural and commercial sectors also, power consumption by ac motors is quite substantial. On an average, the energy consumed by a motor during its life cycle is 60-100 times the initial cost of the motor. Therefore efficiency of the motor is of paramount importance both during selection and operation. Even small increase in efficiency improvement can make a big difference in energy savings with accompanying decrease in air contamination. High electrical conductivity of copper in the rotor structure of a squirrel cage induction motor can achieve a reduction in overall energy losses of around 11%–19 % and a consequent increase in energy efficiency. This paper reviews the implementation of Die-Cast Copper Rotor (DCR) Motor, Efficiency improvement, Energy saving potential, adoption of DCR Technology in India and the comparisons of various efficiency standards besides the application of DCR motor in agricultural pump sets. The needs and tasks regarding the technology are also discussed.

K e y w o r d s: induction motor, premium efficiency, efficiency improvement, die cast copper rotor, DCR technology, and efficiency standards

1 INTRODUCTION

The electric motor has a long history of development since its invention by Nicola Tesla in 1888, with earlier effort aimed at improving power and torque and reducing cost. The need for higher efficiency became apparent during the late 1970's and by the early 1980's and at least one British manufacturer had started to market a premium range of motors with improved efficiency. Now the trend is towards the design and manufacturing of motors with a small improved efficiency at a small extra cost. It is needless to state that this extra cost could be realized in the savings in the operating cost.

Since, efficiency being the ratio of the amount of work produced i.e. output power to the amount of energy consumed *ie* input power, the Induction motor losses are the difference between input and output powers, and can be classified into five categories [1]:

1. Iron losses: magnetic losses in the core laminations, hysteresis, and eddy current losses, labeled as P_c.
2. Stator I^2R resistance losses: current losses in the stator windings, P_s
3. Rotor I^2R resistance losses: current losses in the rotor bars and end rings, P_r.
4. Windage and friction losses: mechanical drag in bearings and cooling fans, P_w.
5. Stray load losses: mainly iron and joule losses. Also called additional load losses, increasing with load and result from a multitude of sources, such as surface and slot conditions, leakage flux, *etc.* They are normally difficult to measure and calculate, P_l.

Relative proportion of five loss components of an induction motor is dependent on the motor size. Taking the 4-pole motor as an example, loss distribution is shown in Figure 1. Accordingly, Mr. Fuchsloch and his SIEMENS colleagues provide the typical loss distribution, shown in Figure 1 in their recent research work concerning the next generation motors [2], and the areas for improvements of the efficiencies are shown in Figure 2. Furthermore, they analyzed all the different factors and evaluated their influences to motor performance and different dependencies between each other. The individual factors have to be carefully investigated due to the inter dependence with each other. Sometimes an increase obtained from on one such factor may not contribute to a resultant improvement in efficiency. In addition, the cost and commercial impact have to be considered as well.

This paper has four main sections — Section 2 deals with the history of motor efficiency standards, which include the international standards for motor efficiency assessments. Section 3 discusses with various methods used for constructing the rotor of a squirrel cage induction motor. Section 4 investigates problems involved in DCR technology and their solutions to overcome. It also includes the advantages of DCR technology, the technical issues, the research in market and overview of competitor. Section 5 presents the adoption of DCR technology in India. It also deeply discusses about the ICPCI project

* Department of Electrical & Electronics Engineering in Karpagam College of Engineering, Coimbatore, India, manoish07@yahoo.co.in, ** EEE Dept., Government College of Technology, Coimbatore *** Mehala Machines India Ltd., Coimbatore, India.

ISSN 1335-3632

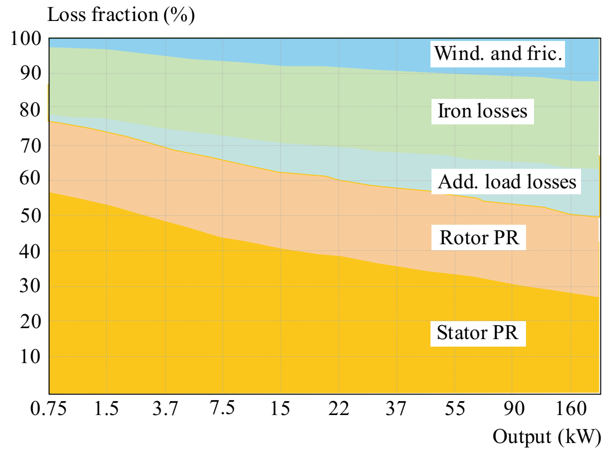

Fig. 1. Loss distribution for a 4-pole induction motor

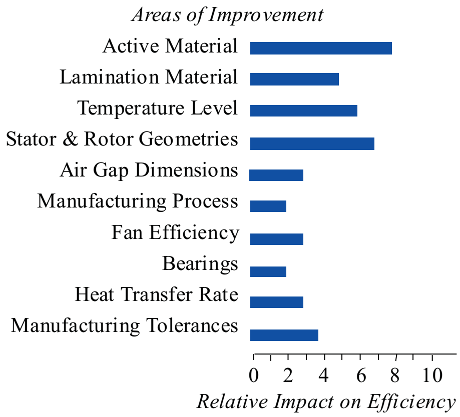

Fig. 2. Impact of the possible areas for improving the motor performance

at Coimbatore motor and pump clusters and its adoption in agricultural pump sets in India.

2 HISTORY OF MOTOR EFFICIENCY STANDARDS

During the year 1992, Congress passed the Energy Policy Act (EPAct), which granted the USA Department of Energy (DOE) the authority to set minimum efficiency standards for certain classes of electric motors. EPAct rules for motors became effective Oct. 24, 1997. EPAct did not create new efficiency performance levels but rather established a minimum efficiency level in US. Upgrading motors from pre-EPAct level to EPAct efficiency levels increases motor efficiency by 2.3 %. In 1994, NEMA issued definitions for "energy efficient" motors. These motors must have nominal efficiencies meeting or exceeding NEMA MGI. EPAct covers general-purpose motors rated from 1 to 200 hp; 2-, 4- and 6-pole (3600, 1800 and 1200 rpm); horizontal; T-frame; single speed; continuous duty, 230 V, 460 V or 230/460 V; NEMA Designs A and B. Efficiencies of these so-called "EPAct motors" are from one to four percentage points higher than the previous "standard-efficiency" motors.

NEMA revised MGI-1993 to include the specification of a design E motor and they were specified to satisfy the International Electro technical Committee (IEC) standards. These standards allow motors to be designed for higher efficiency with lower restrictions on torque and starting current than design B motors [3].

In the year 1996, the Consortium for Energy Efficiency (CEE) launched its Premium Efficiency Motors Initiative. Motors meeting the CEE standards are designated as "CEE Premium Efficiency^{SM}" which is 0.8–4 % more efficient than EPAct motors.

The European Union (EU) and Committee of European Manufacturers of Electrical Machines and Power Electronics (CEMEP) have developed a motor efficiency classification scheme for motors during the year June 2000. Motors covered by this agreement are defined as totally enclosed fan ventilated (IP 54 or IP 55) three phase A.C. squirrel cage induction motors in the range of 1.1 to 90 kW, with 2- or 4-poles, rated for 400 V-line, 50 Hz, S1, Duty Class, in standard design. Motors sold in Europe had an efficiency marking designated as EFF1 for their best efficiency, and EFF2 for standard efficiency. There is a lower EFF3 level family of motors that the EU is discouraging from being manufactured. Motor efficiency of EFF1 is comparable to that of U.S. EPAct efficiency values [4].

Based on the above classifications, the Indian Electrical and Electronics Manufacturers Association (IEEMA) developed IEEMA-19: 2000. This formed the basis for the development of IS: 129615-2004 for Energy Efficient Motors by the Bureau of Indian Standards. Table 1 shows the comparison of efficiency levels as per different standards for a few 3 phase/4pole ratings.

In May 2001 NEMA announced a new motor efficiency standard; NEMA Premium^{TM} efficiency. These motors are required to have 20 % lower losses than EPAct motors. NEMA Premium^{TM} applies to single-speed, polyphase, 1 to 500 hp, 2-, 4-, and 6-pole (3600, 1800 and 1200 rpm) squirrel cage induction motors, NEMA Designs A or B, 600 V or less, (5 kV or less for medium voltage motors), and continuous rated. In the month of June 2001, NEMA and CEE agreed to align the NEMA Premium^{TM} and the CEE Premium Efficiency^{SM} efficiency levels to co-promote the standard.

After NEMA released General Specification for Consultants, Industrial and Municipal: NEMA Premium Efficiency Electric Motors (600 Volts or Less) in 2003, most of the major motor manufacturers put more and more effort to meet or even to exceed the NEMA Premium® Efficiency requirements. The intent of this specification is to outline the minimum requirements for three- phase AC induction motors labeled with "Premium®" applied to municipal and industrial applications for operation on voltages 600 volts or less, rated 500 horsepower or less, operating more than 2000 hours per year at greater than 75 percent of full load.

While efficiency values for NEMA Premium^{TM} has been indicated in the Table 1, the forgoing discussions

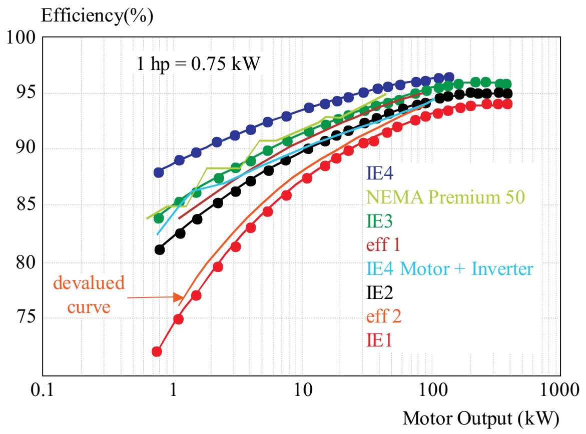

Fig. 3. Different efficiency levels comparison by CEMEP [7]

Table 1. Comparison of Efficiency Levels as per Different Standards for a few 3 Phase/4 Pole Ratings

kW	EPACT	IEEE 841.2004	CEMEP/IEMA-19 /BIS 12615 EFF1	EFF2	NEMA Premium
0.75	82.5	84	82.5	73	85.5
1.1	84	85.5	83.8	76.2	86.5
3.7	87.5	–	88.3	84	89.5
7.5	89.5	90.2	90.1	87	91.7

Table 2. Efficiency Results of a given Motors using Various Testing Standards

Standard	Full Load Efficiency (%) 7.5 hp	20 hp
Canadian (CSA C390)	80.3	86.9
United States (IEEE - 112, Test Method B)	80.3	86.9
International (IEC - 34.2)	82.3	89.4
British (BS - 269)	82.3	89.4
Japanese (JEC - 37)	85.0	90.4

however will be dealing only with motors up to EFF1 level. Since not much of information is available on NEMA Premium efficiency motors. Although a mention has been made at the end of this paper on Premium efficiency of a few leading international manufacturers who utilized DCR besides other improvements.

2.1 INTERNATIONAL STANDARDS FOR MOTOR EFFICIENCY ASSESSMENT

It is critical that motor efficiency comparisons be made using a uniform product testing methodology. There is no single standard efficiency testing method that is used throughout the industry. The most common standards are:

- IEEE 112 –1984 (United States)
- IEC 34-2 International Electro technical Commission (Europe)
- JEC-37 (Japanese Electro technical Committee)
- BS-269 (British)
- C-390 (Canadian Standards Association)
- ANSI C50.20 same as IEEE 112 (United States)
- IS 12615 – 2004 read with IS 4889 – 1968 (India)

The common practice for testing of motors in the 1 to 125-hp size range is to measure the motor power output directly with a dynamometer. The standards for testing of motor efficiency differ primarily in their treatment of stray load losses. The Canadian Standards Association (CSA) methodology and IEEE 112 - Test Method B determine the stray load loss through an indirect process by measuring mechanical output. The IEC standard assumes stray load losses to be fixed at 0.5 percent of input, while the JEC standard assumes there are no stray load losses.

The efficiency of a motor, when tested using the different standard conventions, can vary by several percentage points. Table 2 shows a full load efficiency test results of 7.5 hp and 20 hp motors using different international standards [5 ,6].

Although the IEC method is easy to use, it overestimates efficiencies by up to 2 % for motors smaller than 10 kW and underestimates them slightly for motors larger than 700 kW. The IEEE is more accurate, but is not perfect either because it relies on the accuracy of the torque Transducer.

Emerging technologies push the efficiency into new heights. However, so far there is no formal standard available concerning the so-called “Super Premium Efficiency” level. Besides, many different energy efficiency standards for cage induction motors are already in use with new classes currently being developed, which make it difficult for manufacturers to design motors for a global market and for customers to understand differences and similarities of standards in different countries. Hence, IEC has proposed a project regarding new international motor efficiency classification system IEC 60034-30 that can eventually include the new Super Premium efficiency level. IEC 60034-30 (Ed. 1.0) states efficiencies respectively for both 50 Hz and 60 Hz and integrates different well-known efficiency standards with its own Energy Efficiency Classes as IE4, IE3, IE2 and IE1, shown in Table 3.

As shown in Figure 3, presented by Conard U. Brunner from SEEEM, it is observed that IE4 identifies the motor efficiency approximately from 88 % to 97 % compared with IE3’s 84 % to 96 % in the same output power scope. One aspect needs to be clearly pointed out is that these advanced motors for IE4 usually require power electronics (frequency converters) to operate, and since grid frequency and number of poles of converter-fed machines are not directly related to speed these motors are typically rated for a speed range and classified by torque rather than power, as described in IEC 60034-30 Ed. 1.0 draft.

Table 3. Integration of different global standards according to IEC 60034-30

Efficiency Levels	IEC60034-30 (Ed. 1.0)	Corresponding to other standards	
		50Hz	60Hz
Super Premium Efficiency	IE4	Around 15 % reduced losses based on IE3	
Premium Efficiency	IE3	15 % – 20 % reduced losses based on IE2	US American NEMA Premium
High Efficiency	IE2	CEMEP-EU eff1	US American EPAct
Standard Efficiency	IE1	CEMEP-EU eff2	Brazilian regulations

Data pertaining to the curves depicted in Fig.4

Output Power (kW)	0.75	1.1	1.5	2.2	3	4	5.5	7.5	11	15	18.5	22	30	37	45	55	75	90	110	132	160	200 *up to* 370
IE3 2poles	80.7	82.7	84.2	85.9	87.1	88.1	89.2	90.1	91.2	91.9	92.4	92.7	93.3	93.7	94.0	94.3	94.7	95.0	95.2	95.4	95.6	95.8
IE4 4poles	83.1	84.9	86.2	87.8	88.8	89.7	90.7	91.5	92.4	93.0	93.5	93.7	94.2	94.6	94.9	95.1	95.5	95.7	95.9	96.1	96.2	96.4
IE3 3poles	82.5	84.2	85.4	86.9	88.0	88.9	89.9	90.7	91.7	92.4	92.8	93.1	93.7	94.0	94.3	94.6	95.0	95.2	95.4	95.6	95.8	96.0
IE4 4poles	84.7	86.2	87.3	88.6	89.6	90.4	91.3	92.0	92.9	93.5	93.8	94.1	94.6	94.9	95.1	95.4	95.7	95.9	96.1	96.2	96.4	96.6
IE3 6poles	80.6	82.4	83.8	85.4	86.6	87.7	88.7	89.7	90.8	91.6	92.1	92.5	03.1	93.5	93.9	94.2	94.7	94.9	95.2	95.4	95.6	95.8
IE4 6poles	83.0	84.6	85.9	87.3	88.4	89.3	90.2	91.1	92.1	92.8	93.2	93.6	94.1	94.4	94.8	95.0	95.5	95.6	95.9	96.1	96.2	96.4

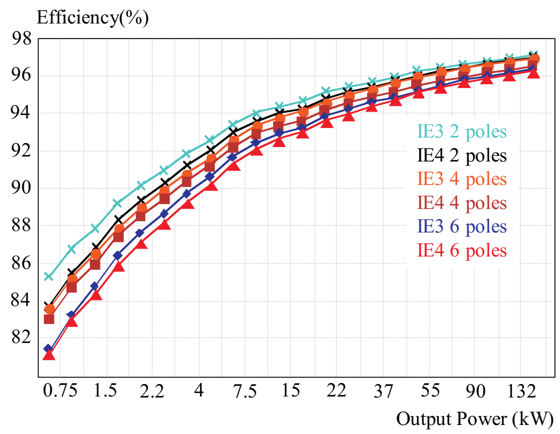

Fig. 4. IE3 (Premium) and IE4 (Super Premium) efficiency levels comparison *vs* rated output power (according to IEC 60034-30, ≈ 15 % lower losses subtracted from IE3)

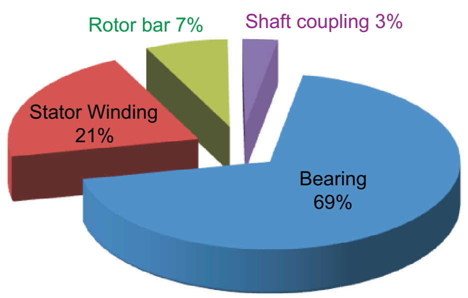

Fig. 5. Extrapolated distribution of failure by motor component

As one can see in Figure 3, there is approximately 1 % difference between IE1 and eff2, also between IE2 and eff1, which is due to the fact that in the new testing standard, the additional (stray) load losses are determined from a test, whereas in CEMEP they were considered as flat 0.5 % of input power, that is why the curve is called "Devalued curve". In the latest edition of IEC 60034-30 (2008-04-30), the IE4 efficiency class could be defined by reducing the losses by 15 % relative to IE3. Then, the efficiency for different output power rating could be calculated as:

$$P_{\text{loss\_IE3}} = \frac{P_{\text{Rated-output}}}{\eta_{\text{IE3}}} - \text{Rated-output}$$

$$P_{\text{loss\_IE4}} = (1 - 15\,\%)P_{\text{loss\_IE3}}$$

$$\eta_{\text{IE4}} = \frac{P_{\text{Rated-output}}}{P_{\text{Rated-output}} + P_{\text{loss\_IE4}}} \times 100\,\%$$

A more detailed comparison is shown in Figure 4. The draft standard also indicates that other technologies than cage-induction motors will be required for IE4 and the scope of IEC 60034-30 would be revised consequently.

In order to eliminate the scruples such as premium efficiency gained by compromise other performance characteristics and the motor reliability, Austin. H. Bonnett and Chunck. Yung [8] made a study based on similar enough motors and operation conditions to compare the construction, performance and reliability for Pre-EPAct, EPAct and Premium Efficient motors.

Two major components in extrapolated distribution of motor failure, is shown in Figure 5. By checking, which are bearing system (69 %) and stator winding (21 %); there are no significant changes in the bearing systems and the bearing operating temperatures as well as the winding insulation class. Hence it could be expected that there is no differences between three motor generations due to bearing failures and operating temperatures.

They claimed that if reliability is defined as the failure of the motor calculated based upon the MTBF (Mean

Table 4. Various Facets Comparison for Different Rotor Construction

PARAMETERS	ADC	Al BAR	CuDC	Cu BAR
Cost	1	2	2	4
Efficiency	2	3	1	1
Design Flexibility	2	4	1	2
Size	2	1	2	1
Tooling/Capital	2	1	3	1
High Inertia/ Multiple Restart	2	2	1	1

Table 5. Overall Efficiency improvement of Cage Induction Motor by Substituting DCR for Die-cast Aluminium in the Rotor

			EFFICIENCY (%)			ROTOR LOSS
kW	HZ	POLES	Al	Cu	DIF-FERENCE (%)	REDUC-TION (%)
3	50	4	82.0	84.1	2.1	46
3	60	4	83.2	86.4	3.2	58
5.5	60	4	74.0	70.0	5.0	19.2
7.5	50	4	84.2	87.4	3.2	50
7.5	60	4	85.0	86.5	1.5	10
11.2	60	4	89.5	90.7	1.2	40
15	50	4	90.1	91.0	0.9	44
18.8	60	4	90.9	92.5	1.6	40
30	60	4	88.8	90.1	1.3	11.6
90	60	4	91.4	92.8	1.4	16.3
200	60	4	92.0	03.0	1.0	12.5

Time between Failure), then there is no significant difference between those three motor generations. They also indicated that one should be cautious when applying the conclusion to the smaller sizes of motors, to different enclosures or to earlier generations of motors. From their previous work, it is optimistic to assume that Super Premium could also be achieved without sacrificing reliability. One of the methods for achieving the induction motor efficiency for premium and super premium levels could be possible by using DCR technology.

3 ROTOR CONSTRUCTION METHODS

The basic losses in an induction motor consist of resistance losses in the stator winding and rotor cage, iron losses, friction and windage losses, and stray loss. The resistivities of copper and aluminium for circular mil, per foot at 20 °C are 10.37 Ω and 16.06 Ω respectively. Hence, for the same current requirement, the substitution of copper for aluminium results in $(16.06-10.37)/16.06 =$ 35.4 % reduction in resistance loss [9]. This idea leads to provide a copper bar in the rotor structure instead of aluminium bar. For a long time, the motor manufacturers have noticed that a simple substitution of aluminum for copper in the squirrel cage of induction motors will generally provide a significant reduction in I^2R losses, and consequently an increase in motor efficiency, due to the fact that the electrical conductivity of copper is nearly 60 % higher than that of aluminum. This is often done in large motors in which squirrel cages are fabricated from bars of material brazed to end rings, which is the so-called fabricated copper bar. A study was carried out by Mark Hodowanec and Willian R. Finley [10] to present four different rotor constructions (aluminum die cast "ADC", copper die cast "CuDC", fabricated aluminum bar "AlBar" and fabricated copper bar "CuBar") concerning their manufacturing process and properties, rotor stress, electrical performance, rotor bar heat capacity *etc*, they summarized different facets and provided a comparison shown in Table 4, where the comparison is relative one, with a lower number indicating an advantage.

The fabrication costs are more than die-cast technology due to the labor-cost. The die-cast as a state-of-the-art technology makes an increase of rotor size each year due to the manufacturing advancements. The previous challenges of die casting copper, which are higher temperatures and pressures compared with die casting aluminum, have been solved with the development of a die casting process using nickel-base alloy die inserts operated at elevated temperature. Substantial progress in understanding and managing the porosity problem characteristic of high-pressure die-casting has also been reported in [11, 12, 13].

Active development of the die-cast copper rotor motor begun in 1997 has now resulted in a growing market with about 250,000 units in service and still growing at a rapid rate. The DCR technology has been a significant effort of the world copper industry through the International Copper Association Ltd (ICA) managed by the Copper Development Association (CDA). This DCR project has been conducted jointly with die casters, motor manufacturers in all major motor markets word wide and academia. A sizeable data bank of motor performance test results now exists illustrating the several advantages to using the DCR [14].

3.1 Efficiency of DCR Motor

Lie and Pietro [15], Jown G. Cowie et al. [16] and F. Parasiliti [17] pointed out that significant improvement in motor efficiency could be achieved by substituting copper for aluminum in a die-cast rotor for a squirrel cage induction motor. The results are shown in Table 5.

Poloujadoff *et al* [18] made economic comparisons between aluminum and copper squirrel cages. They concluded that when the initial cost is considered, the initial price of copper cages is higher by 30 %, but the savings in operating losses is seven or eight times the increase in price. From Table 5, the use of DCR is one method enabling motor efficiency to be increased as much as 1.5 %–3 % above what is currently possible using die-cast aluminium rotor with out changing any other parameters. These efficiency increases are expected to be higher on small motors, decreasing 0.55 on larger designs.

Significant efficiency improvements could be attributed to adding more copper to the windings, upgrading the laminations to premium-grade low-loss steel, enhanced lamination designs, precision airgap between rotor and stator, and reducing fan and other losses in the motor. Furthermore, Mr. Malinowski, Mr. McCormick and Mr. Dunn [19] from Baldor reviewed design and production techniques, which are required to fulfill the NEMA Premium efficiency standard, and introduced new research being done to further improve efficiency level, including better lamination steel slot designs and die-cast copper rotors. The efficiency level is upgraded mainly by reduction in stray load loss and core loss as well as some reduction in windage and friction losses. It has been proved that with DCR, together with optimized laminations could greatly helped to achieve efficiency stated in Table 5 economically. One thing needs to be noted is that a reduction windage loss, which is normally accomplished by reducing the external fan diameter, will greatly improve the efficiency of the motor, meanwhile the tradeoff is temperature rise in the winding, which will lead to some increase in the stator resistance loss. Therefore, the designers should always keep in mind to find a balance among the diverse losses so that the overall motor performance is optimized.

4 PROBLEMS IN DCR TECHNOLOGY AND SOLUTIONS

The manufacturing details for DCR are identical to ADC. The melting point for aluminum alloys is in the 676 °C (1250 F) range. The material used for the rotor's die-casting mold is often H-13 tool steel, which is not highly stressed at these temperatures. Die life can be in the hundreds of thousands of rotors depending on die complexity. Copper melts at 1083 °C (1982 F). This high melting temperature results in failure of conventional die steels by thermal fatigue of the surface ("heat checking") in less than 100 shots [17]. The solutions to tooling issues related to die-casting of copper have been identified and the tool life can be considered acceptable now [20, 21]. THT Presses, Inc has demonstrated economical means to die cast copper utilizing equipment developed specifically for *Copper Rotors Cast Vertically* task. The details about the THT approach are discussed in [22]. The DCR is now being employed by several manufacturers as a cost-effective way to achieve EPAct and Eff1 efficiency levels or to reach or exceed NEMA Premium levels. SEWEurodrive and Siemens AG in Germany, in particular, have made extensive investments to optimally design the motor while copper in the rotor. In [23–26], the comparison or test for different power ratings of motors (Most of these motors are SEW's DT/DTE and DV/DVE series.) have been discussed, together with some summaries about the achievement and optimal designs. Consequently, from the studies above, it appears that the process of die casting copper rotors can be reliable and robust. The motor total energy losses could be reduced by 15 % $\sim$ 23 %. Further improvements in process and rotor design such as optimization of the steel laminations and slot shape should extend copper's lead in efficiency over aluminum [27].

The cost of DCR is higher by about 15 % as compared to the motors of existing efficiency levels when replacing aluminium by copper die casting without any other change. But the extra cost may prove to be nominal. A copper rotor in a 15 hp motor could result in a 1.2 % efficiency gain and difference in retail list price of $ 10 to $ 12 per motor. For a $ 900 to $1 500 motor, the payback may be measured in months. In order to offset the cost of the DCR following solutions are identified [28].

- Development of dedicated motor design and configurations of laminations optimized for DCR's
- Identifying and sourcing of appropriate electrical steel for the core packs.
- For motors with copper die-cast rotors there is a need for a more perfected technology of melting and die-casting. Then only mass-production of rotors at an affordable cost is possible.

4.1 Advantages of DCR

A lot of studies have been done by CDA-USA and ICA. They conclude that improved efficiency at a small increase in cost or alternatively reduced cost for the prevailing efficiency levels, reduced temperature rise during operation, reduced manufacturing cost and reduced weight could be achieved when applying die-cast copper instead of aluminum. Improving motor efficiency brings significant energy savings. Cooler running motor means longer motor life. Improved conductor bar and end ring consistency reduces maintenance cost [29].

4.2 Technical Issues

Starting torque

The copper rotor motor has the advantage of high torque at running speed and its starting torque is lower than in aluminum rotor motors (85 Nm instead of 90 Nm in a 5.5 kW motor), which is beneficial for gearbox life. In applications where lower starting torque is a problem, a modified design of the rotor slot offers a solution. It is found that the measured inter-bar resistance is lower in DCR than in cast aluminium rotors. This leads to a reduced pull-out torque and increased stray-load losses [30]. For a continuous rated motor this cannot be a problem. However, this effect is offset by efficiency increases due to the other factors contribute the substantial efficiency increases.

Higher start-up current

The higher conductivity of copper, i.e. its lower electrical resistance, will result in a slightly higher start- up current since the slot area remains the same. (7.0 times the nominal current for a 7.5 kW copper rotor motor, instead of 6.0 times for its aluminum counterpart). Soft

Table 6. High efficiency motors from competitor companies in the market [32]

COMPANY	COUNTRY	NAME FOR THE HIGHEST EFFICIENCY	EFFICIENCY LEVEL
A.O.Smith	US	E-Plus 3	EPAct standards
Baldor	US	Super-E Premium Efficiency	NEMA Premium
Brook Crompton	UK	WK Premium efficiency motor	EFF1
Emerson	US	NEMA Premium efficient motor	NEMA Premium
GE	US	XSD Ultra NEMA Premium efficiency TEFC	NEMA Premium
HYOSUNG	KR	Premium high efficiency motor	NEMA Premium
LEESON	US	Premium efficiency WATTSAVER	NEMA Premium
Rockwell	US	N/A	NEMA Premium
SEW-eurodrive	DE	DTE/DVE	Exceed NEMA Premium
Siemens	DE	Ultra Efficient(GP100/100A)	Exceed NEMA Premium
Sterling Electric	US	N/A	NEMA Premium
TECO	CA/US	Global XPE series	NEMA Premium
TOSHIBA	US	Premium FC-EQPIII XT	NEMA Premium
WEG	US	NEMA Premium Rolled Steel motor	NEMA Premium

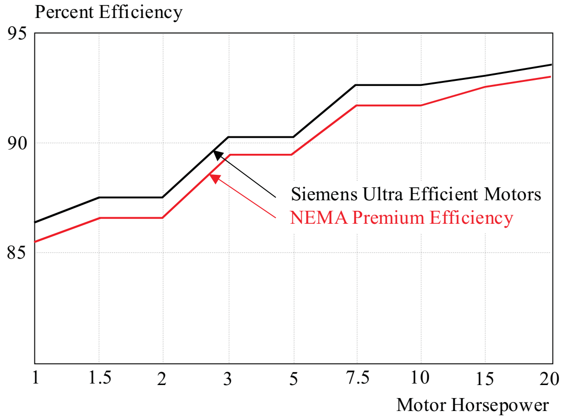

Fig. 6. Siemens Ultra Efficient Motor and its efficiency compared with Premium Efficiency (IE3)

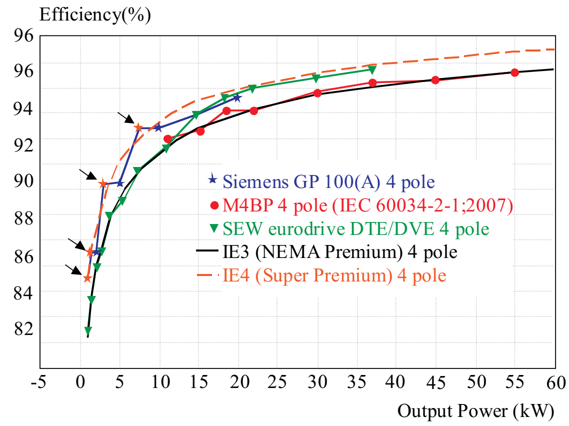

Fig. 7. Efficiency *vs* output power comparison between ABB, Siemens and SEW motors

starter can be used to avoid that this higher current aspects the electricity system. Also, since motors are increasingly being driven by inverters, inrush and starting currents become less of an issue.

Rotor inertia

The higher rotor weight increases rotor inertia. This improves the motor's efficiency, but can be a problem in certain applications -for example motors that frequently switch direction at high speed. A survey among manufacturers, users, researchers, engineers and members of associations, reveals that the copper rotor motor has now become an accepted technology (82 %). A majority assess the technology ready for mass production (74 %). Higher efficiency (42 %), lower heat production (24 %) and reduced cost (11 %) are seen as major advantages. The main application domain is for industrial low voltage induction motors of 1 up to 100 kW, but the technology also has potential for fractional kW motors [31].

4.3 Market research and competitor overview

Going through with most of the motor manufacturers' product catalogs as shown in Table 6, the conclusion could be made that leading manufacturers are aiming to obtain even higher efficiency than NEMA Premium®. Baldor seems to be striving to achieve the Super Premium Efficiency level, as one could understand by taking a look at their Premium motors' name, which is Super-E® Premium Efficient Motor. The Baldor's Super-E® motors meet or exceed the efficiency levels defined by NEMA Premium®, however, there is still some distance to the Super Premium Efficiency (IE4) requirement for larger power rating. Baldor achieves the higher efficiency levels by a more focused motor design, paying particular attention to the active materials. Whereas SEW and Siemens are already in the front-line. Leroy-Somer has been making PM motors to replace the induction motors for some areas.

SEW-Eurodrive has been active in an extended effort to design the motor to optimally use copper in the rotor to upgrade their DT/DV series to DTE/DVE. *Ultra Efficient TEFC motor* of Siemens has the highlight feature of a *Copper Rotor* (Siemens exclusive, leading-edge, DCR design), thus Siemens motors have industry-leading efficiencies, shown in Figure 6. From Figure 6 it is seen that the efficiency levels beyond NEMA Premium level.

A comparison could be made to understand the market products efficiency level with reference to ABB (test method: IEC2007), Siemens and SEW-Eurodrive premium efficiency motors (test method unknown). Due to the limitation of the data availability, the comparison only cover 4 poles motor for a general impression, where the IE3 and IE4 levels are also stated, see Figure 7. As we can see from the figure, Siemens' motors have four points of power rating, where the efficiencies exceed the IE4 level. The output power ratings are 1 kW, 1.5 kW, 3 kW and a comparison could be made to understand the market products efficiency level with reference to ABB (test method: IEC2007), Siemens and SEW-Eurodrive premium efficiency motors (test method unknown). Due to the limitation of the data availability, the comparison only covers 4-pole motor for a general impression, where the IE3 and IE4 levels are also stated, as shown in Figure 7. As we can conclude from the figure, Siemens' motors have four points of power rating, where the efficiencies exceed the IE4 level. The output power ratings are 1 kW, 1.5 kW, 3 kW and 7.5 kW. SEW motor fulfills IE3 at low power range ($1.1\,\mathrm{kW} \sim 11\,\mathrm{kW}$), and at output ratings higher than 15 kW, the efficiencies are slightly lower than IE4. The ABB motor M4BP series meet IE3, but all of them are less efficient than SEW and Siemens motor. The reason could be the use of copper rotor for both SEW and Siemens motor, which also indicates the efficiency improvement potential of ABB motor if the DCR concept, is applied.

As the cost of energy goes up, the trade off of the cost for some technologies, which were thought to be expensive, will be compensated by the energy saving. At the same time as new motor technologies develop, high efficiency motors will go beyond the typical standard asynchronous squirrel cage AC induction motors.

5 INDIAN SCENARIO FOR ADOPTION OF DCR MOTOR

India, the world's second largest emerging energy market (after china), faces a chronic energy shortage say up to 20 % during peak periods while energy use is growing multifold. The problem is especially felt in rural areas, where 63 % of households do not have any electricity at all. One step toward meeting this need was taken by the International Copper Promotion Council India (IPCPI), which is supported in part by a grant from an arm of the Small Scale Industries Development Bank of India and funded by the USAID Eco Project. The Council tested copper rotors in motors used for pumping water, one of the country's leading agricultural uses for electricity.

5.1 ICPCI project at Coimbatore Motors and Pumps cluster

Coimbatore, popularly known as Manchester of South India, is situated in the western part of the state of Tamil Nadu. It is well known for its textile industries and has excellent potential for industrial growth. An Indian company in Coimbatore has developed Asia's first ever-copper rotor in motors to help conserve energy. After two years in extensive research, during the year 2002, the Tirupur based company succeeded in developing a copper die-cast rotor motor to replace aluminium cast rotor. Mehala Machines India Ltd, based in Coimbatore has replaced aluminium rotors with copper as the other good conductors [33, 34].

In order to test the reliability of Indian made Die-Cast Copper Rotors and confirm the gains and performance in various other important parameters, a project was conceived and carried out in Coimbatore Motors and Pumps cluster by International Copper Promotion Council (India) — ICPCI during the year 2003. Small Industries Development Bank of India (SIDBI) and Technology Bureau for Small Enterprises (TBSE) provided Motors and Pumps cluster by ICPCI. Small Industries Development Bank of India (SIDBI) and Technology Bureau for Small Enterprises (TBSE) provided assistance for the same.

Nexant Inc. (USA) helped in developing the concept and in formulating the various dimensions, schedules, etc for the project. Institutions like Coimbatore District Small Scale Industries Association (CODISSIA) and The Southern India Engineering Manufacturers' Association (SIEMA) played active roles in helping the industry grow and prosper with the help of institutions like SIDBI and National Small Industries Corporation Ltd. (NSIC). The facilities like testing Center called Small Industries Testing and Research Center (SITARC) established by the cluster members has rendered testing support. Ratings and types of motors that were chosen covered industrial sector, agricultural sector as well as domestic applications. The samples include single and three phase types of A.C. motors as well as ratings and types presently using both Die-Cast aluminum rotors and Copper Bar rotors. The ten Die-Cast copper rotors, for the eight ratings of motors chosen were sourced from an Indian manufacturer, based on the drawings and the supply of rotor stampings by the various manufacturers, participating in the project. These were assembled into motors and assembled with the conventional type of rotors used by them for performing comparative tests. These tests were carried out in the respective factories and some samples from each of the ratings were subjected to exhaustive tests at SITARC. Field tests were also conducted later to confirm performance and reliability under actual field conditions. Based on these tests a summary of the average performance variations of the motors between the range 0.5 h.p–5 h.p with Die-Cast copper rotors in comparison with Die-Cast Aluminium rotors are as shown in Table 7. While understanding the comparison of performance it is

Table 7. Comparison of various performance parameters between DCR and die-cast aluminium rotors

Parameters	Variation Factor
Reduction in slip	2%
Increase in starting current	10%
Decrease in starting torque	17%
Improvement in Efficiency	2.8%
Decrease in Temperature	7.50 °C
Decrease in Full load Current	4%
Chance in Full load p.f	Negligible

to be noted that the motors are tested with DCR and conventional aluminium die cast rotors without any change in the rotor slot configuration and rotor stamping stacks.

5.2 Adoption of DCR in Agricultural pump set

It is estimated that about 30 % to 40 % of electrical energy produced in India is consumed by motorized pump sets employed in agriculture sector. Numerous field studies have revealed that 90 % of the agri-pump sets used in India are far inefficient and are wasting power worth of Crores of Rupees. Because there is no energy classification for pumps due to large variety of pumping systems. One of the important factors that contribute to the inefficiency in the pumping system is low efficiency of electric motor employed in it. Therefore, the overall efficiency of Submersible Pump can be increased by increasing the efficiency of its prime mover, which can be achieved by using DCR technology instead of conventional Copper Fabricated Rotor (CFR) Technology.

This paper [35] pointed out the overall Efficiency improvements in Submersible Pump Sets by increasing the efficiency of its prime mover, *ie* Squirrel cage induction motor by using Die cast Copper Rotor (DCR) technology. By reducing the stack length of DCR the various electrical parameters including the low voltage performance are measured and compared with the existing CFR in a 3 h.p and 5 h.p, 3 phase and 1 h.p Single phase wet type water cooled induction motors in accordance with IS- 9283. The overall performance of Submersible Pump Sets is also practically verified in accordance with IS-8034. The cost comparison between the existing CFR and DCR's are also reported and found that by merely replacing CFR with reduced core length DCR we can save 20 % of the initial cost with out sacrificing the overall efficiency of the pump set as indicated by IS-8034.

6 CONCLUSION

As could be seen a review of the various aspects like implementation of Die-Cast Copper Rotor (DCR) Motor, Efficiency improvement, Energy saving potential, adoption of DCR Technology in India and application of DCR motor in agricultural application has been made in this paper. The efforts put forth the development of energy efficient an electric motor has since yielded results. A conservative estimate of Mw/kWh of energy consumption will go long way particularly at juncture of energy shortage. Apart from energy savings, the DCR motor also reduces the production of greenhouse gases and push down the total environmental cost of electricity generation. Therefore the adoption of these motors can give immense benefits to the user as well as the country and the global environment.

Acknowledgement

The authors would like to thank the management of Karpagam College of Engineering, and M/s Megala Machine Works India Ltd Coimbatore, Tamilnadu, India. for their infrastructure and testing facilities provided to complete a part of our research work.

References

[1] BOGLIETTI, A.—CAVAGNINO, A.—LAZZARI, M.—PASTORELLI, M.: Induction Motor Efficiency Measurements in Accordance to IEEE 112-B, IEC 34-2 and JEC 37 International standards, in Conf. Rec. IEEE-IEMDC'03, Madison, WI, 2003, pp. 1599-1605.

[2] FUCHSLOCH. J. F.—FINLEY, W. R.—WALTER, R. W.: The Next Generation Motor-Designing a New Apporoach to Improve the Energy Efficiency of NEMA Premium Motors, IEEE Ind. Appl. Magazine (Jan/Fab 2008).

[3] NEMA Standards Publication No. MG1, National Electrical Manufacturers Association (NEMA), Wahington, D.C., 1993.

[4] MANOHARAN, S.—DEIVASAHAYAM, M.—RANGANATHAN, G.: "Energy Efficient Motors - An Overview, SIEMA News Letter, Coimbatore **5** No. 12 (Dec 2006), 2-7.

[5] KUSHARE, B. E.—WAGH, K. K.—KULKARNI, S. Y.: The Complete Guide to Energy Efficient Motors, International Copper Promotion Council (India) (2003), 18–20.

[6] PARASILITI, F.—VILLANI, M.—PARIS, C.—WALTI, O.—SONGINI, G.—NOVELLO, A.—ROSSI, T.: Three-Phase Induction Motor Efficiency Improvements with Die-Cast Copper Rotor Cage and Premium Steel, SPEEDAM 2004, Capri, June 16–18, pp. 3–4.

[7] BRUNNER, C. U.: International Harmonization of Motor Standards Saves Energy, APEC Workshop, Beijing, 3 December 2007.

[8] BONNETT, A. H.—YUNG, C.: Increased Efficiency versus Increased Reliability, IEEE IndustrialApplications Magazine (Jan/Fab 2008).

[9] HSU, J. S.—FRANCO-FERREIRA, E. A.: Method of Manufacturing Squirrel Cage Rotors, U.S. Patent NO. 6,088,906, July 18, 2000.

[10] FINLEYW. R.—HODOWANEC, M. M.: Selection of Copper versus Aluminum Rotors for Induction Motors, IEEE Transactions on Industry Applications **37** No. 6 (Nov/Dec 2001), 1563-1573.

[11] PETERS, D. T.—COWIE, J. G.—BRUSH, E. F. Jr.—MIDSON, S. P.: Use of High Temperature Die Materials and Hot Dies for High Pressure Die Casting Pure Copper and Copper Alloys, Proceedings of the 2002 Die Casting Congress, Rosemont, IL, Sept 30–Oct 2, 2002.

[12] PETERS, D. T.—COWIE, J. G.—BRUSH, E. F. Jr.—MIDSON, S. P.: Advances in Pressure Die Casting of Electrical Grade Copper, Amer. Foundry Society Congress, Paper No. 02-002, Kansas City, MO, 2002.

[13] PETERS, D. T.—MIDSON, S. P.—WALKINGTON, W. G.—BRUSH, E. F, JR.—COWIE, J. G.: Porosity Control in Copper Rotor die Castings, Transactions of the North American Die Casting Association Congress, Indianapolis, IN, 2003.

[14] PETERS, D. T.—COWIE, J. G.—BRUSH, E. F. Jr.: Advantages of the Copper Rotor Motor – Performance, Energy Savings and Environmental, Copper (Dr. Jean-Marie Welter, ed.), Published Online: 22 Oct 2007, Wiley-VCH Verlag GmbH & Co. KgaA, 2006.

[15] LIE, S.—Di PIETRO, C. Copper Die Cast Efficiency Improvement and Economic Consideration: IEEE Transaction on Energy Conversion **10** No. 3 (Sep 1995), 419–424.

[16] COWIE, J. G.—BRENDER, D. T.—PETERS, D. T.: Die-Cast Copper Rotors for Improved Motor Performance, IEEE Pulp and Paper Conference, Charleston, SC, 2003.

[17] PARASILITI, F.—VILLANI, M.: Design Strategies and Different Materials for High Efficiency Induction Motors. A Comparison, EEMODS, Heidelberg.

[18] POLOUJADOFF, M.—MIPO, J. C.—NURDIN, M.: Some Economical Comparisons between Aluminum and Copper Squirrel Cages, IEEE Transactions on Energy Conservation **10** No. 3 (Sep 1995), 415–418.

[19] MALINOWSKI, J.—McCORMICK, J.—DUNN, K.: Advances in Construction Techniques of ac Induction Motors Preparation for Super-Premium Efficiency Levels, IEEE Transaction on Industry Applications **40** No. 6 (Nov/Dec 2004), 206–211.

[20] PETERS, D. T.—COWIE, J. G.—BRUSH, E. F. Jr.—MIDSON, S. P.: Die Cast Copper Motor Rotors: Die materials and process Considerations for Economical Copper Rotor Production, Energy Efficiency in Motor Driven Systems (EEMODS) conference, Treviso, Italy, 2002.

[21] SAKHUJA, A.—BREVICK, J. R.: Prediction of Thermal Fatique in Tooling for Die Casting Copper via Finite Element Analysis, Materials Processing and Design: Modeling, Simulation and Applications, Proceedings of the 8th International Conference on Numerical Methods in Industrial Forming Process, AIP conference Proceedings, vol. 712, Columbus OH, 2004, pp. 1881–1886.

[22] THIEMAN, M.—KAMM, R.—JORSTAD, J.: Copper Motor Rotors: Energy Saving Efficiency, Now Also Economic Feasibility, Electrical Insulation Conference and Electrical Manufacturing Expo 2007, 22-24 Oct 2007, pp. 328–333.

[23] KIMMICH, R.—DOPPELBAUER, M.—KIRTLEY, J. L.—PETERS, D. T.—COWIE, J. G.—BRUSH, E. F.Jr,: Performance Characteristics Of Drive Motors Optimized For Die Cast Copper Cages, Proceedings of Fourth International Conference on Energy Efficiency in Motor Driven Systems 2005 (EEMODS 05), p. 110.

[24] BRUSH, E. F., Jr.—COWIE, J. G.—PETERS, D. T.—Van SON, D. J.: Die-Cast Copper Motor Rotors: Motor Test Results, Copper Compared to Aluminum, Proceedings of EEMODS 3rd International Conference, Treviso, Italy, 2002, pp. 136–143.

[25] KIRTLEY, J. L. Jr.—COWIE, J. G.—BRUSH, E. F. Jr.—PETERS, D. T.—KIMMICH, R.: Improving Induction Motor Efficiency with Die-Cast Rotor Cages, Power Engineering Society General Meeting, IEEE, 2007.

[26] STARK, C.—COWIE, J. G.—PETERS, D. T.—BRUSH, E. F. Jr.: Copper in the Rotor for Lighter, Longer Lasting Motors, ASNE San Diego Section, Fleet Maintenance Symposium, 2005, 30 Aug-1 Sept 2005.

[27] KIRTLEY, J. L.Jr.: Designing Squirrel Cage Rotor Slots with High Conductivity, Proceedings of the International Conference on Electrical Machines, Cracow, Poland, Sep 2004.

[28] MANOHARAN, S.—DEVARAJAN, N.—DEIVASAHAYAM, M.—RANGANATHAN, G.: Enriched Efficiency in Squirrel Cage Induction Motor by using DCR Technology, National Journal of Technology **3** No. 4 (Dec 2007).

[29] www.copper rotor motor.org.

[30] CHANDURSADARANGANI, A. S.: The Effects of Inter Bar Currents in Cast Aluminium and Cast Copper Rotors, Proceedings of International Conference on Electrical Machines, 2008.

[31] Induction Motor with Die Cast Copper Rotors, www. Leonardo-energy.org. Feb 2006.

[32] Production Catalogues for the Competitive Companies-Websites.

[33] http://www.industry20.com/ReadArticle.php?StoryId=163.

[34] http://www.skyscrapercity.com/showthread.php?t=524675&page=20.

[35] MANOHARAN, S.—DEVARAJAN, N.—DEIVASAHAYAM, M.—RANGANATHAN, G.: Cost Effective Production of Submersible Pump Sets Using DCR Technology, i-Manager Journal on Electrical Engineering **2** No. 4 (Nov/Dec 2008).

Received 25 February 2009

Subramanian Manoharan received ME (Electrical Machines) degree from PSG College of Technology, Coimbatore, in 2004. Prior to that he completed his BE (EEE) from Government College of Technology, Coimbatore in 1997. He is currently working as an Assistant Professor, Department of Electrical and Electronics Engineering in Karpagam College of Engineering, Coimbatore, India. He has more than 13 years of teaching experience. He has published three papers in National level journals, presented papers in National and International Conferences and authored 5 books. He is currently pursuing his PhD in the area of Electrical Machines and Drives. He is a life member of ISTE, SSI and member of IE (India) and IEEE.

Nanjundappan Devarajan, Assistant Professor, EEE Department, Government College of Technology, Coimbatore. He received BE (EEE) and ME (Power Systems) from GCT Coimbatore in the year 1982 and 1989. He received PhD in the area of Control Systems in the year 2000. He published 85 papers in the national and international conferences. He published 27 papers in international journals and 10 in national journals. Under his supervision currently 10 research scholars are working and 4 scholars completed their PhD His areas of interests are control systems, electrical machines and power systems. He is member of system society of India, ISTE and FIE.

Subbarayan M. Deivasahayam received his BE degree from PSG College of Technology, Coimbatore, in 1972. He has 35 years of experience in the field of Design, Erection and Commissioning of power plants with Government of India & abroad. He has published & presented papers in National and International Conferences. He is currently working as Joint Managing Director of Mehala Machines India Ltd, Coimbatore, India.

Gopalakrishnan Ranganathan is a graduate in Electrical Engineering from PSG College of Technology, Coimbatore. He has 45 years of rich and varied experience in the fields of design, development, standardization and quality assurance of rotating electrical machines. He has been heading the Coimbatore unit of the erstwhile multinational GEC ALSTOM India Ltd. He is currently a consultant engineer of repute. He has contributed greatly in the design and development and energy efficiency improvements of asynchronous motors. He is the life member in various societies like IE (India), Institute of Standards Engineers, and National Institute of Quality and Reliability *etc.*