AIR-CORE COMPENSATED PULSED ALTERNATORS

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Abstract

A compensated pulsed alternator is a generator capable of delivering high power energy pulses with current waveform flexibility. This versatile machine has applications in various fields where power density is at a premium. Recent advances in applying fiber/epoxy composites to rotating electrical machinery [1] have greatly enhanced the power density capabilities of this machine. A characteristic of these new machines is an absence of ferromagnetic material in the magnetic circuit, and they are therefore referred to as "air-core" compulsators. This paper discusses the topological considerations and the capabilities of the family of machines called the air-core compulsators.

Introduction

The compensated pulsed alternator (compulsator) was conceived at the Center for Electromechanics at The University of Texas at Austin in 1978. It was developed, then, as a power supply for laser flashlamps. The use of active compensation with the help of a compensating winding connected in-series with the armature winding enabled the machine to generate short pulse widths required by the flashlamps. The first prototype compulsator was iron cored. Since then various compulsators and rotary flux compressors have been designed, built, and tested for a variety of applications. At each stage the performance has been altered according to the application. However, the general trend has been to improve the power density. This trend is indicated in figure 1.

Compensation techniques have also been developed to generate a broader range of pulse shapes.[2] These pulse shapes range from very peaky as required by flashlamps to flat-topped as required by electromagnetic launchers. Specific, tailored pulse shapes required by certain applications in countermeasures and for driving electrothermal guns are also possible.

Figure 1 also indicates a large gain in power density obtained by going from iron-core to air-core machines. The Electromagnetic Gun Weapon System (EMGWS) compulsator to be commissioned in 1990 will have a power density of 1,700 kW/kg and the next generation compulsators are envisioned to have power densities in excess of 10,000 kW/kg. Most of these gains have been made possible by applying fiber/epoxy composite technology to rotating electrical machinery. Fiber/epoxy composites have greater strength and also modulus-to-density ratio. This combination allows them to be spun at high tip speeds. High rotational speeds have made it possible to alleviate some of the limitations due to the bond strength of epoxy and also increased the energy density of the machine. Simultaneously research has been conducted on increasing the bond strength of the epoxy from 24 MPa (3,500 psi) to 55 MPa (8,000 psi).

In iron-core machines it is advantageous to utilize the magnetic circuit in order to reduce the excitation power requirements. One is therefore limited by the saturation field strength in iron. Air-core machines by their very nature require higher excitation currents. It is therefore not an advantage to limit the excitation field strength around 2 Teslas (T) as with iron-core machines. The limitation on excitation field strength is now determined by thermal considerations or mechanical strength considerations of the field coil conductor. These limitations are generally higher than the saturation field strength in steel. The thermal limit can be made a secondary consideration by pulse charging the field coil so that the field coil is on only for a short time prior to and during the main discharge pulse. The excitation field strength then is only limited by mechanical considerations.

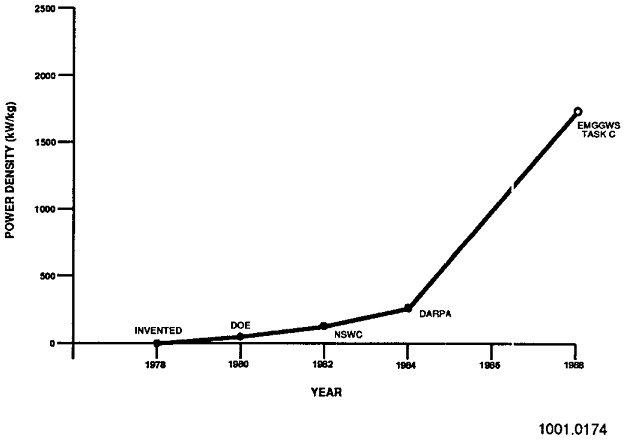

Figure 1. Trend for the power density of the compulsator

All the factors discussed above result in an improved power and energy density. Higher power densities make the compulsator more amenable to field-portable and space-based applications.

Topological Considerations

Two basic configurations have been evaluated for the air-core compulsators: a) The drum type of machine and b) the disk type of machine. Figures 2 and 3 show two drum-type machines with external and internal rotors respectively. Figure 4 shows a disk-type machine with a stationary field coil. The disk-type machine could have a stationary armature and a rotating field coil.

Energy Density

There are two types of energy storage densities to consider: a) the energy density of the rotor and b) the energy storage density of the entire machine. The energy storage density of the rotor is given by:

$$e_{sdr} = \frac{V_t^2}{4}\left[1+\left(\frac{r_i}{r_o}\right)^2\right]$$

where

V_t = tip speed of the rotor
r_o = outer radius of the rotor
r_i = inner radius of the rotor

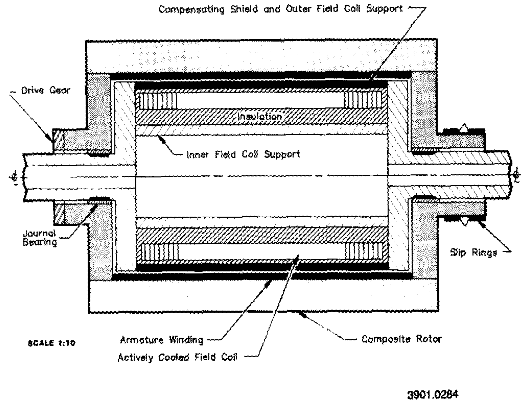

Figure 2. Air-core compulsator with external rotor

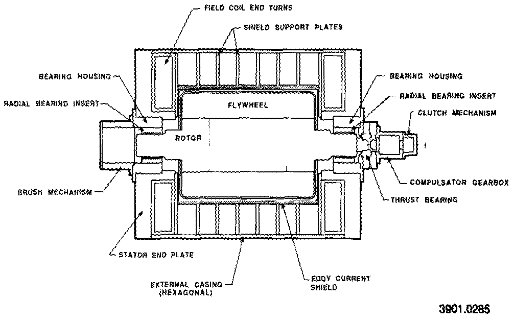

Figure 3. Air-core compulsator with internal rotor

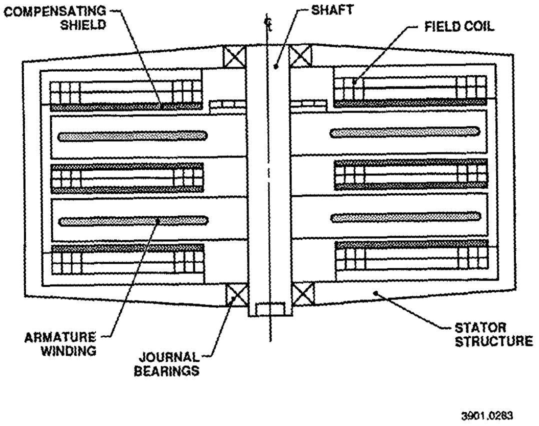

Figure 4. Disk-type compulsator

Based on the above equation it is clear that in order to maximize the energy storage density of the rotor it is necessary to maximize the inner radius given a fixed outer radius. The shell rotor of the external rotor machine therefore has the highest energy storage density. For a given tip speed the internal rotor and the disk-type rotor have the same energy storage density since the only difference in the geometries is the length-to-diameter ratio.

Making a quantitative comparison of the energy storage density based on the entire machine mass is difficult because the mass of the stator also needs to be considered relative to the mass of the rotor. This may vary depending on the application. The overall energy storage density is given by:

$$e_s = \frac{v_t^2}{4}\left[\left(\frac{r_o}{r_g}\right)^4 - \left(\frac{r_i}{r_g}\right)^4\right]\frac{\rho_r}{\rho_t} \cdot \frac{l_r}{l_t}$$

where

r_g = geometric mean of the outer rotor radius and the outer machine radius
ρ_r = average density of the rotor
ρ_t = average density of the entire machine
l_r = length of the rotor
l_t = length of the machine

Tip Speeds

With the drum-type machine the rotor winding needs to be supported by a high strength banding against centrifugal loads. This banding experiences a tangential stress due to centrifugal loading. With the external rotor the function of energy storage and banding are combined into one component since the armature winding spins at the inner surface of the rotor. With the internal rotor machine the armature winding spins near the outer surface of the rotor, thus requiring a banding solely to keep the armature flywheel interface under compression. The thickness of the banding in the internal rotor case is limited by other considerations such as coupling with the stator windings. This coupling is important from a standpoint of maximizing the peak power of the machine. The tip speeds possible with the external rotor machine are therefore higher than the internal rotor machine.

Flywheels for applications other than electrical machinery have been built which can attain tip speeds in excess of 1,200 m/s. Two internal rotor, air-core compulsators have been designed at tip speeds in the 500-to 600-m/s range. With external rotor machines and radially thin windings the tip speeds can be raised up to 1,200 m/s.

The rotor windings in the disk type of machine are difficult to support. This difficulty stems primarily from the orientation of the windings. The windings instead of being laid axially as in the drum type of machine are now laid radially. A banding is no longer adequate to support these windings, since it would experience a large pressure corresponding to the radially thick winding. The rotor windings therefore have to be supported in shear along the entire radial length. The result is a machine with a lower tip speed, since the shear strength of an epoxy bond is relatively low.

Rotor Dynamics

From a standpoint of energy and power density the external rotor machine has the greatest advantages. However from the standpoint of rotor dynamics it is the most difficult to maintain subcritical. The internal rotor and the disk type of machines are relatively easier to support dynamically. The composite materials used in the construction of the rotors of these air-core compulsators have a very high damping coefficient, greatly reducing the amplitude of vibration associated with passing through a critical speed. This makes shell-type rotors feasible.

Voltage and Current capabilities

The peak voltage generated per unit length of the machine is given by $\vec{E} = \vec{V} \times \vec{B}$, where v is the tangential velocity of the winding and B is the peak radial component of the excitation field. Table 1 gives a comparison of these values for iron-core and air-core compulsators.

Table 1. Comparison of voltage capabilities

TYPE	Velocity m/s	Radial Field T	E Volts/m
IRON CORE	200.0	2.0	400.0
AIR CORE	550.0	4.0	2200.0

This clearly shows an increase in generated voltage of over five times per unit length as compared to iron-core machines.

Since the same generated voltage can be obtained with a shorter machine or fewer number of turns the machine inductance is also lower. This combination helps to enhance the peak current and therefore the power capability of the machine, especially while driving low impedance loads.

Compression Ratio

For the same physical disposition of the windings the minimum inductance of an air-core and iron-core compulsator is about the same. However the maximum inductance is significantly different for the two cases, especially when considering the unsaturated inductance of the iron-core machine. The result is that the compression ratio obtained for identical winding geometries could be lower by an order of magnitude in the case of the air-core machines, compared to iron-core machines. The compression ratio is of importance to the extent that it affects the pulse width (full width half maximum). The minimum short circuit pulse width is given by:

$$\Delta t_{\frac{1}{2}} = \frac{2}{p\omega_m}\cos\left(\frac{CR-3}{CR-1}\right) \quad \text{sec}$$

where

ω_m = mechanical speed of the rotor
p = number of pole pairs
CR = compression ratio

Figure 5 shows the change in pulse width with the tip speed for an air-core compulsator. Also shown on the same plot is the pulse width obtained from an identical iron-core machine at a tip speed of 150 m/s, which is the maximum tip speed possible for a laminated rotor. This plot shows that for the same geometry an air-core machine must have a tip speed in excess of 600 m/s in order to reduce the pulse width below the unsaturated iron case. This tip speed is certainly possible and is at the bottom range of the tip speed possible for air-core machines.

The compression ratio of an air-core machine varies as (t/g+1), whereas the compression ratio of an iron-core machine varies as $(t/g)^2$.[3] Where t is the pole pitch of the winding and g is the effective gap of the armature and compensating windings. Thus the air-core machines have a lower compression ratio but are less sensitive to the ratio of the pole pitch to effective gap.

Field Distribution

The absence of ferromagnetic material in the magnetic circuit contributes significantly to increase the power and energy densities of the compulsator. The absence of the ferromagnetic material to channel the flux however, results in significant stray fields. This is true of drum as well as disk-type machines. The presence of stray fields in compact, field-portable and space based applications is not desirable. Therefore some form of shielding is required to reduce the stray fields. The other option is to use a machine with a significantly higher number of poles. Using a higher number of poles results in faster decay of the far fields as illustrated in figure 6.

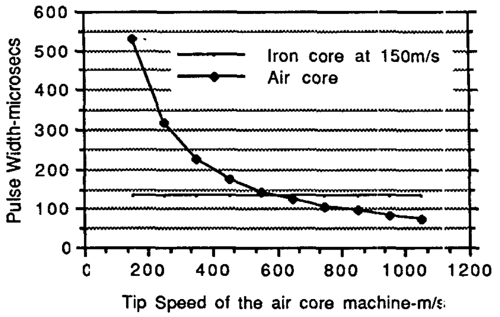

Figure 5. Pulse width as a function of tip speed for air-core machines

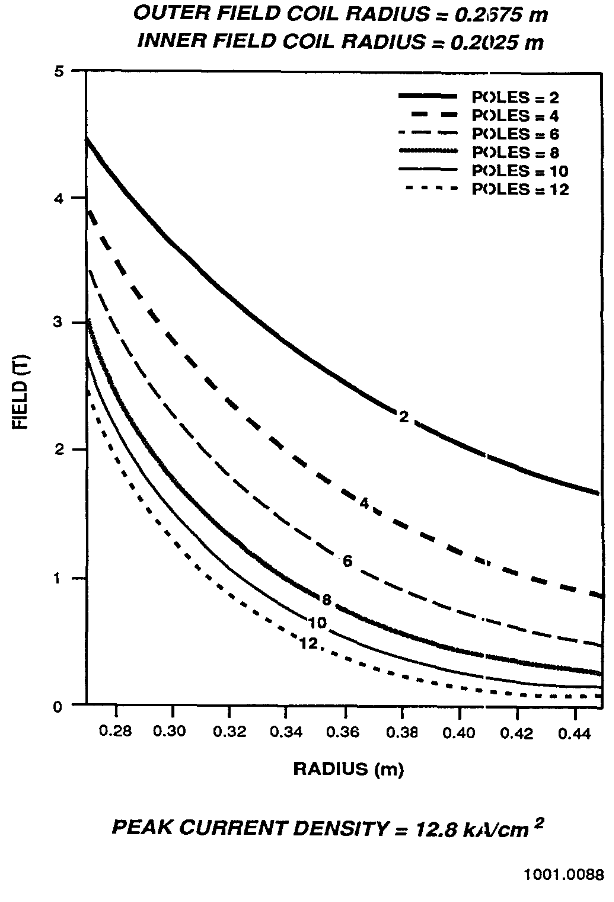

Figure 6. Radial field distribution as a function of poles

Using a higher number of poles is also accompanied with its problems. Since the excitation fields decay faster with distance, a greater number of ampere-turns are required to obtain the same discharge performance. This is illustrated in figure 7, where the ordinate is normalized with respect to the ampere-turns required for a 2-pole machine. The result is a heavier machine or a machine with greater field coil losses.

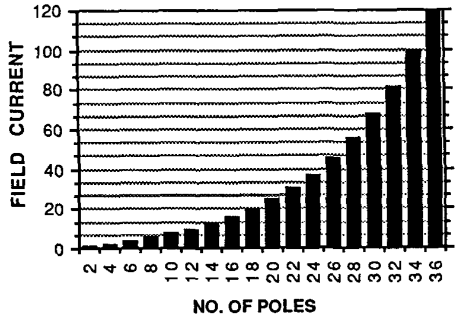

Figure 7. Current in the field coil for the same generator performance

Another peculiarity of air-core machines is the presence of relatively strong, tangential excitation fields near the armature winding. These tangential fields interact with the axial currents and produce significant radial forces. These radial forces in combination with the discharge induced radial forces produce a non-uniform radial force distribution, which requires special attention in order to support.

Excitation Scheme

As discussed earlier the air-core machines have a greater excitation requirement compared to iron-core machines. This implies running the field coil conductor to higher current densities in order to maintain reasonably good coupling between excitation field and armature conductors. Superconducting, hyperconducting or cryogenically cooled coils could be used where the application so permits. An alternate scheme, where this is not feasible, is to pulse charge an ambient temperature field coil. This reduces the energy dissipation in the conductor thus limiting the temperature rise to a reasonable level.

Pulse charging the field coil requires a considerable amount of power. A separate power supply to achieve this task would offset the benefits of the air-core machine. Self excitation of the field coil is therefore used. The armature winding itself is used to provide excitation power to the field coil if the characteristics are acceptable. A separate excitor winding could also be provided which has its characteristics optimized to charge the field coil.

The output of the excitor winding is rectified through a full wave rectifier and the output of the rectifier is fed directly to the field coil. Phase control of the rectifiers is used to regulate the current and also to reclaim the magnetic energy from the field coil when the discharge pulse is completed.

Means of Improving the Capabilities

Several significant improvements have been accomplished in the area of power and energy density of air-core compulsators [4]. Efforts are ongoing to increase the performance of these machines beyond their present capabilities.

Higher tip speeds are certainly possible. The dynamic behavior of these machines under supercritical operation needs to be investigated. It is necessary to determine the damping associated with the composite materials from a standpoint of the amplitude while transitioning through a critical speed and also in order to determine the onset of the instability associated with this damping.

Higher field strengths can be achieved by applying superconducting or hyperconducting materials. If high temperature superconductors prove feasible it would have a significant impact on the design of these air-core machines.

Research is ongoing to increase the bond strength in shear of the epoxy in the range of 83 MPa (12,000 psi). This would help in combination with higher tip speeds to reduce the pulse width and increase the power density significantly.

Acknowledgements

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