RECENT DEVELOPMENTS IN ELECTRICAL MOTORS AND DRIVES

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ABSTRACT

The state-of-the art of electric motors, associated components and market related problems have been discussed. Recently, new topologies of high torque density motors, high speed motors, integrated (smart) motors and special motors have been developed. Progress in electric motors technology is stimulated by new materials, new areas of applications, increased reliability demands, integration of components and modern approaches to the CAD. New types of motors can find broad applications only if their cost and quality is competitive to currently used motors.

I. INTRODUCTION

Electric motors are used in a broad power range from mWs to MWs. Major areas of applications of electric motors include: industrial electromechanical drives, domestic life, automobiles with combustion engines, information equipment, public life, transportation and electric vehicles, machine tools, hand power tools, toys and amusement machines, vision and sound equipment, aerospace, defense forces, medical and healthcare equipment, pumping systems, marine and underwater propulsion.

In order to increase the reliability and simplify the maintenance, d.c. commutator motor drives are gradually replaced by brushless motor drives. Permanent magnet (PM) brushless motors fall into the two principal classes of *sinusoidally excited motors* and *square wave* (*trapezoidally excited) motors* [6].

The electrical drives family has the biggest share in the electric and electronic market. Nowadays, the d.c. commutator motor drive sales are almost without change whilst the demand for a.c. motor drives increases substantially each year.

Small PM motors are especially demanded by manufacturers of computer equipment, medical instruments, measurement technology, automobiles, robots, and handling systems. From today's perspective, the Far East (principally Japan, China and South Korea), North America and Europe will remain or become the largest market area.

Advances in electronics and PM materials have outpaced similar improvements in associated mechanical transmission systems, making ball screws and gearing the limiting factors in motion control. For the small motor business, a substantially higher integration of motor components will increasingly help to bridge this gap in the future. However, there is always the question of *cost analysis*, which ultimately is the key factor for specific customer needs.

II. STATUS OF ELECTRIC MOTORS

A.c. motors

Cage induction motors have been the most popular electric motors in the 20th century. Recently, owing to the dynamic progress made in the field of power electronics and control technology, their application to electromechanical drives has increased. The rated output power ranges from 70 W to 500 kW, with 75% of them designed with four pole stators. The main advantages of cage induction motors are their simple construction, low price, simple maintenance, no commutator or slip rings and low torque ripple. The disadvantages are their small air gap, the torque proportional to the voltage squared, the possibility of cracking the rotor bars due to hot spots at plugging and reversal, and lower efficiency and power factor than those of synchronous motors. Over 10% of applications use some type of electronic controller either in the form of solid state *soft starters* or *frequency inverters.*

Synchronous motors have several advantages in comparison with induction motors such as controllable power factor, proportionality between the torque and input voltage, speed dependent only on the input frequency and number of poles, larger air gap and better adaptation to pulsating load torque than induction motors. Synchronous motors can operate with unity

Table 1. Comparison of cage induction motors, PM brushless motors and SRMs.

Parameter	**Cage Induction Motor**	**PM Brushless Motor**	**SRM**
Power density	Satisfactory	Highest	Lower than PM
Maximum shear stress, N/m^2	Up to 20,000	Over 60,000	Up to 35,000
Air gap	Small, fraction of mm	Up to 1mm or more	Small, fraction of mm
Efficiency	Satisfactory; Good for energy efficient motors	Over 90%	About 1% more than that of induction motor
Power factor $cos\phi$	0.8 to 0.9	High, up to 1.0	Switched d.c. motor
Performance at low Speed (VVVF)	Satisfactory	Good	Torque is high, but efficiency low
Torque - voltage characteristic $T=f(V)$	$T \propto V^2$	$T \propto V$	$T \propto V$ at constant peak current
Torque ripple	Less than 7%	About 10%	Over 20%
Overload capacity factor T_{max}/T_{rated}	1.6 to 3.2	About 2	Highest
Power electronics converter	Not necessary for constant speed drive	Necessary	Necessary
Cost	Cost-effective motor	Still expensive motor	Cost-effective motor

power factor and even deliver the reactive power to the supply system (power factor correction). Synchronous motors with PM excitation are the most efficient motors and have the highest power density (*output power-to-mass* or *output power-to-volume).* Their drawback is much higher price than that of induction motors and maintenance of the brush sliding contact in the case of electromagnetic excitation. The largest synchronous motors are rated over 20 MW.

Brushless PM motors

Rare earth PMs improve the *output power-to-mass* ratio, efficiency, dynamic performance, and reliability [6]. The prices of rare earth magnets are also dropping which is making these motors more popular. A brushless PM motor has the magnets mounted on the rotor and the armature winding mounted on the stator. In a d.c. commutator motor the power losses occur mainly in the internal rotor which limits the heat transfer and consequently the armature winding current density. In PM brushless motors the power losses are practically all in the stator where heat can be easily transferred through the ribbed frame or, in larger machines, water cooling systems can be used [11].

The brushless PM motor shows more advantages than its induction or synchronous reluctance counterparts in motor sizes up to 10 - 15 kW. The largest commercially available motors are rated at least at 750 kW (1000 hp). There have also been successful attempts to build rare-earth brushless PM motors rated above 1 MW (Germany).

The armature winding of brushless PM motors is usually distributed in slots. When cogging (detent) torque needs to be eliminated, *slotless windings* are used. In comparison with slotted windings, the slotless windings provide higher efficiency at high speeds, lower torque ripple and lower acoustic noise. On the other hand, slotted windings provide higher torque density, higher efficiency in lower speed range, less PM material and lower armature current.

In a *hybrid brushless PM motor* an auxiliary d.c. field winding helps to increase the speed range over constant power region [3].

Stepping Motors

The *stepping motor* is a singly-excited motor converting electric pulses into angular displacements. It has salient poles both on the stator and rotor and polyphase stator winding. Stepping motors are classified as motors with active rotors (PM rotors), motors with reactive rotors (reluctance type) and hybrid motors (windings, PMs and variable reluctance magnetic circuit). A two-phase *hybrid stepping motor* performing 200 steps per revolution is nowadays a popular motor in *factory automation systems*. Very high resolution can be achieved in the so called *microstepping* mode in which the basic motor step is subdivided by proportioning the current in the two-phase winding.

Switched Reluctance Motors (SRMs)

The *SRM* is a polyphase doubly-salient electric motor with no winding and no excitation system on the rotor. The electromagnetic torque is very sensitive to the *turn-on angle* and *turn-off angle* of the stator phase current. Thus, the SRM controller requires information about the rotor position. The fundamental difference between a stepping reluctance motor and SRM is that the second one needs rotor position sensors. In a three-phase SRM the number of stator poles can be 6 (one phase winding per pole pair) or 12 (one phase winding per two pole pairs) while the number of rotor poles should be 4 or 8, respectively. SRMs can provide the highest *performance-to-cost* ratio, have perspectives of applications in energy efficient drives, high speed drives or fault tolerant drives. Their main drawback is the need for keeping a small air gap and suppressing the torque ripple and acoustic noise. The acoustic noise can be reduced by the use of profiled phase voltage, currrent or magnetic flux waveforms, mechanical techniques or modified pole geometries. Power electronics converters for SRMs are similar to inverters; however, the switching frequency is lower and current sharing between solid state devices is better. The technology of standard speed SRMs rated below 10 kW is now mature (e.g. *Emerson*, St. Louis, MI, U.S.A.). Hot market for SRMs comprises washers, dryers, blowers, compressors, servo systems, aircraft and automobile starter-generators. Table 1 contains a comparison of cage induction motors, PM brushless motors and SRMs rated up to 10 kW.

Servo motors

Servo motor technology has changed in recent years from conventional d.c. or two-phase a.c. servo motor drives to new maintenance-free brushless three-phase *vector-controlled a.c. drives* for all motor applications where quick response, light weight and large continuous and peak torques are required.

III. PROGRESS IN ELECTRIC MOTORS TECHNO LOGY

Electric motors are decidedly not part of an old-fashioned area of research. They are the most popular machines of everyday life and the number of their types increases with the development of science and technology, e.g. SRMs, piezoelectric motors, transverse flux motors, written pole motors, various hybrid motors, smart motors, linear motors, etc. Progress in electric motor technology is now stimulated by:

- materials engineering: NdFeB PMs, high temperature superconductors, amorphous laminations, powder materials, high temperature ferromagnetic alloys, piezoelectric ceramics, magnetostrictive alloys with 'giant' strains, magnetic memory alloys, wires with heat activated adhesive overcoats, very thin insulation materials, high temperature insulating materials, magnetic liquids, etc.;
- impact of power electronics: variable speed drives, switched reluctance motor drives;
- impact of new control strategies: self-tuning electromechanical drives, 'intelligent' drives, fuzzy control, sensorless control;
- impact of new energy sources, e.g. solar panels, fuel cells, etc.;
- new areas of applications e.g. robotics, electric cars, aerospace, vacuum, high pressure liquids, harsh environment, nuclear technology, mechatronics, microelectromechanical systems (MEMS), computers, consumer electronics, large drives, bullet trains, linear metro, magnetic levitation trains, naval applications, electromagnetic launchers, correction of satellite trajectories;
- need for energy saving (energy efficient motors);
- demand on high speed motor drives, e.g. motors for compressors;
- demand on high torque gearless motor drives, e.g. electric vehicles, light electric traction, machine roomless elevators;
- reliability demands: elimination of brush sliding contacts, fault-tolerant motors, increased time of trouble-free operation;
- new topologies: written pole motors, transverse flux motors, hybrid motors, piezoelectric motors, resonant motors, superconducting motors, oscillatory motors, rotary-linear motors, etc.;
- integrated electromechanical drives (motor, encoder, gears, solid state converter, protection, controller, computer interface in one frame);
- application of magnetic bearings and bearingless motors;
- increased performance-to-cost ratio;
- reduction of noise, vibration, torque ripple, electromagnetic and RF interference;
- impact of computational electromagnetics: finite element method, boundary element method, edge element method;
- applications of optimization methods, e.g. artificial neural networks, genetic algorithm, etc..

II. MATERIAL ENGINEERING

Permanent magnets

Owing to the invention of high energy SmCo PM magnets in the 1960s and NdFeB in the 1980s, a revolutionary progress has been made in construction of high efficiency and high power density PM machines. The best sintered NdFeB has B_r = 1.45 T and H_c = 1100 kA/m. The operating temperature of some NdFeB magnets is over 250^0C. The use of PMs for field excitation systems of electric motors brings the following benefits: (a) no electrical energy is absorbed by the excitation system and thus there are no excitation losses which means substantial increase in the efficiency, (b) higher torque or output power per volume than when using electromagnetic excitation, (c) better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap), (d) simplification of construction and maintenance, and (e) reduction of prices for some types of machines. The cost of sintered NdFeB PMs used for the mass production of PM motors is now below US$ 100 per kg.

Soft magnetic powder composites

New *soft powder materials* which are competitive to traditional steel laminations have recently been developed [1,8]. Powder materials are recommended for 3D magnetic circuits e.g. claw-pole, transverse flux and disk type motors.

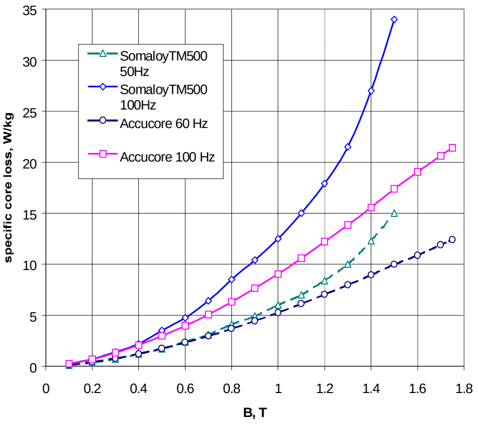

Fig. 1. Comparison of specific core losses for *Accucore and Somaloy*™ 500.

Specific core loss curves for *Accucore* [1] and *Somaloy*™ 500 [8] powder materials are shown in Fig. 1. At 10 kA/m the magnetic flux density is 1.72 T for Accucore and 1.54 T for *Somaloy*™ 500.

High saturation ferromagnetic alloys

Cobalt-iron alloys have the highest known saturation magnetic flux density, about 2.4 T. They are the natural choice for applications where mass and space saving are of prime importance. The nominal composition e.g. for HiSat50 is up to 50% cobalt, 2% vanadium and the rest is iron. The specific mass density is from 7950 to 8150 kg/m^3 , hardness about 315 in Vicker's scale and specific core loss about 20 W/kg at 2 T, 400 Hz and 0.1 mm thickness.

High temperature ferromagnetic materials

Aircraft *integrated power units* (IPUs), i.e. switched reluctance starter/generators mounted on the central shaft of the gas turbine engine require operating temperatures at least 600^{0}C [4]. Fe-Co-V alloys (up to 50% cobalt) can provide saturation magnetic flux density approximately 1.6 T at 850^{0}C. Cobalt-iron alloys Hiperco 50HS, Hiperco 50 and Hiperco 27 from *Carpenter Technology Corporation*, U.S.A. and AFK1 from *Imphy s.a.*, France, are currently used for prototypes of reluctance machines and short stroke actuators.

Amorphous ferromagnetic materials

Core losses can be substantially reduced by replacing standard electrotechnical steels with *amorphous magnetic alloys*. Table 2 shows some magnetic, electrical and mechanical properties of METGLAS® amorphous alloys.

Application to the mass production of electric motors is limited by hardness, up to 1100 in Vicker's scale. One of effective methods of cutting is a liquid jet.

Table 2. Physical properties of iron based METGLAS® amorphous alloy ribbons (*AlliedSignals, Inc.*, Morristown, NJ, U.S.A.).

	2605CO	2605SA1
Saturation magnetic flux density, T	1.8	1.59 annealed 1.57 cast
Specific core loss at 50 Hz and 1 T, W/kg	less than 0.28	about 0.125
Specific density kg/m^3	7560	7200 annealed 7190 cast
Electric conductivity, S/m	0.813x10^6	0.769x10^6
Hardness in Vicker's scale	810	900
Stacking factor	less than 0.75	less than 0.79
Curie temperature, ^{0}C	415	392
Maximum service temperature, ^{0}C	125	150

Wire insulation with heat activated adhesives

A new method of securing conductors in slots that does not require any additional material (epoxy resin) and uses very low energy input, has emerged in the last few years [10]. This method uses copper *wires coated with a heat activated adhesive*. The adhesive, typically a polyvinyl butyral, is usually activated by heating the finished coil as a result of passing electric current through it.

High temperature wires

Windings that operate at temperatures over 600^{0}C require *nickel clad copper* or *chrome-iron clad copper* with *ceramic insulation*. Ceramic coating is primarily a refractory-glass compound. It can withstand flexibility and braiding requirements consistent with normal coil practices. If the packing factor is less important, wires with ceramic insulation can be replaced by *fiberglass sleeved wires*.

Superconductors

In power engineering, *superconductivity* can find its practical application in large turboalternators, d.c. machines, linear synchronous motors, energy storages, magnetic levitation vehicles, transmission cables and fault-current limiters. The use of superconductivity in electrical machines reduces the excitation losses, increases the magnetic flux density, eliminates ferromagnetic cores, and reduces the synchronous reactance (in synchronous machines).

In 1986, the first so called *high temperature superconductors* (HTS) were discovered at the IBM Research Laboratory in Zurich, Switzerland. At 60 to 80 K (liquid nitrogen) thermal properties become more friendly and criogenics can be 40 times more efficient than at 4.2 K (liquid helium). Currently available on the market silver heathed BSCCO-2223 HTS has demonstrated nearly 3 T magnetic flux density at 30...35 K [2].

V. HIGH POWER DENSITY MOTORS

PM transverse flux motor

The electromagnetic power density of an a.c. machine is proportional to the electromagnetic loadings and rotational speed. At constant armature current and diameter, the line current density A of transverse flux machines increases with the number of poles. To maximize the air gap magnetic flux density B_g, the flux paths in ferromagnetic parts should be as short as possible. Transverse flux machines have shorter flux paths than traditional longitudinal flux machines. Recently, *transverse flux motors* have been considered as motors with larger shear stresses $\sigma = B_g A$ than classical longitudinal flux motors. Consequently, the torque and power density is high. A transverse flux motor has a toroidal armature winding embraced by U-shaped ferromagnetic cores (Fig. 2). Polyphase motors are assembled of single-phase modules (Fig. 2b).

The most important advantages of PM transverse flux motors are high torque and power density, simple stator winding consisting of a single ring-shaped coil, modular construction, the more the poles the less the torque pulsation, excellent motor for gearless electromechanical drives and operation as a standard PM brushless motor using a standard encoder and power electronics hardware. On the other hand the stator core uses large number of “transverse flux” magnetic circuits and good quality powders materials should be used to make the construction economical. Careful attention must be given to the power factor which is inherently low and to the cogging torque which is inherently high.

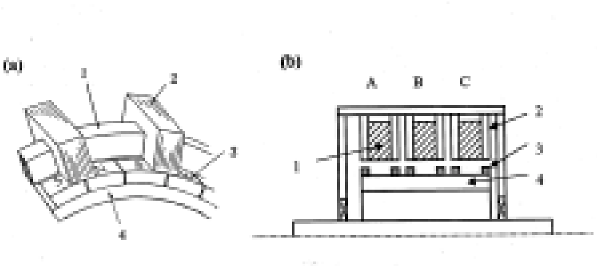

Fig. 2. Transverse flux PM brushless motor: (a) single phase unit, (b) modular configuration of a three-phase machine: 1 – armature (stator) winding, 2 – armature core, 3 – PM, 4 – magnetic circuit of the rotor.

PM disc type motors

Disc type or *axial flux motors* provide better heat transfer and allow for higher line current densities than standard cylindrical motors. At present, the highest power density for disc type PM brushless motors with water cooling system exceeds 2.2 kW/kg (*Kaman Electromagnetics*, Hudson, MA, U.S.A. [11]).

The line current density and stator winding current density can be maximized by designing an efficient cooling system. Direct water cooling system and hollow armature conductors can provide the most efficient heat transfer.

Disc type motors can totally be iron free motors provided that PMs are arranged in the so called Hallbach array [6].

VI. HIGH SPEED MOTORS

The speed of a.c machines increases with increase in the input frequency. High input frequency reduces the dimensions of electrical machines. *High speed gearless electrical motors* find a lot of applications as spindle motors, pump motors, gas compressor motors, airconditioner compressor motors, etc. Elimination of gear trains improves the efficiency of the system, reduces the dimensions and noise and simplifies the construction and maintenance. Cage induction motors and SRMs seem to be the most economical candidates for high speed applications.

VII. BEARINGLESS MOTORS

The concept of a *bearingless* cage induction motor is shown in Fig. 3. A conventional induction motor produces only the torque (tangential force). In a bearingless motor the stator and rotor consists of two parts. In addition to the tangential force they also produce radial forces. The radial force must be fully controllable and normally a special control winding is required [12].

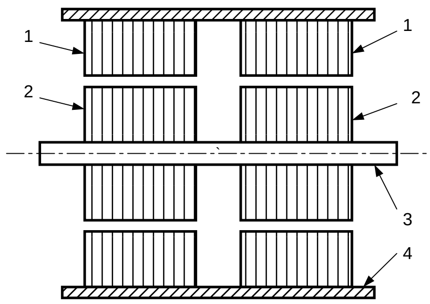

Fig. 3. The concept of a bearingless a.c. motor: 1 – stator, 2 – rotor, 3 –shaft, 4 –frame.

VIII. WRITTEN POLE MOTORS

A *written pole motor* has a special coil that `writes’ poles onto a ring of magnetic material attached to the rotor. The number of poles and their positions can be continuously varied while the machine in operating. This design offers a high efficiency, unity power factor, very low start-up current and ride through power interruptions of up to 15 s [7]. Written pole motors are now available in sizes from 7.5 to 55 kW and are used in remote rural areas with single phase reticulation systems. A written pole motor can be joined with a written pole generator through a shared, external high inertia rotor that creates a motor-generator set delivering the highest quality power.

Conventional motors driving large inertial loads require special electrical or electronic current reducing devices to avoid excessive winding temperatures. Since the starting current is only about 30% of that of an equivalent cage induction motor, a written pole motor can start directly with high inertia load without any solid state starter. Therefore, written pole motors and generators can be used very effectively as machines integrated with flywheel energy storage systems.

IX. PIEZOELECTRIC MOTORS

Piezoelectric motors, also called *ultrasonic motors* operate on the principle of piezoelectric effect which produces mechanical vibrations in the ultrasonic range (Fig. 4). The most popular motors are travelling wave piezoelectric motors, invented in Japan in 1982. The

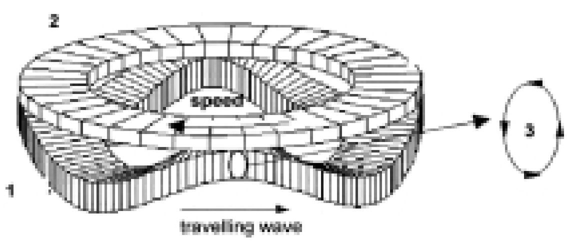

Fig. 4. Principle of operation of a travelling wave piezoelectric motor: 1 – stator, 2 – rotor , 3 – orbital of surface particle.

stator has electrodes arranged in two-phase configuration and is fed from a two phase inverter at the frequency above 20 kHz (not audible). The rotor turns in the oposite direction to the travelling wave due to friction between the stator and rotor. Piezoelectric motors produce high electromagnetic torque at low speeds, high holding torque at zero speed, contain only few components and run silently. Typical applications include auto-focus lenses, timepieces, window blinds, *x-y* positioning stages, robotics, automobile industry and consumer goods.

X. INTEGRATED ELECTROMECHANICAL DRIVES

The *integrated electromechanical drive* combines the electromechanical, electrical and electronic components, i.e. motor, power electronics, position, speed and current sensors, controller, communication IC and protection together into one package (Fig. 5). Sometimes, the integrated electromechanical drive is called the *smart motor*, similar to *smart power devices* i.e. devices integrating analog, digital and power functions on one single piece of silicon [9]. Smart motors have the following advantages [13]:

- the number of input wires to the motor is reduced;
- traditional compatibility problems are solved;
- standing voltage wave between the motor and converter increasing the voltage at the motor terminals is reduced;
- simple installation.

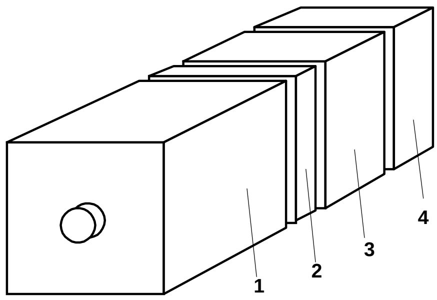

Fig. 5**.** Integrated (smart) electromechanical drive: 1 – brushless motor, 2- encoder, 3 – power electronics converter, 4 – control unit.

To obtain an even more compacted design a sensorless microprocessor control is used. The cables connected to a smart motor are generally the power supply and speed signal. All kinds of brushless motors can be used in integrated drives. However, PM brushless motors show the best performance. *Packaging* makes thermal and electromagnetic compatibility issues more complicated. Excessive heat generated by the motor or power electronics module can damage other components.

XI. SOLID STATE CONVERTERS

Switching capabilities of currently available thyristors, GTOs and IGBTs for high power applications are shown in Fig. 6. [15] IGBTs are now ousting GTO thyristors even at higher range of power and they have already replaced BPTs [15]. IGBTs will be the main choice for railway traction application in the nearest future [15]. High power thyristors are key solid state devices in the maximum power range. The *integrated gate commutated thyristor* (IGCT) is the optimum combination of the low-loss thyristor technology and the snubberless, cost-effective GTO for medium and high voltage power electronics applications [14].

Silicon will remain as the basic material for solid state devices in the next 10 to 20 years. *Silicon carbide* (SiC) and *diamond* have been suggested as suitable materials for the construction of new generation of semiconductor devices. SiC can be used in harsh conditions up to 600^0C.

Water cooled solid state converters are about 80% smaller than standard air cooled converters of the same size (150 kW). In addition, cost decreases by 20% versus optimized air cooled converters. Fig. 7 shows the construction of a water cooled variable speed drive developed by *Reliance Electric (Rockwell Automation)*, Cleveland, IL, U.S.A. The tubing system is embedded into a cast aluminum heat sink. Solid stated devices and capacitors are fixed directly to the heat sink. Control circuitry boards are attached to the front metal panel.

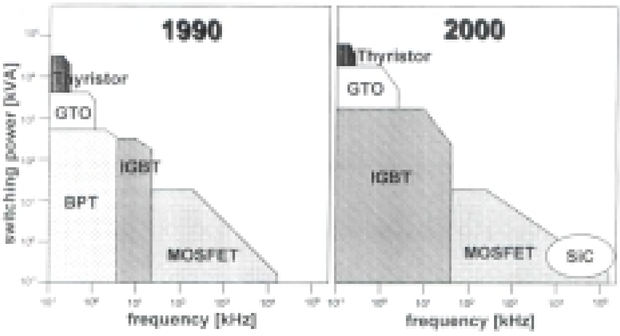

Fig. 6. Progress in solid state devices [15].

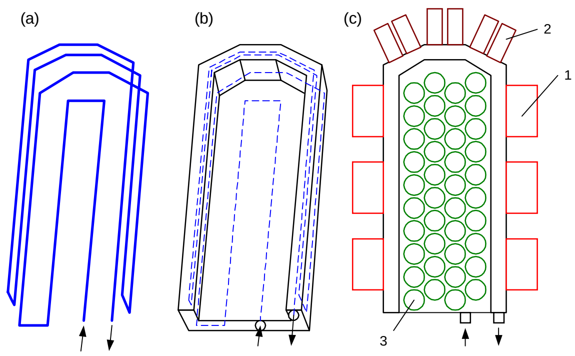

Fig. 7. Construction of liquid cooled solid state converters developed by *Reliance Electric*, Cleveland, IL, U.S.A.: (a) formed swaged copper tubing, (b) cast aluminum heat sink, (c) heat sink with solid state devices an capacitors. 1 – IGBT, 2 – diode, 3 – capacitor.

XII. MECHATRONICS

A new technology called *mechatronics* emerged in the late 1970s. Mechatronics has been defined as the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes. Applications of mechatronics can be found in the aerospace and defence industries, in intelligent machines such as robots, automated guideway transit, computer-controlled machine tools and in consumer products such as video casette players and recorders, cameras, CD players and quartz watches.

A typical example of a novel mechatronics application is in the control of multi-shaft motion. A gear train has traditionally been employed with the performance, i.e. speed, torque and direction of rotation determined by the motor and gear rated parameters. Such a configuration is acceptable for constant speed of each shaft but where variable speeds are required, a different set of gears is needed for each gear ratio. In the mechatronics solution each shaft is driven by an electronically controlled motor, e.g. a PM brushless motor with feedback which provides more flexibility than can be obtained from mechanical gear trains. By adding a microprocessor or microcomputer, any required motion of the mechanism can be programmed by software. In the future, the computer based controller will not only handle the speed control, but it can also support the commissioning, make simulations, provide communication and make decisions.

XIII. ENERGY CONSERVATION

The contemporary world faces enormous increase in energy consumption and drastic pollution of our planet. Politicians and decision makers should take into considerations the opinions of scientists and engineers how to effectively minimize these problems.

The world electricity consumption was estimated as about 12,000 TWh per annum in 1996 and it is predicted to increase to about 19,000 TWh in 2010 and about 22,000 TWh in 2020 [6]. The industrial sector, in developed countries, uses more than 30% of the electrical energy. More than 60% of the electrical energy is consumed by electric motor drives. It has been estimated, that in developed industrialized countries, roughly 20% of electrical energy can be saved by using more efficient control strategies for electrical drives.

This means that *electrical machines have an enormous influence on the reduction of energy consumption*. Electrical energy consumption can be saved in one of the following ways: (a) good housekeeping, (b) use of variable-speed drives and (c) construction of electric motors with better efficiency.

Most energy is consumed by three-phase induction motors rated below 10 kW. An *energy-efficient induction motor* produces the same shaft output power, but uses less electrical input power than a standard efficiency motor. Energy efficient induction motors have: (a) more copper in the winding, (b) higher quality and thinner steel laminations in the stator, (c) smaller air gap between the stator and rotor, (d) reduced ventilation (fan) losses and (e) closer machining tolerances.

XIV. POWER QUALITY

With growing applications of power electronics, *power quality* related issues become more vital. Converter fed drives deteriorate the power quality of the utility system and vice versa - the poor quality of power supply results in degrading the drive performance. To improve the power quality, development of EMI filters, converters with EMI suppression components, novel static VAR compensators, PWM active power line conditioners (APLC) and flexible a.c. transmission systems (FACTSs) is more and more important. The ideal solution is a *green power electronics*, i.e. with no harmonics pollution and unity power factor.

XV. FUTURE

The development of electric motors technology is stimulated by new materials, new areas of applications, increased reliability demand, new topologies, integration of components, new control strategies and modern CAD techniques.

- Motors with brushes and sliding contacts are gradually replaced by brushless motors. In particular, d.c. commutator motors are replaced by converter fed cage induction motors and PM brushless motors. Market demand on a.c. and brushless motor drives increases while the demand on d.c. commutator motors will decline in the nearest future.
- Cage induction motors have been the most popular motors in the 20th century and, unless the price of other motors drops down, they will be in the highest demand at the beginning of the 21st century.
- PM brushless motors are the most efficient electric motors with the highest *output power-to-mass* and *output power-to-volume* ratio.
- Although SRMs are less efficient than PM brushless motors, SRMs can be a preferred choice in many applications, because they have neither PMs nor rotor windings and are fault tolerant motors.
- Water cooled motors and solid state converters can reduce the volume by 50 to 80% and cost by 10 to 30%.
- More integration of electric machines with mechanical components, i.e. aircraft IPUs or traction electromechanical drives is expected.
- Electrical motors operating at high temperatures between 500 to 600^0C can be commercially available in the next few years [4].
- New type of motors can find broad applications only if their price and quality is competitive to currently used motors.
- The vector control and adaptive control have nowadays become common control techniques which upgrade the control performance of a.c. motors to the same or higher level as that of d.c. commutator motors.
- Encoders, resolvers and position sensors will be gradually replaced by sensorless methods of control.
- Fast development of electrical drives integrated with solid state converters and `intelligent' controllers is expected in the next few year.
- The converter of the future will have much more computational capability including communications and diagnostics.
- Fuzzy logic allows to control electric drives by implementing human expert knowledge.
- From the `save our planet' and `improved quality of life' point of view, energy conservation and power quality are the highest priority requirements to be met when designing, installing and refurbishing electric motors and drives.

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