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Abstract

The compensated pulsed alternator (compulsator) has been proposed as a possible alternative to capacitor banks for driving xenon flashlamps for pumping neodymium glass laser amplifiers for NOVA. An algorithm for sizing rotor diameter and angular velocity as a function of flashlamp impedance, peak current, and delivered energy is described. It is shown that the armature inductance variation is a major consideration when matching the pulsed alternator to the load. Finally, conceptual design parameters of a four pole, laminated rotor compulsator are presented.

Introduction

The Center for Electromechanics (CEM) of The University of Texas at Austin has proposed the compensated pulsed alternator as an alternative power supply for driving xenon flashlamps for the NOVA Laser Program at Lawrence Livermore Laboratory. The compulsator is a single phase alternator with a laminated rotor (armature) and solid steel stator with copper field windings wound on salient poles. The subtransient reactance of the machine is minimized by connecting a compensating (damper) winding on the quadrature axis of the stator in series with the rotor armature winding. A sectional end view of a simple compulsator is shown in Figure 1.

The compulsator differs from a conventional short circuit generator in several ways. The armature winding is located on the rotor, and is connected in series with the compensating winding via slip rings. Therefore, the compensating or damper winding is not closed on itself, but carries full armature current. Secondly, the compensating winding has the same number of turns as the rotor winding and is of the same geometry, rather than being constructed in squirrel cage fashion. Finally, both windings are located in the air gap, rather than being imbedded in slots. The operation of the machine is described in detail in other papers presented at this conference.[1,2,3]

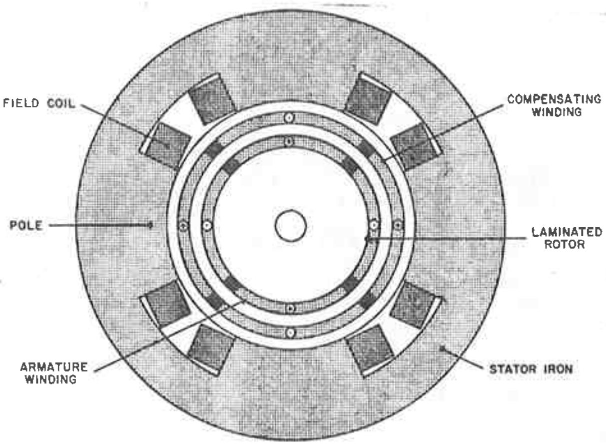

Figure 1: Cross Section of Compensated Pulsed Alternator

Output Current Waveshape

The varying coupling between the armature winding and compensating winding results in rotary compression of the armature flux which increases the amplitude and decreases the half width of the output current pulse. Therefore, a compulsator with an open circuit sinusoidal frequency of 120 to 180 Hz can deliver 0.5 - 1.0 msec pulses to a low impedance load such as a xenon flashtube. A typical single current pulse waveform is shown in Figure 2.

Flashlamp Load

The compulsator is a low impedance device with the

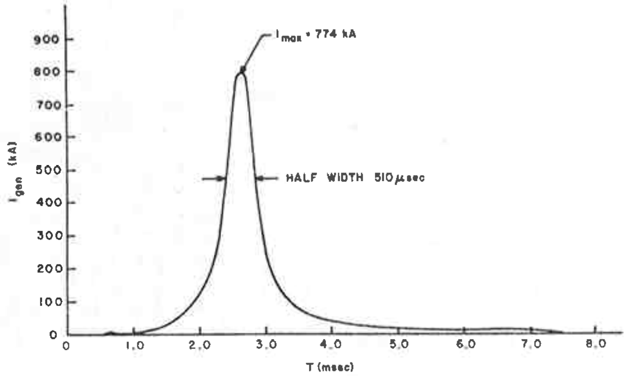

Figure 2: Typical Current Pulse Into Flashlamp Load

capacity to deliver current pulses of several hundred kiloamps. It is therefore necessary to connect multiple flashlamp circuits in parallel to maximize energy delivery per pulse. One lamp configuration now being considered for NOVA consists of two 15 mm x 20 mm x 112 cm long xenon flashlamps connected in series. One hundred or more of these series circuits are connected in parallel with inductors placed in each leg to insure proper current division. The equivalent impedance of the flashlamp load is modeled as a nonlinear resistance given by

$$R_{load} = n_s K_o (n_p i_{load})^{-1/2} \text{ ohms} \qquad (1)$$

where K_o is the lamp impedance constant (one lamp), n_s is the number of lamps in series per circuit (2), n_p is the number of parallel lamp circuits, and i_{load} is the total load current. It is shown in a companion paper that the energy delivered per pulse to each flashlamp is given by[4]

$$W_{lamp} = f K_o i_p^{3/2} \Delta t \text{ joules} \qquad (2)$$

where Δt is the half width of the pulse, f is a waveshape factor, i_p is the peak current per lamp, and K_o is the impedance constant of the lamp (~87.5 ohm-amp$^{1/2}$ per lamp, 175 ohm-amp$^{1/2}$ for series pair).

If the energy delivered per pulse, peak lamp current, and lamp impedance constant are specified, then the compulsator must be designed to provide the proper current waveshape.

$$(f\Delta t)_{compulsator} = \left(\frac{W_{lamp}}{K_o}\right) i_p^{-3/2} \text{ (sec)} \qquad (3)$$

<u>Rotor Diameter and Speed</u>

One algorithm that has been used to determine the angular velocity of the rotor is based on the observation that for typical circuits the effective armature flux linkage is constant during the main portion of the output current pulse. That is the product of the effective transient armature inductance and current is a constant. Therefore, the output current i_{load} may be described by

$$i_{load}(\theta_m) = L_o i_o / L(\theta_m) \text{ amps} \qquad (4)$$

where θ_m is the angular displacement between the axes of the rotor and compensating windings, and L_o and i_o are initial values of inductance and current at $\theta_m = \theta_{mo}$ established during the startup phase of the discharge. The effective armature inductance versus angular position is given by

$$L(\theta_m) = L_{min} + \Delta L[1 - \cos(N_p \theta_m/2)] \text{ H} \qquad (5)$$

Using Equations 4 and 5 the pulse half width Δt is given by

$$\Delta t = (4/N_p \omega_m) \cos^{-1}(1 - a/A_k) \qquad (6)$$

where N_p is the number of poles, ω_m is the angular velocity of the rotor and the terms a and A_k are

$$a = 1 - \cos(N_p \theta_{mo}/2) \qquad (7)$$
$$A_k = L_o/L_{min} - 1 \qquad (8)$$

A_k is defined as the flux compression factor. Again, using Equations 4 and 5 and integrating the resistive power dissipated in the flashlamps, the LHS of Equation 3 is given by

$$(f\Delta t) = 2\theta_{mo} S/\omega_m \qquad (9)$$

where S is a constant of integration which depends on N_p, θ_{mo}, and A_k. A typical value of S is 0.255 for a four pole machine with θ_{mo} = -0.294 and a flux compression factor A_k equal to 14. The angular velocity of the rotor ω_m can then be plotted as a function of diameter to provide the proper pulse width if the flux compression factor A_k is known as a function of machine diameter and number of poles. A typical curve is plotted in Figure 3.

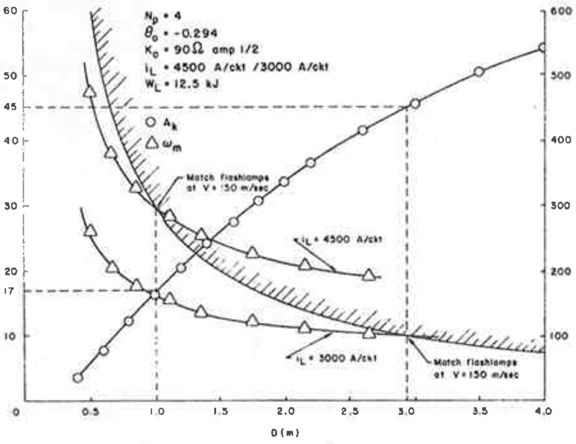

Figure 3: Flux Compression Factor and Angular Velocity versus Rotor Diameter for Flashlamp Load

Assuming that the maximum allowable tip speed for the rotor is 150 m/sec based on centrifugal forces acting on the air gap rotor winding, the diameter of the rotor is found by the intersection of the angular velocity curve and the constant tip speed curve. It can be seen from Figure 3 that a 1.02 m diameter four pole compulsator will drive the flashlamps at a peak current of approximately 4500 amps per circuit and a pulse width of 500 μsec.

Flux Compression Factor A_k

The factor A_k scales as $(\tau/g)^2$ where g is the effective air gap between the windings and τ is the polar pitch $(\pi D/N_p)$.[5] Therefore,

$$A_k \propto \left(\frac{D}{gN_p}\right)^2 \qquad (10)$$

Since the ratio of effective air gap to diameter does not scale linearly, the compression factor A_k generally increases with diameter. A_k decreases with the square of the number of poles. Other factors which influence A_k include system voltage (insulation thickness), radial build of air gap conductors, mechanical gap clearance, and pole construction (laminated versus solid). To maximize delivered energy, the minimum inductance L_{min} must be reduced as far as possible. The factor A_k is chosen to match the desired pulse width and peak current and is selected based on tradeoffs including mechanical stress in the alternator, external switching requirements, and amplifier gain.

Conceptual Design

Assuming a rotor diameter of 1.02 m and a rotational speed of 2800 rpm from Figure 3, a conceptual design of a compensated pulsed alternator was developed. It should be noted that the final alternator design and flashlamp configuration have yet to be frozen. However, this one design does indicate the type of machine used to drive multiple flashlamp circuits that are anticipated. The basic generator performance parameters are listed in Table 1. A sectional view is shown in Figure 4.

Table 1: Compulsator Parameters

Number of poles	4
Rotor diameter (m)	1.02
Rotor tip speed (m/sec)	150
Angular velocity (sec^{-1})	294
Flux compression factor A_k	17.6
Open circuit voltage (kV)	10.3
No. of rotor conductors	23
Armature resistance (mΩ)	8.5
Minimum inductance (μH)	8.6
Effective air gap (mm)	4.05
Magnetic air gap-main field (cm)	4.3
Field MMF/pole (kA-t)	105
No. turns/pole	28
Field current-pulsed (kA)	3.76
Field power/pole (kW)	114
Outer diameter of back iron (m)	2.51
Shaft diameter (m)	0.32
Shaft length (m)	4.8
Total mass (metric ton)	87.6
Inertial Energy Store (MJ)	108

System performance parameters are listed in Table 2. The tabulated case includes realistic models for the ignitron switches, includes the growth of the plasma diameter from startup to full bore, and utilizes capacitive assist startup as described in the companion paper.[4]

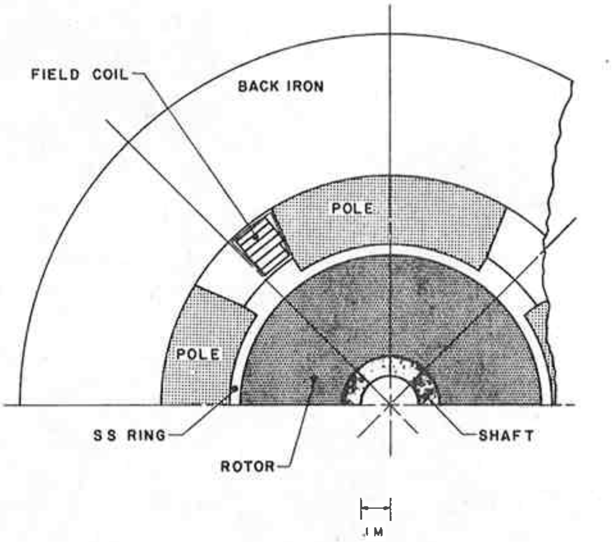

Figure 4: Cross Section of Conceptual Compensated Pulsed Alternator Power Supply for NOVA

Table 2: System Performance Parameters

Peak lamp voltage (kV)	10.9 (12.5)*
Peak current (kA)	774 (963)
No. lamp circuits	198
Energy delivered (MJ)	4.52 (6.2)
Pulse half width (μsec)	510 (510)

*Numbers in parentheses for +3π/64 radian phase shift of compensating winding past quadrature axis.

Note that the delivered energy is increased if the axis of the compensating winding is shifted so that the point of minimum inductance lags the point of maximum open circuit voltage. The increased delivered energy must be weighted against increased localized shear stress on the adhesive bond between the air gap winding and the surface of the rotor. However, the 3π/64 phase shift should be satisfactory mechanically.

Summary

The conceptual design of a compensated pulsed alternator matched to a specific flashlamp load typical of the lamp characteristics anticipated for NOVA has been presented. Final selection of the flashlamp load and alternator parameters are yet to be made, however, pending results of an engineering prototype test program.

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