Energy Efficient Machines

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Introduction

Energy crisis in the world will be one of the factors to impede the economic growth of both developing and developed countries. Bangladesh as one of the developing countries, will face acute problem in the energy sector in the next 5~10 years. If new oil and gas reserves are not found, the whole country with a high population growth will have serious problem. Study [1] by Ministry of Energy and mineral Resources [with a GDP growth of 4.55%] shows that Natural gas requirement up to 2020 will be around 13.7 TCF. By 2050, the gas requirement will shoot up to 65 TCF. Presently Bangladesh has a proven reserve of around 14.7 TCF. Even GDP growth of 3% will require 40 TCF of gas by 2050. The alternative solution to this energy crisis is to optimize the use of available non-renewable energy or to device efficient machines running on renewable energy.

All industrial, commercial and other activities rely on electrical power. Almost 80% of the electrical power is consumed by rotating machines installed in residential, commercial and industrial installations. To meet the challenges arising due to reduction of the source of non-renewable energy, researchers are focusing on design of energy efficient machines. Utilizing renewable energy sources in the machines are excellent options. However, harnessing these sources involve high capital cost with very low efficiency. So designing of energy efficient machine is a very good option for best utilization of the available energy resources.

An example of energy saving can be demonstrated by the following example:

Considering a 10 HP motor running continuously at an efficiency of 85% where the unit electricity cost is Tk.2.50. The annual operating cost for the machine would be:

10x 0.746/0.85x8766 HRx2.50 = Tk. 1,92,336.25/-

If the machine efficiency is enhanced by 1.5%, I,e 86.5%, the annual cost would be

10x0.746/0.865x8766 HRx2.50 = Tk 1,89,001/- which results a saving of Tk 3334 per year for a single medium size motor! And saves energy to the tune of 1334 kWHR.

There are various types of electrical machines. For generation of electrical energy, Generators(or Alternators) are used. While to drive loads electrical motors are employed. Generators may be AC or DC according to the type of voltage they generate. However, dc generators are obsolete now-a-days due to availability of efficient solid state devices for rectification system.

Losses in a machine are: winding losses due to heating of the winding, Iron losses that take place in the core (Eddy current and Hysteresis loss) and friction and windage losses. Energy efficient machines mean reduction of all these losses. Energy efficient machines can be designed by:

1) By redesigning the basic machine structure
2) By selection of energy efficient core and winding materials
3) By interfacing the machine with external devices.

Motors are also classified as AC or DC according to the supply source they use for conversion of electrical energy into mechanical energy. Although dc motors have high starting torque and fairly large speed variation can be attained, but they are not popular due to high cost, requirement of frequent maintenance involving larger space for installation than that of an ac motor of equal size. DC motors may be series wound, shunt wound or compound wound according to the field connection with the armature.

AC motors are classified as induction motor and synchronous motors. Due to easy construction, cheapness, high efficiency, ruggedness, requirement of less maintenance, induction motors are widely used. Almost 95% of the motors used in house hold appliances, industries and commercial enterprises employ induction motors for their enormous advantages and low cost long operating life and almost zero maintenance. Induction motors are again subdivided into: Squirrel cage motors and wound rotor motors. Wound rotor motors are used to obtain high starting torque and less starting current. However they are expensive compared to squirrel cage motors and need frequent maintenance. Limitations of squirrel cage motors are : a) Low starting torque and b) High starting current. Overcoming these two limitations of squirrel cage induction motors these machines may be converted as an high performance energy efficient motors. As these motors are extremely popular and easy to construct, researchers are actively working to improve its performance. As already mentioned, 95% of the motors used in any country are squirrel cage motors, so design of energy efficient squirrel cage motors mean reduction of huge amount of energy I,e relieving pressure on the non-renewable energy sources of the world. Due to the wide and extensive use of squirrel cage induction motors, energy efficient aspect of this type of motor will be discussed first.

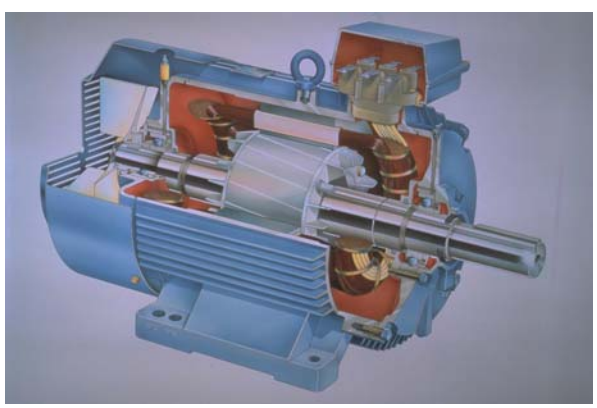

Fig. 1 Cut Away View of a Three Phase Squirrel Cage Induction motor

Fig. 2 Different types of rotors used for induction motors

Energy Efficient Squirrel Cage Induction Motor

One major consideration in the design of high efficiency induction motors is to reduce rotor resistance. Till 1970, Squirrel cage induction motors up to 250 HP were designed with Aluminum die-cast rotor having laminated steel as the core material. After 1970, as the cost of electricity went up, it became more expensive to use less efficient motors. In a research paper [2], it has been shown that significant improvement in motor efficiency can be achieved by substituting Aluminum with copper. However, there are problems associated with copper die-casting process which is being overcome by a research grant by the Italian government [3]

The resistively of copper and Aluminum per circular mil per foot at 20^{o}C are:

$$P_{AL} = 16.06,\ \rho_{CU} = 10.37 \text{ ohms.}$$

Advantages of employing copper cage are:

a) Rotor bar resistance will be reduced by a factor 16.06/10.37 = 1.548. Resulting lower I^2R losses or less heat generation in the rotor.
b) Rotor slot size can be reduced to provide more iron in the rotor teeth and rotor yoke. Rotor will be less saturated and will be cooler.

However, copper die casting of rotor is not so simple. The melting point of copper is 1080^{o}C compared to Aluminum at 660^{o}C. Also copper mass density is approximately 3 times higher than that of Aluminum. Also some of the problems with die casting are: Oxidation, over heating of rotor lamination insulation, porosity in casting and metal fatigue. A comparative efficiency of 10 HP motor having copper cage and Aluminum cage is shown in Fig. 3. One way of designing an energy efficient squirrel cage induction motor is to employ copper (having less resistively than that of Aluminum) as winding material instead of Aluminum.

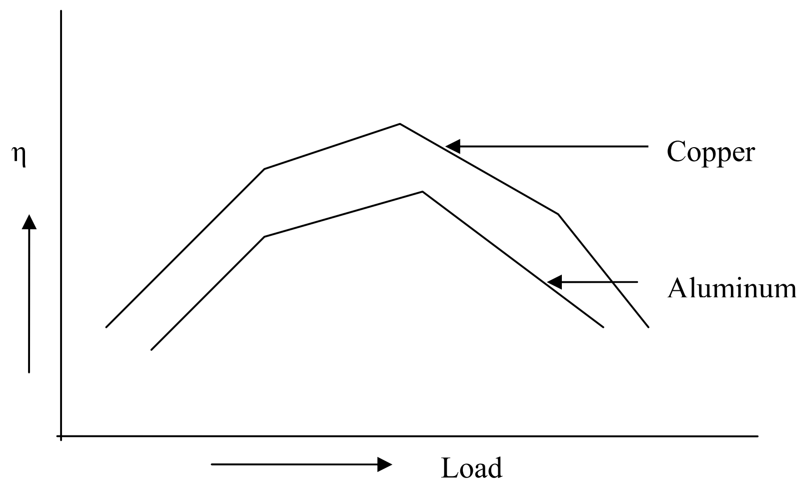

Fig. 3 Efficiency Vs Load Curve for 10HP, 4-pole Induction motor (an average difference of efficiency is 1.5~2%.)

Energy Efficient Machine Design by Proper Selection of Core Material

Normally core loss in a machine is around 30~ 50% of the total losses and about 3% of the machine rating. Research outcome on core materials showed that reduction of core material thickness and stress relief annealing of the core improved machine efficiency [4]. Also influence of silicon content also influences the core loss. Copper motor project [2] showed improvement of efficiency by using die cast copper cage and using core material having high permeability and low loss. Electrical steel of grades 8050, 8050H, 5350, 5350H showed reduction of core loss in machines. The standard electrical steel used in the reference motors construction is labeled 8050.

- low loss electrical steels are: 5350 and 3150
- high permeability electrical steels are: 8050H, 5350H

The influence of electrical steels and copper rotor cage on motor performance have been evaluated by simulations. The results have been compared with commercial motor ones in order to evaluate the achievable improvement due to the use of “premium steels” and copper cage only without affecting the design of standard motors.

Compared with identical Aluminum rotors, die cast copper rotor reduced total energy losses by 15~23% (1.2~1.7% improvement) in the overall efficiency of the motor. As a consequence in efficiency improvement, copper rotor reduced the operating temperature of motor and thus enhancing the life of the motor. As a general rule, for every 10^{o}C increase in motor operating temperature, the insulation life of machine is reduced by half. The most commonly used method to manufacture rotors with copper conductors is referred to as “welded assembly construction”. Such fabrication involves intensive hand labor and therefore is expensive. Copper die-cast rotor construction does not differ significantly from the aluminum one and, in essence, the manufacturing details are identical. The additional manufacturing challenges are increased temperatures and pressures required to die-cast copper: it melts at 1083 °C. Although copper die-cast rotor construction is a much newer technology, current state of the art technology makes it possible to die cast similarly sized rotors in copper as can be cast in aluminum. The integrity and reliability of copper die-cast is just as good as in aluminum die-cast. The primary reason copper die-cast rotors are not common place yet is because it requires specialized equipment (investment) and know-how in this field.

Copper Bars with Aluminum End Rings

Using the process described above, motor rotors may certainly be produced with copper conductor bars and copper end rings. However, there may be an opportunity for cost reduction in using aluminum end rings with copper conductor bars. An aluminum end ring would require at least a 55% larger cross sectional area than a copper one due to its lower conductivity. However, because the density of copper is 3.29 times that of aluminum the weight of the larger aluminum end ring would be only 47% that of a copper ring. Based on recent pricing of copper and aluminum, an aluminum end ring is estimated to cost 60% less than its copper equivalent.

End ring thickness

In the case of large brazed copper rotors, pure copper bars are commonly used with copper alloy end rings, whose higher resistively provides a higher starting torque and lower starting current. Thermal stresses during starting do not result in any cracking in the brazed joints. The quality and strength of a friction-welded joint can be expected to be equal to or surpass that of a brazed joint. However, when there is a difference in coefficient of thermal expansion (CTE), as in the case of copper bars and aluminum rings, further investigation of the thermal stress situation will be required.

Efficiency Improvement of Machines by Insertion of Superconducting Materials

The Discovery of High Temperature Superconductivity

The Japanese officially launched their Super-GM program in September 1987, with a long-range objective of developing superconducting generators and other electric power applications that they expected to offer for sale to the utility market following the turn of the century (Ogawa 1992).

It was during this time period that the discovery was made of high temperature superconductors (HTS), which offered the advantage of cooling via liquid nitrogen instead of liquid helium. In the United States there was almost an immediate resurrection of interest in superconducting applications, with the Department of Energy (DOE) and Defense Advanced Research Projects Agency (DARPA) taking the lead in research and development of electric power applications. In 1988, DOE began its Superconductivity Program for Electric Power Systems, which primarily supported work at the national laboratories focused on development of wire and tape HTS materials for use in electric power equipment. This DOE program has evolved into the present effort, established in 1993, called the Superconductivity Partnership Initiative (SPI), which is helping to fund the industrial development of electric power components using HTS materials.

Advantages of High Temperature Superconducting Coils

The advantages offered by HTS wire or tape over conventional LTS materials that rely on liquid helium may not be completely obvious. For some applications, the overall impact on efficiency of HTS technology due to operation at liquid nitrogen temperature may be insignificant in comparison to LTS technology operating at liquid helium temperature. For example, for a large (>100 MVA) ac synchronous machine, the impact on the machine efficiency derived from the 25-50 times reduction in refrigerator power consumption offers no major economic advantage; even complete elimination of refrigerator power consumption would only show an improvement in machine efficiency of ~0.02% for a 300 MVA rating (Blaugher 1996). Of more importance than the efficiency improvement is that use of a liquid nitrogen ambient would lead to reduced capital costs for the refrigeration plant and reduce the complexity of the cryogenic design. Even more important would be the projected improvement in the entire cryogenic system with respect to reliability.

Synchronous machines

One of the first high field superconducting power applications considered was to apply high-current-density superconducting wires to electric power synchronous generators. It is important to note that the early rationale for SC ac machines primarily emphasized the use of superconductors to achieve higher current densities, which allowed an overall reduction in cross-section and field winding volume compared to ordinary copper-wound rotors. The reduced winding volume thus led to a reduction in the size and weight of the entire machine. The preferred design approach for an ac SC machine developed and demonstrated during the 1970s was to use a stationary room-temperature armature with a rotating SC field winding, which posed difficult problems concerning transferring cryogen into a rotating vacuum-insulated container (Edmonds 1979, 673).

Following the first demonstration of an ac synchronous machine with a rotating SC field winding in 1971, major research programs were initiated in the United States, Europe, Japan, and the USSR -- the United States and Japan being the major players (Thullen et al. 1971). During the 1970s, a number of machines were built and successfully tested, highlighted in Table 1, that completely demonstrated that ac superconducting machines could be built in large sizes suitable for electric utility installation. The 12,000 rpm SC four-pole rotor test by Westinghouse for the United States Air Force (USAF) Wright-Patterson Laboratories, demonstrated, due to the high centrifugal loads on the superconducting winding, that larger machine diameters with ratings near 1,000 MVA could be successfully constructed and operated with liquid helium (Parker et al. 1975).

The principal arguments advanced during this period were that ac superconducting machine technology could achieve (1) efficiency improvements near 1%, (2) decreased size and weight for equivalent ratings, (3) ability to manufacture larger size generators than is possible with conventional technology, (4) improved steady state and transient system performance, and (5) reduced life-cycle costs, assuming reliability and maintenance comparable to existing units.

The prospect of approximately 1% increased efficiency for the SC machine offered to the utilities substantial savings in annual operating costs as a result of reduced fuel consumption. The savings in fuel costs were, in fact, so large over the ~40-year lifetime of conventional machines that they could almost completely offset the initial cost of the generator. This savings, however, was completely dependent on the SC generator having a reliability profile identical to that of a conventional unit. Furthermore, if the SC generator experienced even one additional day of outage per year compared to a conventional unit, the efficiency-derived savings would be essentially eliminated. The reliability and maintenance profile for an SC generator must therefore be identical with a conventional machine to ensure its economic benefit. Because it would take many years to produce sufficient operating experience to obtain an acceptable reliability profile, the utilities adopted a reserved attitude towards the projected savings resulting from improved efficiency.

SC ac machine technology, however, in addition to efficiency improvement, offered an impressive list of system improvements that caught the interest of and excited utility customers. Studies by the Japanese under their Super-GM program have confirmed and cited these system improvements as a major driver for the eventual commercialization of superconducting generators (Ogawa 1992).

To summarize the commercial interest in developing superconducting generators, technical interest was originally driven by the ability of SC generators to increase current density, which permitted higher magnetic fields and allowed a reduction in weight and size. In addition, the technology made possible the realization of increased machine efficiency because of the elimination of I^2R heating in the field winding, which quickly became the focal attraction of SC machines. Subsequent experience revealed marked improvement in SC generator system interactions over those of conventional machines, and this aspect turned out to be particularly attractive to utility customers. The cryogenic aspects, although of concern, were not viewed as a limitation for utility consideration of LTS ac synchronous machines. The utilities, however, did view with great suspicion the overall operational implications of cryogenics, that is, the unlikely prospect that a generator using liquid helium could be constructed and operated with reliability and maintenance profiles identical to those of conventional generators. They viewed the added requirement for a refrigerator more as a reliability issue than as a cost or machine efficiency issue.

Brushless PM Motors

Large brushless PM motors offer numerous benefits, among them high power density and high efficiency without rotor losses. Benefits come at a price, as manufacturing and material costs—including that of high-performance magnets—add up fast. Brushless PM motors also need a variable-frequency drive for control.

Powertec Industrial Motors Inc.USA is a company with a history of manufacturing high-performance brushless PM motors (and drives), currently up to 400 hp for standard products. Expertise centers in military/defense, severe industrial, and explosive-atmosphere applications. At one time, the company produced brushless dc motors up through 600 hp (*CE*, Dec. 1992, p. 79). These machines, measuring about 25-in. on the OD, used ferrite permanent magnets and were offered in air-cooled and liquid-cooled versions. They're custom products not routinely manufactured today. A new design for up to 1,000 hp is planned for 2006.

Neodymium-iron-boron (Nd-Fe-B) and samarium-cobalt are two rare-earth magnet materials available today for industrial motors. They're similar in magnetic density, but samarium has better high-temperature characteristics (albeit at higher cost), Lee notes. While Nd-Fe-B magnet pricing has declined substantially in the last five to seven years, it remains more costly than equivalent materials used in ac induction rotor construction. 'Magnet cost and low manufacturing volume affect the cost premium for brushless PM motors and therefore the probability of choosing them for a given application,' concludes Lee. He further points to the low-speed design of Siemens' high-torque motors. 'In our opinion, large PM motors with rated speeds between 800 and about 5,000 rpm have no real advantage compared to conventional induction machines,' continues Lehning. PM technology also can be 'interesting' for high-speed motors—for example, at 10,000 rpm and more—where efficiency is higher than that of ac induction machines. 'However, applications in that area are usually very specialized,' he adds.

Siemens' Lehning likewise mentions the falling cost of high-performance magnets that make PM motor technology more attractive. However, the overall technology is still costlier compared to induction motors. 'Therefore, PM motors will not replace conventional induction motors for standard applications in the foreseeable future,' he says. Lehning also notes improvements in design tools and 'know-how' for development of PM motors behind the new visibility of this product line.

Economic pressure for shorter time-to-market is growing for all product manufacturers. To help its customers realize benefits of digital servo systems in higher power processes and machines, Yaskawa has been extending IPM motor technology to its production facilities in ever higher power ratings, says the company.

Italian company Oemer Motori Elettrici Spa is another manufacturer whose offerings include large brushless PM motors. Among them are torque motors that range up to 300 kW for gearless, direct-drive applications to 500 rpm; liquid-cooled, three-phase servo motors providing ratings to 318 kW at 5,000 rpm; and high-performance units that reach to over 1 MW output at up to 2,600 rpm nominal speed for dynamic industrial applications. Oemer's product line was on exhibit at the SPS/IPC/Drives show in Germany in November 2005.

Benefits of permanent magnet machines

PM machines boast 1-2% higher efficiency than ac induction or synchronous motor alternatives at full load—and 10-15% more efficiency at partial load, according to DRS Technologies. Efficiency derives from full-rotor excitation without current and without associated losses at all speeds. Thaxton cites an example of a low-speed marine propulsion motor achieving an amazing 99.3% efficiency.

Motor cooling is simplified since the rotor generates little or no heat. Only the stator needs cooling and, because it's an 'outer structure,' water cooling becomes more attractive. Simpler cooling design also leads to flexible motor geometry. 'PM machines support a much wider range of aspect ratios than conventional motors. Short, large-diameter and long, narrow machines are feasible, as are both radial (conventional) and axial (pancake) air-gap designs,' he says.

Compact brushless PM motors reduce size and weight to about ½ to 1/3 of conventional machines, plus offer the simplicity of one stator winding, which translates to reliability. In contrast, induction motors have a rotor and a stator winding, while wound-field synchronous (WFS) motors are even more complex structurally. They include a main stator, main rotor, exciter rotor, exciter stator windings and, generally, a rotating rectifier, explains Thaxton.

DRS Technologies has demonstrated prototype PM motors that achieve higher power for a given speed than conventional machines, allowing more flexible load matching and eliminating gears (in a direct-drive motor design). 'PM motors are at cost parity with conventional machines. As long as the application requires a VFD, little reason exists to choose a conventional machine,' continues Thaxton.

Efficiency Optimization by Utilizing the Skin Effect

For an induction motor, the limitation are high starting current and low starting torque at the start up of the motor. High current at the start up may damage the starting equipment. If the motor is started with less starting current, the associated losses will be minimized giving rise to better efficiency and better starting and running performance. Presently focus is being made at the insertion of magnetic materials in the rotor of squirrel cage induction motor. The rotor frequency of an induction motor varies from 50 Hz at the start to 2.5~3 Hz at the full running condition of the motor. The skin effect may be utilized to optimize the performance of such kind of motors.

Double cage rotors attempt to increase rotor resistance at start up. This uses an outer cage of high resistance material such as brass and inner cage of low resistance such as copper. Upon start up the high resistance brass limits the starting current. After wards current can penetrate in the rotor to take advantage of low resistance copper cage. [6]

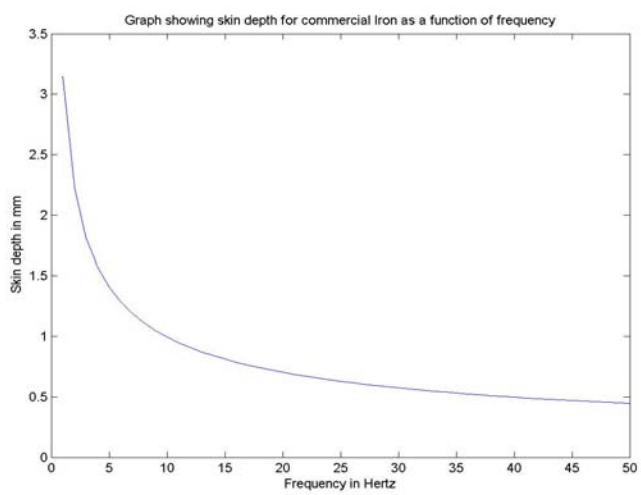

Fig. 4 Skin Effect in an Iron strip

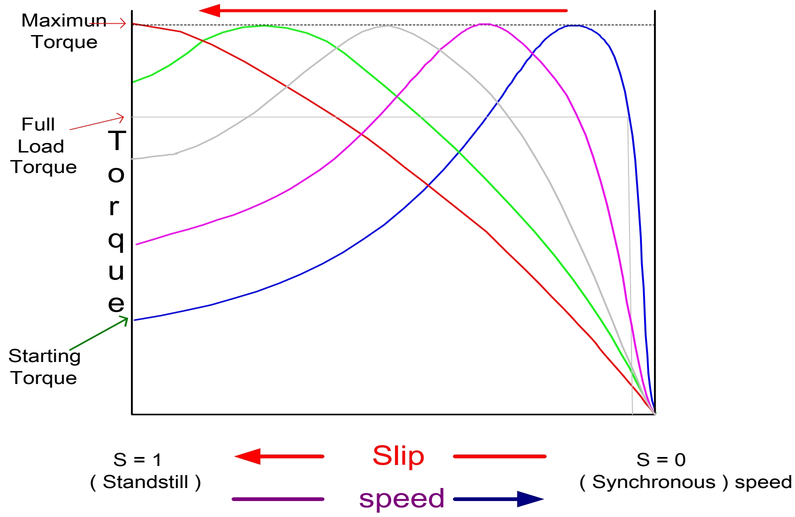

Fig. 5 Torque slip curve of Induction motor with variation of Rotor resistance

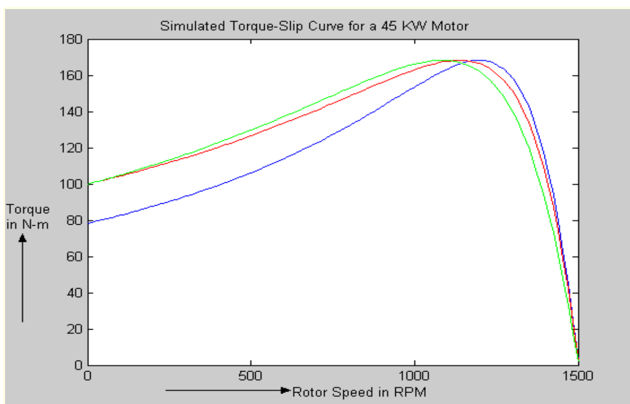

Fig. 6 T-S curve of induction motor with ferro-magnetic Material inserted in the rotor

Fig. 7 Rotor fabricated with iron insertion

A rotor including a core and a screen [7] rigidly attached to the iron core. Screen exhibits multi layer structure each succeeding layer being made with a decreasing electrical conductivity.

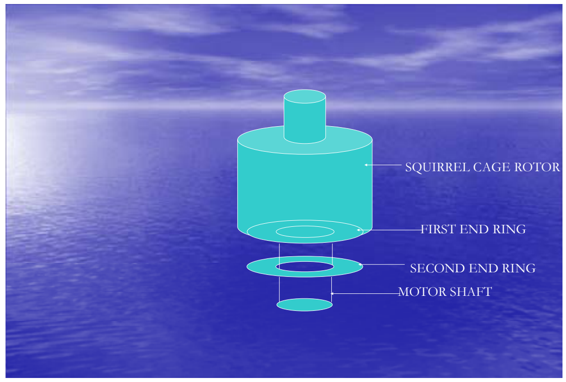

Fig. 8 Rotor with two end rings

Two end rings are employed for the rotor. The first end ring has a higher resistance than that of the second ring. When the motor starts, the first end ring is attached to the rotor which produces higher resistance to limit the starting current and to enhance the starting torque. As the rotor comes to the rated speed, the second end ring engages to reduce the overall resistance of the rotor. Thus the efficiency and running performance of the motor is unaffected.

Efficiency Improvement by External Device

Voltage *and frequency control (V/f method):*

If voltage or frequency is varied for the speed control, the motor losses enhance and the efficiency degrades. If the ratio of voltage to frequency is held constant, the machine flux remains constant

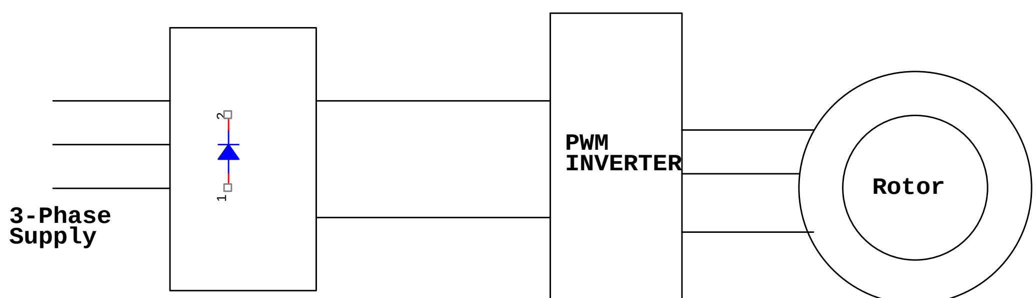

Fig. 9 Volts/Hertz control of Induction motor

Slip power recovery

The slip power in the rotor circuit may be returned to the supply. The controlled rectifier is working in the inversion mode with a certain delay in the firing angle. The variation of the delay angle permits power flow and speed control. This is also known as static cramer drive.

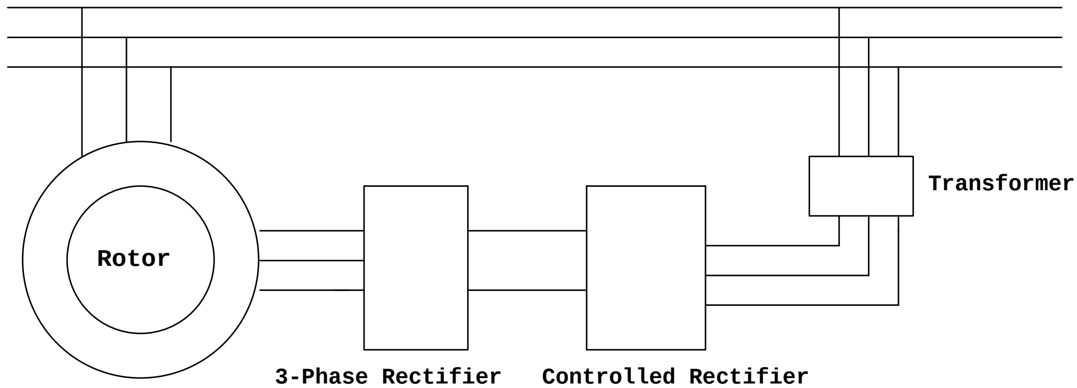

Fig. 10 Slip power recovery from induction motor

Conclusions

To improve machine efficiency, the following strategies may be adopted:

1. Using of improved magnetic materials (e.g. Premium steel)
2. Replacement of Aluminum cage with Copper cage
3. Changing of slot dimensions and reducing of machine air-gap.
4. Change of stack length and laminations.
5. Design of permanent magnet machines.
6. Utilizing skin effect for efficiency and performance improvement of SCIM
7. Interfacing machines with external devices for optimum performance.
8. Use of superconducting materials in the machine

The substitution of copper for aluminum has allowed to move the 3 and 7.5 kW motors in the Eff2 class. The efficiency improvements are not uniform for all the sizes and vary from 0.9 points for the 15 kW to 3.2 points for the 7.5 kW. For the 15 kW it is interesting to remark that the tolerance on the new efficiency could classify this motor like as Eff1. The use of 5350H electrical steel (premium steel) improves efficiencies of 0.4, 0.7 and 0.9 points from smaller to larger motors. However, premium steel and copper rotor do not give rise any further movement (from Eff2) for the 3 kW and 7.5 kW, while the 15 kW reaches the Eff1 class (without tolerance).

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[6] Standard Handbook of Mechanical Engineers 7 th Ed. Pp; 15-63
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Appendix

Table 1 High Temperature Superconducting Applications: Industry's Wire Performance Requirements

APPLICATION	INDUSTRY-DRIVEN DEVICE GOALS							
	J_c (A/cm^2)	Field (T)	$Temp_{op}$ (K)	I_c (A)	Wire Length (m)	Strain (%)	Bend radius (m)	Cost ($/kAm)
Fault-current limiter	10^4 - 10^5	0.3-3	40-77	10^3 - 10^4	1,000	0.2	0.1	10-30
Large motor (1,000 Hp)	10^5	2-4	25-77	100-500	1,000	0.2-0.3	0.05	10
Motor (125 Hp)	1.5 x 10^4	1.0	27	75-80	~300		0.01	10-100
Generator (100 MVA)	5 x 10^4 [a]	4-5	20-50	500-1,000	500-1,000	0.2	0.1	10
SMES (1 MWh)	10^5	5-10	20-77	10^4	1,000	0.2	1	2-5
Transmission cable	10^4 - 10^5	<0.2	65-77	25-30 [b]	100	0.4	2 [c]	10-100
Transformer	10^4 - 10^5	0.1	20-77	200-1,400	1,000	0.2	0.2	10

Table 2Comparison of Superconducting Electric Power Applications to Conventional Technologies

Superconducting Electric Power Applications	System Performance	Reliability & Maintenance	Efficiency	Operating Lifetime	Installed Cost [1]	Competing Technology
AC synchronous generators	Improved steady state and transient	Must be equivalent	Higher by 0.5-1.0%	Longer	Equal or higher	Gaseous and liquid-cooled
AC synchronous motors	No change	Must be equivalent	Higher by 1.0 to 2.0%	Longer	Higher	Induction and addition of VSD
AC underground transmission	Ability to double the rated capacity	Must be equivalent to conven. undrgd.	Slightly higher	Longer	Higher	• Cu/Al • "FACTS" • extruded
Fault-Current Limiters for transmission & distribution	Reduces transient currents on system components	Comparable to circuit breakers	More efficient T & D system	Longer than circuit breakers	2 to 10x circuit breaker	• Solid State breakers • Reactors • "FACTS"
Transformers for transmission & distribution	No change [2]	Must be equivalent to conven. transf.	Slightly higher by 0.1-0.2% [3]	Longer	Higher	• Iron Core
Storage Superconducting Magnetic Energy Storage (SMES)	Improves power quality and conditioning, spinning reserve, VAR & AGC	Comparable to other T&D components	Most efficient storage technology	Longer	Higher	• Flywheels • VAR Comp. • Batteries • STATCOM • Capacitors