FUNDAMENTAL LIMITATIONS AND DESIGN CONSIDERATIONS FOR COMPENSATED PULSED ALTERNATORS

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Abstract

Since the beginning of a project intended to demonstrate the feasibility of using a compensated pulsed alternator (compulsator) as a power supply for NOVA and other solid state laser systems, a great deal of interest has been generated in applying this type of machine to supply energy for other types of loads. This paper outlines the fundamental limitations imposed on the design of such a machine by the mechanical, thermal, magnetic, and electrical properties of the materials used. Using these limitations, the power and energy available from the machine are calculated as functions of machine dimensions. Several configurations for the machine and their relative merits for various applications are also discussed.

Introduction

Recently interest in pulsed power for a variety of applications including magnetic and inertial confinement fusion experiments, advanced weapons systems and industrial manufacturing processes has resulted in many developments in pulsed power supply technology. In several areas inertial energy storage has emerged as an attractive alternative to magnetic or electrostatic energy storage because of the very high energy densities available at relatively low cost. The problem of converting the stored inertial energy to electrical energy, however, has not been satisfactorily resolved in most cases. Conventional alternators are limited in power output by their own internal impedance and although pulsed homopolar generators, having low internal impedance, are capable of very high power outputs, they accomplish this at low voltages which are not always desirable.

In essence, pulse rise times are limited by inductive voltage drop ($L\frac{di}{dt}$). In its simplest form an alternator consists of a single turn coil of wire spun in a magnetic field (Figure 1). Increasing the output voltage of such a machine (to produce faster $\frac{di}{dt}$) requires increasing the magnetic flux density, increasing the surface speed of the rotating coil, or increasing the number of turns in the coil. Ultimately, the magnetic flux density and surface speed of the coil are limited by material properties. The alternator voltage increases linearly with the number of turns in the coil, but unfortunately the inductance, which limits pulse rise time, rises with the square of the number of turns resulting in no gain in output power.

$$(V(t))_{max} = B\ell v$$

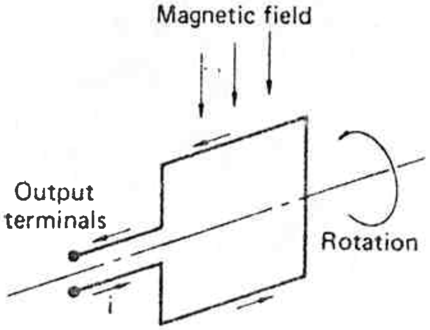

Figure 1: Simple Alternator

The compensated pulsed alternator or compulsator (Figure 2) uses a stationary coil almost identical to the rotating one and connected in series with it to increase output power by flux compression.[1,2] As the two coils approach one another, the magnetic field generated by the output current is trapped between them and compressed and the effective inductance is therefore reduced. When the two coil axes coincide the inductance is minimized, but the alternator voltage can be at its maximum value. This results in the generation of a very large magnitude current pulse from the machine. In addition the compulsator output voltage during the inductance change can be considerably higher than the open circuit voltage due to $i\frac{dL}{dt}$ effects. As the rotating coil passes the stationary one the inductance again rises to its normal (higher) value, commutating the pulse off.

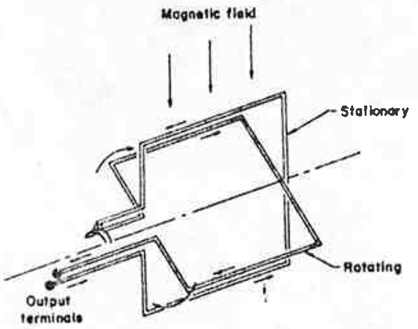

Figure 2: Compensated Pulsed Alternator

Since the compulsator is essentially a variable inductor in series with a conventional alternator, and depends upon minimizing circuit inductance to generate an output pulse, it is not well suited for driving inductive loads. It is well suited, however, to both capacitive and resistive loads.[2,3] The use of a pulse transformer to increase compulsator output voltage has also been investigated[3] and appears to reduce the net output by about 25%. This paper is intended to indentify and characterize the fundamental limitations to compulsator performance and to suggest some approaches for extending these limitations. For convenience the fundamental limitations to compulsator performance can be divided into three groups; those dealing with the effect of load characteristics, those limiting output power, and those limiting minimum pulse width.

Effect of Load Characteristics

A simplified (lumped parameter) circuit for a compulsator connected to a resistive load (such as a flashlamp) is shown in Figure 3.

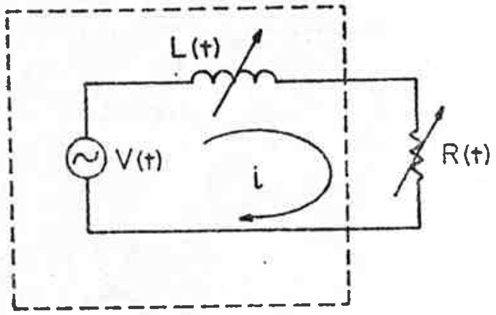

Figure 3: Simplified Circuit Compulsator Driving Resistive Load

The differential equation for this circuit can be written as:

$$\frac{d}{dt}(Li) + Ri = V(t) \qquad (1)$$

where L and R are the total instantaneous circuit inductance and resistance, V(t) is the "alternator" voltage (open circuit voltage) due to the armature coil rotating in the applied magnetic field, and i is the instantaneous current. The solution to equation (1) is:

$$i = \frac{1}{L}\left[(L_o i_o) + \int_o^t V(t)e^{\int\frac{R}{L}dt}\,dt\right] e^{-\int\frac{R}{L}dt} \qquad (2)$$

where L_o and i_o are initial values of inductance and current at the beginning of the pulse (when the circuit is closed). The first term within the brackets of equation (2) represents the contribution to total output current made by the flux compression aspect of the compulsator while the second term represents the current due to the volt-seconds supplied by the alternator. The first term primarily affects the shape of the output pulse while the second term determines the energy delivered to the load. For a wide range of resistive load cases investigated the compulsator has been found to reduce the basic alternator half cycle pulse width by a factor of about 8.

For a capacitive load such as a transfer capacitor the basic circuit is shown in Figure 4 and the differential equation for the circuit is:

$$\frac{d}{dt}(Li) + Ri + \frac{1}{C}\int i\,dt = V(t) \qquad (3)$$

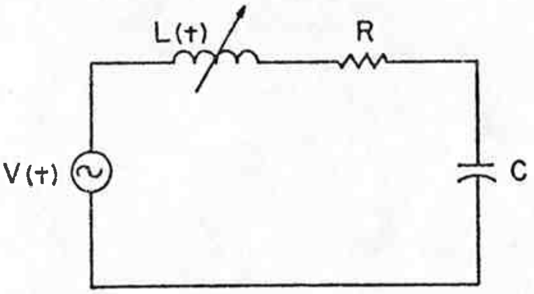

Figure 4: Simplified Circuit
Compulsator Driving Capacitive Load

Although the analytical solution of this second order differential equation is quite cumbersome it can be solved numerically and the energy delivered to a capacitive load by a compulsator has been shown to be

$$E = \eta\,\frac{\left(\int_0^t V(t)dt\right)^2}{2L_{min}} \qquad (4)$$

where L_{min} is the minimum total circuit inductance and η is a numerically determined constant which has been found to be around 0.5 for most cases of interest. For the capacitive load case the compulsator has been found to compress the basic alternator half cycle pulse width by a factor of about 4.

Limitations to Peak Output Power

It is apparent from equations (2) and (4) that the compulsator's primary advantage, in terms of high output power, over the conventional alternator comes from flux compression, or more specifically, from the interaction of the discharge current with the inductance variation. This in turn implies that the inductance variation must be maximized and since the maximum inductance in the uncompensated position is relatively insensitive to machine variables, really requires that the minimum inductance in the compensated position be reduced as much as possible. This requirement suggests the use of radially thin air gap windings distributed uniformly over the rotor surface rather than salient pole windings or even distributed windings in slots since the slot teeth increase the winding inductance. A significant limitation to peak output power comes then from the conflict between the requirement for minimum radial air gap between the rotor and stator windings in order to minimize L_{min} and the dielectric strength of the air gap insulation on the windings. The inductance variation is given by $(\frac{\tau}{g})^2$ for an iron cored machine (unsaturated) and by $\frac{\tau}{g}(1 + \frac{g}{\tau})$ for an air cored machine where τ is the conductor width per pole and g is the radial air gap between conductors, so that the sensitivity of machine performance to this air gap limitation is readily apparent.

A second limitation on output power imposed by this air gap winding concerns the shear strength of the insulation system used to bond the stator and rotor windings to the stator and rotor structures. The interaction between the compulsator discharge current and the radial component of the magnetic field in the air gap due to that current causes a tangential force on the conductors which slows the rotor, converting stored inertial energy to electrical energy. This force results in a tangential shear stress on the insulation bond between the conductors and the rotor or stator. This radial magnetic field component which depends upon the time and position history of the currents as well as the permeability and eddy currents in the surrounding structure has been calculated for several cases using a transient, nonlinear, finite element magnetic field mapping code developed by the Center for Electromechanics. For these cases an average surface current density of 10 MA/m was found to produce stresses which could be withstood by insulation systems with shear strengths of 28 MPa (4000 psi). The peak mechanical power output of the machine is simply the product of this peak allowable shear stress, the active surface area of the rotor and the rotor surface speed. For a rotor surface speed of 150 m/sec, such as is used for the Lawrence Livermore Laboratory engineering prototype compulsator (Figure 5)[4,5] with a laminated steel rotor, the peak output power per unit of surface area is 4.2 GW/m^2. For other configurations capable of operating at much higher speeds which are described later, this limit may exceed 10 GW/m^2.

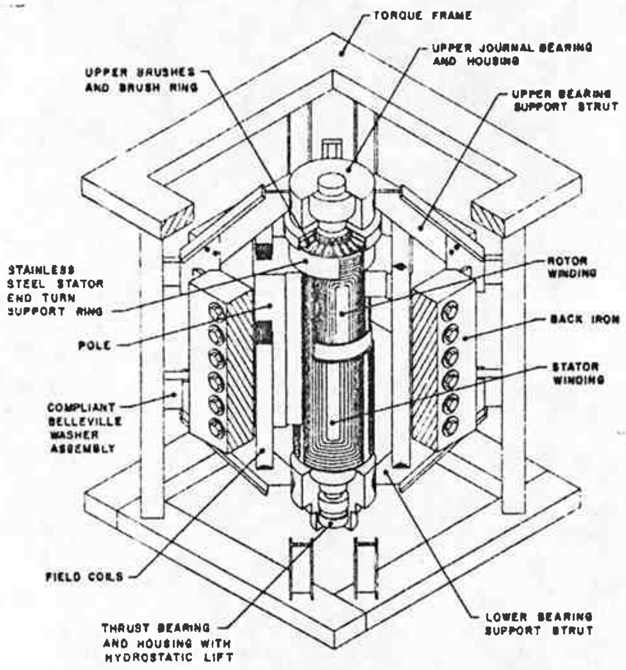

Figure 5: LLL/CEM Prototype Compulsator

Finally, the requirement that the rotor and stator conductors be radially thin in order to generate minimum inductance is in conflict with the extremely high current densities achievable in the compulsator in that thermal heating of the conductors may become a limiting factor especially in the case of repetitive pulses. This thermal limit can become even more restrictive in that skin effects can confine the fast rising current pulses to the surfaces of the conductors resulting in even more severe heating. This skin effect can be overcome by using stranded and transposed conductors but these increase the minimum inductance somewhat as well as complicating the construction of the machine.

Limitations to Minimum Pulse Width

The relationship of the compulsator output pulse width to the basic (alternator) half cycle pulse width has been discussed for various loads. This, of course, suggests that as faster pulses are required the base electrical frequency of the alternator must be increased. The electrical frequency ω_e of the alternator is given by:

$$\omega_e = \frac{P}{2}\,\omega_m$$

where P is the number of field poles and ω_m is the mechanical rotor speed in radians/sec. The mechanical rotor speed is limited by the stiffness of the rotor and its dynamic behavior in the bearings and by eddy current generation due to the alternating magnetic field experinenced by the rotor turning in the hetropolar excitation field. This eddy current limit can be extended by laminating the rotor, but there is a practical limit to the minimum lamination thickness which can be used; and as the rotor laminations are made thinner, rotor construction becomes more difficult and rotor mechanical stiffness suffers.

Increasing the mechanical speed of the rotor has another limitation as well. Increasing rotor speed increases centrifugal loading on the rotor air gap winding. This in turn requires additional banding material in the air gap to restrain the rotor conductors and this leads to increasing the radial air gap spacing which again increases the crucial minimum machine inductance.

This leaves only the option of increasing the number of poles to increase the alternator frequency, but here too we find a limit. As the number of poles increases for a given machine the spacing between poles must decrease. As this pole-to-pole spacing approaches the air gap distance, the applied field leakage exceeds the useful flux cut by the rotor conductors. This point of diminishing returns makes the addition of more poles futile.

Finally, as the base frequency of the compulsator is increased, the volt-seconds per pulse supplied by the excitation field [$\int Vdt$ in equations (2) and (4)] decreases. This drastically limits the output power available from the original compulsator concept for pulse times below 100 μsec.

Alternate Compulsator Configurations and How They Address Limitations

Figure 6A shows the original compulsator configuration to which the limitations discussed in this paper apply. It consists of a multipole wave winding on the rotor connected in series through slip rings with an almost identical multipole wave winding on the stator. The alternator voltage V(t) is generated by the armature winding (only) rotating in the applied magnetic field supplied by the excitation coils. As mentioned previously, the alternating magnetic field experienced by the rotor requires that the rotor be constructed of laminated steel and this results in a substantial reduction in rotor stiffness as well as additional complexity in rotor construction.

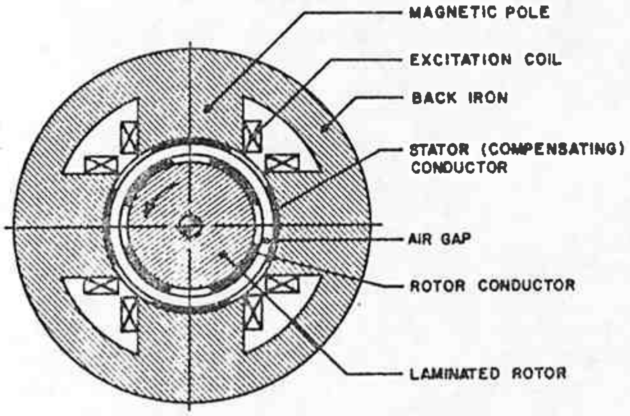

Figure 6A: Stationary Field Compulsator

The rotating field compulsator (Figure 6B) offers one solution to this problem by placing the excitation coils on the rotor, radially inboard of the armature winding. The rotor no longer experiences an alternating applied field and now may be fabricated from a solid forged steel billet. The rotor will be much stiffer and can operate at higher surface speeds. In practice the excitation coils would probably be distributed windings rather than the salient pole construction shown here for clarity. This configuration does require the stator or back iron to be laminated, but the loading of the stator is less severe and much greater design latitude exists for the stator than for the rotor. However, since the excitation coils occupy additional space in the already crowded rotor, flux path considerations dictate that this construction only be used for larger machines.

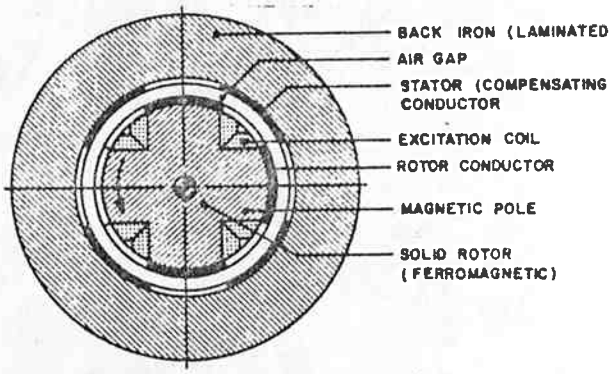

Figure 6B: Rotating Field Compulsator

Another solution to the laminated rotor problem is shown in Figure 6C. By fabricating the armature conductors into filament reinforced composite "cups" which nest together coaxially, the central iron core can remain stationary and thus be solid. Several other benefits accrue from this design as well. Since the rotor inertia is dramatically reduced, a larger portion of the inertial energy is stored in the conductors themselves. This is significant since the conductor inertial energy can be converted with (J x B) body forces rather than the conductor/insulator shear forces necessary to convert inertial energy stored elsewhere in the rotor structure. This alleviates the insulation shear stress limitation and allows higher surface current densities and consequently higher peak output power per unit of active rotor surface area than the configurations shown in Figures 6A or 6B. In addition, the cup rotor construction allows the two halves of the armature winding to be counterrotated, doubling the open circuit voltage of the machine without increasing the circuit inductance. This innovation also doubles the base electrical frequency of the compulsator without imposing the geometric limit of the pole spacing approaching the radial air gap dimension (excessive flux leakage limitation).

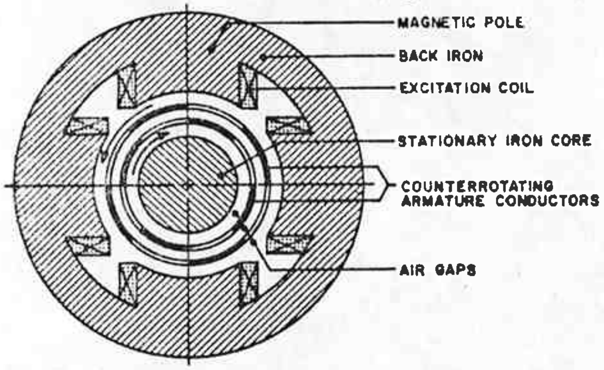

Figure 6C: Counterrotating Cup Rotor Compulsator

Finally, since for very short pulse times (<100 μsec) the volt-second contribution of the applied magnetic field becomes a limiting factor in machine performance, configurations which supply the necessary volt-seconds from an external source (perhaps a capacitor bank or even another compulsator) have been investigated. The configuration shown in Figure 6D is an outgrowth of these investigations. The volt-seconds are supplied to the stationary winding by an external source and the applied flux is then compressed by the rotation of the fluted, conductive (probably aluminum) rotor.[3] The rotor is slowed by the flux compression, inertial energy in the rotor being converted to electrical energy in the stationary winding. Initial investigations have indicated that such a device is capable of producing energy gains of at least a factor of ten over the initially supplied volt-seconds, and can deliver large amounts of energy (>10^6 joules) in substantially less than 100 μsec.

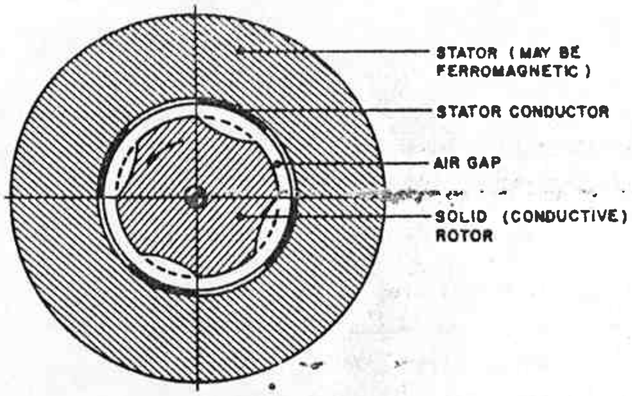

Figure 6D: Brushless Rotary Flux Compressor

Summary and Conclusions

This paper has not only addressed the fundamental limitations to performance of the recently invented compensated pulsed alternator, but has categorized them into three groups; those dealing with the effects of load characteristics, those limiting the peak output power, and those limiting the minimum pulse width. In addition, the authors have suggested some new design approaches, which appear to extend the operating limits of the compulsator concept beyond those of the original compulsator design.

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