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Modern Trends in Eletromechanical Energy Conversion

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Abstract:
Virtually any modern industry, ship, terrestrial vehicle or equipment requires electromechanical energy conversion to meet its objective. As a result, electric machines of various sizes, specifications and topologies abound. An important category of electric machines is Alternators (AC Generators), which develop electrical energy when driven by a prime mover.
There has been a significant push in recent years towards developing high rpm power generation equipment, with a view to reducing the weight and space occupied for a given power output. This paper attempts to explore this topic and investigate the possibility of the use / induction of high to very high rpm energy conversion devices into marine applications.
Technological trends are also highlighted, keeping the discussion at a level that can be easily grasped by the practicing electrical/electronics engineer or an enlightened user.

Keywords: *Alternator, Generator, PMSM, PM, micro-turbine, ultramicro-turbine, Inverter, SRM, VFD.*

1. Introduction

Electric machines and drives today range in power handling capacity from microwatts to several megawatts. Similarly, the topologies and constructional details of these elements constitute a multitude of design choices based on space, power handling, cost and application requirements. A comprehensive coverage of these multitudes is out of the scope of the present paper. This paper focuses on specific areas, which are germane to ship borne platforms, as well as present day trends and possibilities in this application space.

2. Present Day Electric Machine Technology

The workhorse of industry and vehicular platforms today is the common squirrel cage induction motor/generator. It offers a range of advantages that, until the advent of modern rare earth permanent magnet technology, were virtually unparalleled in any other embodiment of electromechanical energy conversion device. It has, after the advent of modern power electronics, replaced DC machines in the large majority of electric drive applications in the few kilowatts to few megawatts range.

The robustness, reliability and simplicity of the squirrel cage induction machine are still benchmarks for these characteristics among modern electric motors. Another feature that has made the induction machine popular is its virtually maintenance free operability over a period of several thousand working hours.

One of the few down sides to squirrel cage induction motors is their relatively high reactive power consumption at light loads. This issue is especially irksome in the case of low speed, high pole number squirrel cage motors.

The other issue that has prevented the induction machine from completely eliminating the use of DC machines is the need for relatively complex power electronics and control schemes even for simple speed and torque control. Particularly in defense applications, the use of Variable Frequency Drives (VFD's) and complex power electronics requires a careful analysis of EMI/EMC related issues.

Conventional synchronous motors still find use in very high power applications or applications demanding a precise speed. Synchronous alternators are the workhorse industry today and are used for practically all power generation requirements.

Conventional DC motors are still used in applications where excellent dynamic performance or speed control is required, without the complex electronics associated with an AC drive.

2.1. Quest for Small and Light Electric Machines

The relentless endeavor to pack more and more power into a given space has given rise to efforts in several areas of electric machine technology.

One of the areas of activity has been the development of permanent magnet (PM) machines. Although PM machines have existed for a long time, their impact on size and weight reduction for a given power output was not felt until the development of rare earth magnet technology. With the development of NdFeB (Neodymium-Iron-Boron) and Sm_2Co_{17} (Samarium-Cobalt) magnets (collectively called "rare earth magnets"), the amount of power that can be packed into an electric machine of a given size has jumped appreciably. The added advantages of these machines are their higher efficiencies when compared to induction machines and their higher power factors, even at light loads. Besides PM motors, Switched Reluctance Motors (SRM), Brushless DC motors (BLDC), etc. have also seen some research dollars (sadly, not research Rupees) in application areas where their specific topologies afford significant advantages over conventional machines.

Innovative cooling techniques as well as the use of very high RPM motors/generators in certain applications is also being considered. Rotating machines with speeds in excess of 1,00,000 RPM are already in use. Rotating machines with speeds upto 1,000,000 RPM are being actively developed! Research in “microturbines”, “ultramicroturbines” and high speed compressor systems is active today.

Another area that has been researched with vigor is materials technology. Electrical steels with low core losses and high saturation flux densities have been developed, which allow a smaller mass of electrical steel to be used to extract a given amount of power from the motor. Research into alloys and the use of lightweight materials such as Titanium has also progressed, with a view to reducing the weight of electrical machines.

Considerable research dollars in the recent past have also been allocated to the development of “superconducting rotating machines”. The basic thought process behind this research being that if the conductors used in making a motor are super-conducting – thereby implying that the power loss is negligible – a high capacity motor can be made quite small. This research has been under wraps for the most part, as the primary consumers for this rather expensive technology are defense establishments. As superconducting behaviour is seen only at extremely low temperatures, cryogenics finds application in this area of electric machine development as well.

2.2. Permanent Magnet Machines

Permanent Magnet (PM) machines or Permanent Magnet Synchronous Machines (PMSM) are commonly used in high end applications such as space, defense, servo control systems, etc. today.

They are built on the basis of rare earth magnets, which are essentially very powerful magnets packing a relatively large “energy product” into a relatively small volume. NdFeB magnets have a higher energy product than Sm2Co17 magnets, although they have a more limited operating temperature range. Conversely, Sm_2Co_{17} magnets are very much more brittle than NdFeB magnets. About 90% of the world's reserves of rare earth magnetic materials exist in the People's Republic of China.

The very high coercivity of rare earth magnetic materials implies usually that special equipment is necessary to magnetize these materials. As a consequence, the majority of rare earth PMSM's today are built by assembling pre-magnetized PM's. This leads to practical issues of handling already magnetized rare earth permanent magnets, which can be very dangerous due to their extreme tendency to attract magnetic metals.

Despite these technical hurdles and despite the relatively high cost of permanent magnets, PMSM's are widely gaining use today due to the following major advantages:

a) Relatively high power density compared to squirrel cage motors, implying a significant decrease in size and weight;
b) Relatively high efficiency and operating power factor, even at light loads;
c) Wide speed range;
d) Robustness, longevity and practically no need for maintenance.

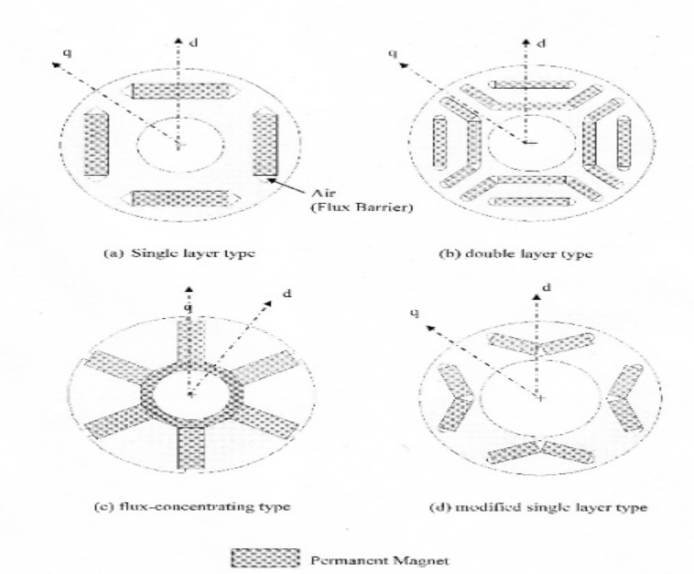

Figure 1: Commonly used permanent magnet layouts in PMSM rotors.

In most PMSM's, the rotor contains the permanent magnet assembly. The stator is typically like any other conventional motor stator. The rotor PM's can be organized in a variety of ways, most commonly being either a “surface magnet” configuration or a “buried magnet” configuration. Most industrial and high reliability, high-speed applications employ buried permanent magnet configurations.

Typical PM rotor layouts are illustrated in Figure 1 alongside. A technical discussion on design aspects is beyond the mandate of this paper and as such is not being taken up here.

2.3. Brushless DC and Stepper Motors

Brushless DC (BLDC) machines and steppers belong to the family of motors, which have "teeth" (saliencies) in the stator and rotor. The stator and rotor have different numbers of teeth. Stator teeth have coils wound around them, while rotor teeth are unwound. Position sensors are mounted in the motor, to detect rotor position.

Intuitively, if a pair of diametrically opposite stator teeth is magnetized (i.e. a current is passed through their coils), the rotor will tend to rotate so that the pair of rotor teeth closest to these stator teeth align with them in the minimal reluctance configuration. Therefore, if successive stator teeth are energized based on rotor position, rotary motion or motor action is seen.

It is readily seen that a BLDC motor can as well have permanent magnets instead of just teeth or saliencies in the rotor. Their control philosophy however still remains the same.

BLDC motor controllers use the rotor position sensors to determine the pair of stator teeth that need to be energized. In recent times, sensorless BLDC controllers have also been used, although their effectiveness at very low speeds (less than 10 rpm) is questionable.

A typical BLDC motor layouts is illustrated in Figure 2 alongside. A technical discussion on design aspects and the various embodiments of BLDC motors is beyond the mandate of this paper and as such is not being taken up here.

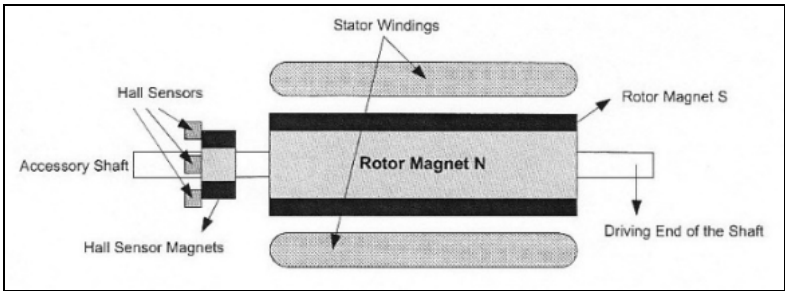

Figure 2: Typical layout of a BLDC motor.

It merits mention that although the term "Brushless DC" somehow suggests a similarity to conventional shunt field DC motors, this couldn't be farther from the truth. In fact, the principle of operation of the two topologies is totally different. However, the similarity between the two lies in the fact that each kind of motor requires a DC power source and the speed of the rotor (at least at low speeds) is proportional to the applied DC voltage.

Brushless DC motors are commonly used in applications where small, reliable, maintenance free motors are required. An example of such an application is hard disc drives, CD/DVD drives, cooling fans, etc.

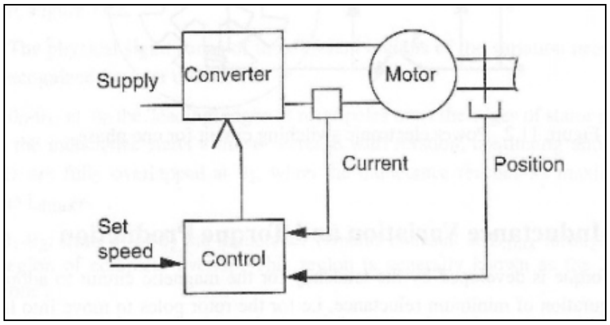

Figure 3

Stepper motors are closely related to BLDC motors, with the step size being smaller or larger based on the precision in rotor position control demanded by the application. The major difference between the two types of motors arises in application, with stepper motors being used for position control applications where they need to stop and start, whereas BLDC motors are used in applications requiring continuous rotation, albeit at variable speed.

2.4. Switched Reluctance Motors

Switched Reluctance Machines (SRM) are cousins of BLDC and stepper motors. In fact, an SRM motor is for all practical purposes a BLDC motor without PM's. In other words, SRM's have rotors made of magnetic material with teeth (typically 4 or 6 teeth) cut into them. No electrical windings exist on the rotor, thus making it extremely robust, reliable and virtually maintenance free. However, the requirement of a power electronic motor controller makes the choice of SRM's cost sensitive.

A typical SRM configuration and its basic control scheme is illustrated in Fig.4 alongside. A technical discussion on design aspects is beyond the mandate of this paper and as such is not being taken up here.

Typically, SRM's trump DC motors and even possibly induction motors on efficiency and performance at low speeds and/or light loads. However, at higher speeds and/or close to rated loads, conventional motors are as good as SRM's, with the significant advantage of requiring virtually no power electronics for operation. SRM's also produce higher intensities of audible noise and vibration than conventional "smooth torque" motors.

All in all, BLDC motors and their cousins have advantages over conventional motors under certain operating conditions, which are equally outweighed by their significant disadvantages under other operating conditions. Furthermore, the cost associated with their electronic controllers makes their choice driven by specific application requirements.

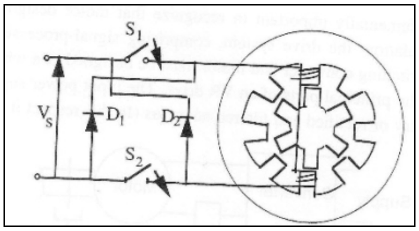

Figure 4: Typical configuration of a Switched Reluctance Motor and its controller.

2.5. Servo Motors

The term "servo motor" refers to any motor, which is used in a "servomechanism" or "servo". Servos are used in motion control applications, where rotor position, velocity, acceleration (or all of these parameters) are controlled by a closed loop feedback system, with position feedback typically derived from a high-resolution encoder or resolver. Examples of servo systems are robots, automated pick-and-place machines, paper mill machines, radar and antenna movement systems, etc.

Either AC or DC motors can be used as servomotors, with AC servos being the equipment of choice in modern times. DC servomotors were used in older servomechanisms, as precise torque control of AC motors has only become possible after the advent of modern power electronics.

The unique feature of servomotors is their relatively low rotor moment of inertia compared to standard motors of equivalent rating. This gives servomotors a relatively "long and thin" appearance when compared with standard motors. This is a direct consequence of the fact that servomotors need to accelerate or decelerate rapidly, based on control inputs.

Apart from this feature, servomotors are virtually the same as conventional motors.

3. High Speed Machines and Micro-Turbines

High speed machine technologies, although somewhat esoteric sounding, could potentially find excellent application in the marine segment today.

Given the limitations of space and time, this paper will focus on providing an insight into the emerging high speed generator technology using micro-turbines.

Research in "micro-turbines", "ultra-micro-turbines" and high speed compressor systems is active today. Power packs in the 100 to 500 KW range are already being manufactured and provide huge benefits in terms of size and weight, fuel efficiency, reliability and parts count. The use of such power packs in the marine segment, especially for smaller vessels where space and weight are at a premium, is being explored and could potentially result in great benefits.

3.1. Relation between Size/Weight and Machine Speed

The universal sizing equation for electric machines is:

$P = C \times D^2L \times \omega$

…(1)

Where:

P: Output power
C: Utilization constant for the machine
D: Overall active diameter
L: Core length
ω: Angular frequency of rotation

It is obvious therefore that for a given output power, the overall machine size (D^2L) is inversely proportional to its speed of rotation.

At the risk of making an inference without rigorous justification, the size of a mechanical prime mover also depends upon the torque developed by it. Therefore, given that:

$P = T \times \omega$

…(2)

Where:

P: Output power
T: Shaft Torque

ω: Angular frequency of rotation

It would seem reasonable to assume that since speed of rotation is inversely proportional to torque generated for a given power rating, mechanical envelope is inversely proportional to speed of rotation.

The above rationale pushes us in the direction of higher and higher rotational speeds, in our quest for smaller sizes and weights.

3.2. What Is A Micro-Turbine?

A micro-turbine is essentially an engine, which has spun off from jetliner and turbo charger technology. Micro-turbines in the 90 to 500 KW range operate at speeds ranging from 25,000 to 90,000 rpm (or even higher).

Micro-turbines are extremely reliable owing to their low parts count, have very low noise and vibration, and compact in size when compared to diesel engines of equivalent rating and low rpm. As a result of heat recovery from recuperated micro-turbines, their fuel efficiency is also extremely high.

The block diagram of a typical micro-turbine is given in Figure 5 below. A "recuperated" micro-turbine essentially draws air from outside and compresses it through its compressor stage. The waste heat re-cuperated after burning is used to pre-heat the compressed air before it enters the combustor and turbine. The combustor raises the temperature of the compressed air by means of fuel which is ignited under constant pressure. The resulting hot gas is passed through the turbine to do mechanical work (high speed rotation). Recuperated micro-turbines employ a heat exchanger to use the waste heat generated from combustion to pre-heat the incoming compressed air. They are therefore more efficient than non-recuperated turbines, requiring less heat to be delivered by the combustion process.

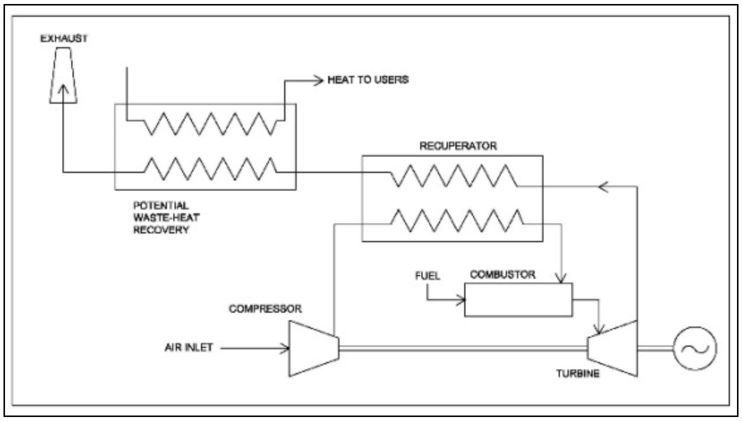

Figure 5: Block diagram of a micro-turbine system.

The micro-turbine can be coupled to various electro-mechanical or mechanical devices as necessary for a given application. For power packs, they are coupled to high speed generators, which develop electrical power used by consumers at a given site or onboard a mobile platform such as a ship.

There is an ongoing debate with regard to the use of micro-turbines as a viable alternative to conventional low rpm diesel generators for ship power applications. They are under pilot usage for smaller ships where emissions sensitivity and performance are of paramount importance. The availability of waste heat utilization is also a positive. Currently, capital costs of micro-turbine power packs are high compared to diesel generators. However, it is the opinion of the author that these costs can only fall significantly in the future.

3.3. High Speed Alternators

Typically, high speed generators are embodied by permanent magnet (PM) machines, although debate is always on in the fraternity as to whether induction generators or switched reluctance (SR) generators are more efficient.

Figure 6 shows the cross-sectional view of a typical high speed micro-turbine power pack using a high speed PM generator directly coupled to a micro-turbine. The bearings shown are magnetic, along with high speed rollers. In practice, air bearings are widely used owing to their relatively lower cost. The permanent magnet rotor consists of salient magnets held together by an encasing ring.

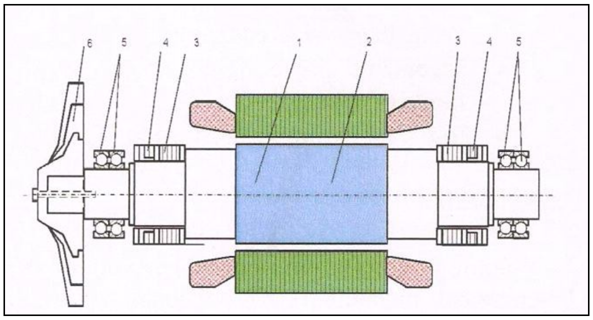

Figure 6: Typical high speed PM alternator for micro-turbine power pack.

The size reduction in PM generators achieved by the increase in rpm is truly breathtaking. For instance, a 90KW, 27,000 rpm alternator could potentially accommodate in a stator outer diameter of less than 6 inches! At higher speeds, even smaller geometries are possible.

3.4. Power Electronic Converter

It is known that there is a fundamental relationship between generated output frequency and the speed of rotation for a generator of a given pole number. The specific equation is:

$n = 120 \times f/p$

…(3)

Where:
n: RPM of alternator
F: Frequency of electrical output
P: Number of poles

It is easy to calculate therefrom that the output frequency of a 4-pole alternator when spun at 25,000 rpm would be 833.3 Hz. The frequency at a rotational speed of 60,000 rpm would be 2 kHz. As a result, there is a need for a power electronic rectifier/inverter to provide an output supply at the conventional 50/60 Hz or DC (or any other frequency of interest for that matter). Figure 7 shows a typical system block diagram for the sort of power electronic converter required for a utility interface with a high speed PM generator.

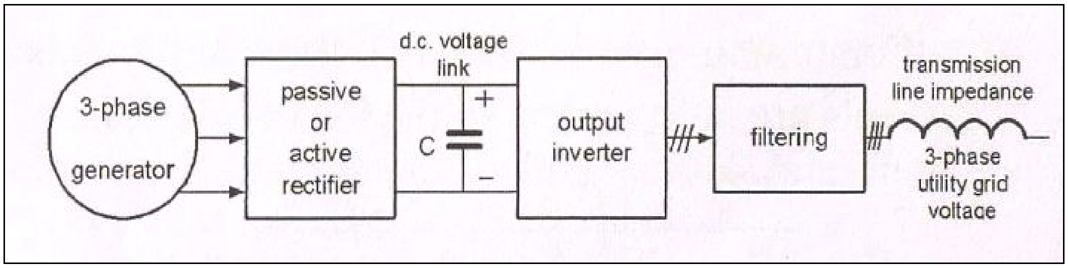

Figure 7: Block diagram of electronic control system for micro-turbine generator.

3.5. Enabling Technologies for High Speed Micro-Turbine Power Packs

One of the key technology enablers for micro-turbines is the use of frictionless air bearings or magnetic levitation (mag-lev) bearings, without which operation at such high rpm's would not be possible. The availability of very high energy density rare earth permanent magnets enables a minimization of PM generator size.

Materials such as advanced ceramics, which allow a significantly higher turbine operating temperature make a difference to size/weight and operating efficiencies.

4. EMI/EMC Considerations

The use of power electronics opens up immense avenues in terms of exploitation of high speed rotating electric machines. However, with the advent of modern power electronic devices of high switching speeds and high current capacity, their ramifications in terms of EMI/EMC need to be clearly understood if they are to be widely used in defense/marine applications.

As an example, the typical IGBT based AC inverter drive operates at a PWM frequency of 1kHz to 12kHz, depending upon application, ripple current and acoustic noise considerations. This operation itself generates high frequency harmonics, which can readily translate into conducted and radiated EMI, especially in terms of MIL standards. Additionally, the extremely fast switching times of devices such as IGBTs can cause a slew of EMI issues due to the spectral content of the steep wave-fronts (typical voltage rise times during hard switching of IGBT's are of the order of 3,000 V/□s).

In view of the potential for both conducted and radiated emissions from modern power electronic drives, EMI/EMC filtering and design needs to be carefully considered in defense applications. As a result of the extensive work done in this area however, total compliance to MIL/IEC standards for EMI/EMC has been achieved.

5. Conclusions

This paper seeks to provide a basic outline for an understanding of the state-of-the-art in modern electric machines technology, for the practicing engineer. Only a broad discussion has been made, as detailed technical analysis needs far more time and space.

The general experience of the author, based on broad interactions in Indian Industry has been that most engineers and professionals still regard electric machines and drives as black boxes, which are of indeterminate character. As a result, the use of advanced techniques of analysis, novel topologies for specific applications, use of high speed machines for specific applications, etc. is still in its very nascent stages in India.

It is the opinion of the author that an in depth understanding of these most basic building blocks of modern industry is vitally important, and, as such, needs to be promoted through seminars, symposiums, technical workshops, training programs, white papers, literature and the like.

6. Acknowledgment

The author thanks the Indian Register of Shipping and in particular its Visakhapatnam branch, for bringing this seminar to life. There is no doubt that this seminar is a step in the right direction. It is of utmost importance in today's context that our shipping industry becomes intimately aware of the present and future trends in electric rotating machinery.

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