DESIGN OF A RISING FREQUENCY GENERATOR/COAXIAL ACCELERATOR

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Abstract--In considering the spectrum of electromagnetic (EM) gun concepts, certain of the coaxial accelerators, or so called collguns, are among the most elegant, and not coincidentally most difficult to realize of the EM accelerator concepts. Paramount among these are those collguns in which a magnetic wave is caused to passively move from the breech to the muzzle, requiring no active sensing and in which no current is transferred between the stator and armature by arcs or sliding contacts. One difficulty with a concept is that the output frequency, voltage, and power of the power supply must increase; and/or, that the stator pole pitch must increase continually from the breech to the muzzle if the projectile is to accelerate efficiently. By utilizing a rising frequency power supply, improved average-to-peak acceleration is expected by eliminating the "dead" sections near the center of the stator coils that result when the pole pitch is significantly longer than the armature.

The Center for Electromechanics at The University of Texas at Austin (CEM-UT), has designed a high efficiency, low mass and volume, matched rising frequency generator (RFG), and coaxial accelerator system to launch a 22 MJ projectile at 1,000 m/s. The RFG produces variable frequency voltage by utilizing a novel variable frequency field excitation scheme. The matched system is designed to accelerate a 44 kg launch package to 1,000 m/s in a 5 m long, 15-stage accelerator, with an average-to-peak acceleration of 0.68 and armature mass-to-launch package mass ratio of 0.25. The RFG is designed for 40 GW peak power at 800 Hz and features a power gain of 26 (output power/field power).

INTRODUCTION

This paper describes work carried out at the Center for Electromechanics at The University of Texas at Austin (CEM-UT), under U.S. Army Armament Research, Development, and Engineering Center (U.S. Army ARDEC), Contract No. DAAA21-90-C-0011. The ultimate goal of this research and development contract was the conceptual design of a high efficiency, low mass and volume, matched rising frequency generator (RFG), and coaxial accelerator system to launch a 15 MJ projectile in the 2 to 4 km/s range. The RFG was to efficiently produce variable voltage amplitude and frequency by utilizing a novel concept of variable frequency field excitation. No restriction was placed on the launchers design.

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BACKGROUND

The RFG concept presented in this paper (Fig. 1) makes use of a polyphase a-c excitation voltage to produce an excitation field rotating relative to the spinning rotor. Just before the launch begins, the RFG rotor is spinning at its design speed (ω_{mech}) while the variable frequency power supply produces a magnetic field in the rotor rotating backward at the same angular velocity ($\omega_{\text{elect}} = -\omega_{\text{mech}}$). This results in zero generated voltage since the rotor magnetic field is stationary with respect to the stator. As the launch begins, the power supply frequency is reduced resulting in a generated voltage frequency ($\omega_{\text{gen}} = \omega_{\text{mech}} + \omega_{\text{elect}}$) that increases from zero frequency up to the mechanical frequency as the power supply frequency goes to zero ($\omega_{\text{elect}} = 0$), and becomes greater than the mechanical frequency as the power supply frequency is increased in the same direction as the mechanical frequency of the rotor.

A unique feature of this RFG concept is that it allows the generator frequency to be varied by simply varying the excitation power supply frequency. This makes feedback control of the generated frequency possible, if desirable, but perhaps more importantly, makes it practical to adjust the generated frequency at the end of the launch to decelerate the armature (while allowing the payload to separate and launch), reclaiming the kinetic energy of the armature in the rotor inertia of the RFG. This, in part, compensates for the high armature mass typically required for coaxial induction accelerators.

Fig. 1. Revised rising frequency generator concept

The liabilities of this concept are primarily associated with the relatively high power which must be provided by the variable frequency excitation power supply. The high power requirements stem from the high reactive power which the variable frequency power supply must provide the field coil at high frequencies and also, because there is direct transfer of power taking place between the field winding and the armature winding by transformer action. The challenge, therefore, is to define an acceptable range of ω_{mech} and ω_{elect} over which the RFG can operate and develop useful performance in a coilgun. A reasonable goal seems to be to require the excitation power to be less than 10% of the output power.

The rising frequency generator is composed of two components: a polyphase alternator (alternator) whose output drives the load (coaxial accelerator), and a polyphase ac power supply (exciter) which supplies a variable current to the excitation winding of the alternator. The alternator is composed of a rotor which stores energy kinetically and contains the excitation windings, and a stator which supports the armature and houses the rotor bearings and brush mechanisms used to supply rotor current.

The power delivered to the load through the mutual inductance of the alternator stator and rotor coils is obtained from two sources: a) the electromechanical power, because of the torque acting on the rotor of the rising frequency generator, and b) the direct transfer of power by transformer action from the exciter coil to the armature coil. Correspondingly, there are two types of voltages generated in the stator coil, i.e., the speed voltage obtained when the rotor is locked and the transformer voltage obtained when the exciter carries an alternating current. The exciter, therefore, does provide some portion of the total load power. It is most desirable for the exciter to be made from solid state electronic components. In order to make the concept feasible, it is therefore necessary to limit the power flow through the exciter to a small fraction of the total power. The amount of real power required to flow through the exciter depends on the electrical frequency of the exciter current relative to the mechanical frequency of rotation. Fig. 2 illustrates the real power requirements vs. load frequency. The y-axis is the normalized power with respect to the power flowing in the system when dc excitation is utilized. The x-axis is the normalized load frequency, i.e.,

$$\omega_n = \frac{\omega_m + \omega_e}{\omega_m}$$

$\omega_n = -1$ implies that the magnetic field produced by the multiphase exciter winding spins in the opposite direction to the direction of rotation of the rotor at twice the mechanical frequency. $\omega_n = 1$ implies that the exciter is providing only dc current to the exciter windings. Accordingly, three regions can be identified.

Region 1: ω_e is negative

$$|\omega_e| > |\omega_m|$$

Region 2: ω_e is negative

$$|\omega_e| < |\omega_m|$$

Region 3: ω_e is positive

$$|\omega_e| > |\omega_m|$$

Fig. 3 shows the direction of rotation of the rotor, the magnetic field produced by the rotor coils, and the net rotation of the magnetic field as viewed by the stator coil. Also shown in the figure, is the range of frequencies of the generator output for each of the three regions. In order to understand the direction of real power flow from the alternator rotor and the exciter, one resorts to the use of Lenz's law which may be stated as, "in case of a change in a magnetic system, that happens which tends to oppose the change"[1].

In region 1, $|\omega_e| > |\omega_m|$ and ω_e is negative. In order to oppose the change, a torque must act on the rotor to speed it up. Electrical power extracted from the exciter, therefore, goes partially to speed up the rotor and partially to the load. In region 2, a torque must act on the rotor to slow it down in order to oppose the change. Also, power is being supplied to the exciter from the rotor. When the exciter supplies dc current to the excitation winding, no power is supplied to the load by transformer action and the system behaves like a conventional generator. Thereafter in region 3, ω_e and ω_m are in the same direction and power is extracted from both the rotor as well as the exciter supply the load. Also, it is shown that the power requirement of the exciter is rising rapidly with increasing frequency in this region.

Fig. 2. Power vs. load frequency

Fig. 3. Direction of rotation of magnetic axis for the three regions

From Fig. 2 and the above discussion, the desirable region to operate in is region 2; as, in this region the real power transfer from the exciter is low and has a known maximum. In reality the range might extend partially into region 3, up to the point that the power extracted from the exciter is equal to the maximum in region 2.

In terms of implementing the above concept, the alternator would preferably be a polyphase air-core machine. Recent studies [2] indicate that this component could weigh as little as 2,500 to 3,000 kg using near term (1992) projections. This estimate is based on energy storage considerations. Several alternatives exist for the exciter. A smaller special purpose rotating machine, or capacitors may be used to supply power to the solid state conditioning circuit. Conceivably, this requirement may be satisfied by an auxiliary winding on the alternator. These alternatives were studied with the goal of achieving the lightest weight and least complex system.

Rising Frequency Generator

Having established the basic operating concepts of an RFG in the introduction, more general features of the machine were identified. A two-phase field excitation design was

adopted, because it is the least complicated design required to produce a rotating magnetic field, and the reactive power requirements necessary to produce a given magnetic field strength would be similar for a design featuring a greater number of phases.

The transition from operating in region 2 to region 3 needs special attention. The direction of rotation of the excitation field is effected by changing the phase relationship of the applied voltage in two of the phases of a three-phase winding. In a two-phase system, the applied voltage needs to be phase shifted 180° (i.e., reversed) in only one phase. In addition, if a reversal in the field phase does not occur at a current zero, the resulting transient alters the harmonic content of the output. Since the rate at which the field frequency ramps to zero is specified by the desired launcher performance, it is by no means synchronized with a current zero in either of the two field windings. At this point in time, a reasonable method of insuring that the reversal of one of the field power supplies occurs at a current zero has not been determined; therefore, most design efforts were being concentrated in region 2 operations.

Accelerator Geometric Issues

Various stator and armature configurations were investigated, with a goal of obtaining average-to-peak acceleration ratios as great as possible, while maintaining compatibility with present day electromechanical power supplies. In addition, it was desired that performance be determined by the RFG so that the pole pitch of the accelerator and coil geometry be constant. Parameters that were studied include: stator length, armature-to-stator length, stator overlap, and multiple armatures.

In order to improve acceleration ratio, the stator coils were arranged in an overlapping geometry. A five-stage accelerator was simulated using an ideal voltage source power as the power supply and obtained an average-to-peak acceleration ratio of 0.59. In addition to a smoother force profile, the closely coupled stator coils are compensated so that they assist in the switching current from one stator to the next and transfer magnetic energy from stator to stator; thereby, reducing the load on the power supply. Because the armature is continually being exposed to a rising magnetic field, its current does not decay or undergo reversal, but instead remains at a nearly constant level throughout the launch. This constant current eliminates the necessity of reestablishing the armatures current at each stator, therefore, the acceleration profile improves.

The length of the armature and stator determine the frequency and voltage required by the launcher as well as the shape of the mutual inductance between the stator and armature. In order to synchronize a two-phase power supply and an overlapping stator coil launcher using the

aforementioned switching scheme, the following relation between generated power frequency, armature velocity, and stator length is necessary for stator coils with a 50% overlap:

$$F_S = \frac{1}{2T_S} = \frac{1}{2 \left\{ \frac{l_S}{v_A} \right\}}$$

simplifying,

$$F_S = \frac{v_A}{2l_S}$$

where,

- F_S = Maximum stator frequency (Hz)
- T_S = Minimum stator period (s)
- l_S = length of stator coil (m)
- v_A = armature velocity (m/s).

For example, if a launcher comprised of 50% overlapping stator coils, 0.16 m long is required to accelerate the armature to 900 m/s, then the maximum frequency required is 2.9 kHz. Generally, it is desirable to keep the operating frequency of the system as low as possible. High frequencies result in higher reactive power requirements and bigger machines. From the equations derived above, it is observed that increasing the length of the stator coil helps reduce the frequency. Thus, in order to maintain operating frequencies within reasonably attainable values, it is necessary to have long stator coils as well as long armature coils.

Solid State Switching

In order for coaxial accelerators to be field deployable, compact, reliable, and repeatable switches are required. Although single package solid state devices are unable to operate at the giga-watt power levels necessary to obtain interesting performance from these types of launchers, solid state switches do satisfy the goals of being compact, reliable, and repetitive. In many instances, they may be arranged in series and parallel combinations in order to obtain the power requirements desired. In the following paragraphs, currently available high-power solid state devices are described and their operational characteristics are listed.

The present power supply and launcher have been designed to limit switching responsibilities to controlled turn-on of stators at peak voltage, passive turn off at current zero, and short turn-off time. Both thyristors, Silicon Controlled Rectifier (SCR's) and Gate Turn-off Thyristors (GTO's), exhibit the desired operating characteristics necessary to make them a likely candidate for the switching role dictated by the present launcher and RFG design. Since passive stator coil turn off at current zero has been incorporated into

all of the present accelerator designs, the controlled turn off provided by a GTO is not necessary. SCR type switches will be of primary interest unless frequency requirements suggest otherwise.

Several parameters govern the selection of an SCR for pulsed applications such as the switching of the stator coils. In a typical coaxial launcher, the frequency of operation of these devices could vary from a few cycles per second to thousands of cycles per second. The low frequency devices (60 Hz) are readily obtainable due to their extensive development for the commercial power industry. Parameters of importance for low frequency applications are the total action and voltage standoff. The former is based on the allowable heat input to the device and the latter is based on the maximum permissible reverse voltage that the device can tolerate without breaking down. As the frequency increases, the di/dt through the device is of considerable importance. When the gate pulse is applied, a conduction wave propagates through the device from the gate outward. The rate of propagation is approximately 0.1 mm/ μ s. At high frequencies, the conduction may not have time to propagate through the entire device and higher local current densities may result. Therefore, $\int i^2 dt$ ratings of these devices are generally lower at high frequencies. The di/dt rating may be increased by using a thinner substrate and/or by distributing the gate. Unfortunately, reducing the substrate thickness has the effect of reducing the SCR's maximum voltage rating and distributing the gate reduces conduction area. Turn-off time is also of considerable importance at higher frequencies because this parameter governs the minimum time which must elapse after turn off before a positive voltage can be applied to the device. The turn-off time is governed by the devices thickness and doping which alters the minority carrier lifetime. A parameter of considerable importance in low as well as high frequency applications is the dv/dt rating of the device. This is of particular importance with predominantly inductive circuits such as the stator coils of the coaxial launchers. This is because the voltage and current in these circuits are out of phase, with the result that when the current goes through a zero, voltage builds up across the SCR almost instantaneously and can trigger the device just as if it had received a gate pulse. Snubber circuits may be employed across the device to reduce the dv/dt. A summary of the trade-offs as a function of device parameters is presented in table 1.

The minimum quantity of SCR's required per stator coil is determined such that none of the nominal operating limits of the device is exceeded. For the launcher design presented below, the action for fusing was by far the critical parameter in determining the required number of parallel devices, and the peak-off state reverse voltage was the critical parameter in determining the required number of series devices.

TABLE 1. SILICON CONTROLLED RECTIFIER PARAMETER TRADE-OFF RELATIONS

Parameter	Voltage Rating	Current Rating	Critical dv/dt	Turn-Off Time	Forward Voltage	di/dt Rating
Edge Contouring	↑↑					
Gold Doping	↓	↓	↑↑	↓	↑↑	↓
Thinner Substrate	↓	↑↑		↓	↓	↑↑
Distributed Gate					↓	↑↑
Better Cooling			↑↑			

System Design

The launcher used for the conceptual design of the system uses 50% overlapped launcher stator coils and each coil will be independently switched. The tactical concept of the RFG using multiphase excitation windings is achievable. However, the size and mass of such a system together with the high field coil reactive power requirements makes it unattractive for the tactical application originally intended. From the earlier discussions, it is apparent that lowering the operating frequency greatly reduces the peak output power as well as the power required by the field coil. There are two ways of achieving a lower frequency, i.e., 1) by lowering the muzzle velocity, and 2) by using larger bore guns. Larger bores permit the use of longer stator coils, thus, lowering the operating frequency. A tactical application corresponding to these two requirements is the M198 Howitzer. This gun has a bore diameter of 155 mm and propels 55 kg to 826 m/s. The corresponding kinetic energy is 18.8 MJ. Thus, this application has about the same energy, however, at a much lower velocity. It is conceivable that this application can be powered by an RFG operating in the range of 1,000 Hz. Table 2 shows the parameters of such a system. The performance of such a system is summarized in figs. 4 through 6.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The goal of this program was to design a lightweight, efficient, RFG powered coaxial induction accelerator suitable for tactical mobile gun applications. A specific goal for the accelerator was to launch a 15-MJ projectile, 2 to 4 km/s.

The corresponding projectile mass ranges from 2 to 7 kg, which suggests practical launcher bore diameters of less than 120 mm. Due to the small bore diameter, the power supply frequency required to achieve the velocity goal makes the systems unattractive. Results from this program suggest that future efforts be directed toward lower frequency (i.e., lower velocity and/or larger bore) applications where an RFG power supply is better suited at operating. The proposed application was comparable with the M1A1, 120-mm tank gun which launches a 7.12-kg round at approximately 1,670 m/s [3]. A lower velocity (lower frequency) application of

possible interest is that of field artillery. The M109 Howitzer, has a 155-mm bore diameter and launches a 43.6-kg round at 826 m/s. A realistic goal for a comparable RFG/coaxial accelerator might be to launch the same projectile at a velocity of 1,000 m/s. In the design presented herein, this goal was achieved while operating at a frequency of less than 1,000 Hz and with a peak power requirement of 20 GW. Another area that may be of interest is military and civilian aircraft launch. An overlapping coil coaxial induction accelerator could be designed with the intent to accelerate 30,000-kg aircraft to 100 m/s over a distance of 100 m. If the stator coils are 1.25 m long and have a bore diameter of 0.25 m, then 160 would be required. Initial calculations suggest that the RFG would be required to provide two-phase harmonic outputs to the accelerator at a maximum of 40 Hz and 1,700 V. The peak power per phase, necessary for the final stages of such a launcher, is approximately 600 MW

TABLE 2. PARAMETER OF THE ARTILLERY SYSTEM

PARAMETER	ARTILLERY SYSTEM	
Total gun length	5.0	m
Bore diameter	160	mm
Total launch package mass	55	kg
Muzzle velocity	900	m/s
Muzzle energy	22.27	MJ
Stator coil length	0.64	m
Armature coil length	0.80	m
Maximum frequency	800	Hz
Launch time	11.5	ms
Average useful power	1.94	GW
Machine Parameters (Iron Core)		
Air-gap speed (counter rotating)	600	m/s
Number of poles	14	
Amp-turns per pole	71.34	kA-T
Coupling factor	0.9910	
Internal subtransient reactance	14.29	mΩ
Maximum open circuit voltage	48.27	kV
Maximum machine power	40.1	GW
Field coil reactive power	1.53	GW
Field coil dissipative power	89.0	MW
Size		
Length	3.28	m
Diameter	1.64	m
Selection Criteria		
Output power/field power	26.2	
Average useful power/output power	0.05

Fig. 4. Simulated velocity and acceleration for artillery system

Fig. 5. Simulated armature temperature and current for artillery system

Fig. 6. Simulated per phase current requirement for artillery system

The previous concept illustrates an alternate application which reduce the frequency of operation and the power requirements of an RFG/coaxial accelerator system. By comparison, the power requirements for the aircraft launcher are 30 times less than that of the full-scale, 155-mm launcher. By selecting an application which required lower velocity and longer stator coils, the operational frequency may be reduced and a significant reduction in the power requirements for the launcher may be obtained. A graphical representation of the relationship between velocity, frequency, and bore size for 50% overlapped stator coils that have a length-to-diameter ratio of 4, is shown in Fig. 7. This figure suggests that the velocities necessary to obtain earth-to-space orbit may be obtained at modest frequencies, if the bore size is on the order of a meter in diameter.

Fig. 7. Relationship between velocity, frequency, and launch bore diameter for 50% overlapped stator coils with a L/d of 4

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