MULTIPHASE RAILGUN SYSTEMS: A NEW CONCEPT

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Multiphase Railgun Systems: A New Concept

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Abstract: This paper investigates multiphase railguns powered by multiphase compulsators. The polyphase system offers several advantages over the single phase system. The multiphase compulsator relaxes the strong dependence between the current pulse width necessary for the railgun and the design parameters of the generator (number of poles, rotor diameter, and tip speed) thus allowing the compulsator to be designed for optimum power density and electromechanical energy conversion. The paper examines in particular the two, three and six phase systems.

The authors also explore different methods of achieving high acceleration ratios in multiphase railgun systems. Some of the methods analyzed are ramping up the field current of the compulsator to counter the back electromotive force of the gun, utilizing a railgun with varying inductance per unit length (L'), and using an external variable inductor in series with the compulsator. The different features of each method are highlighted using simulation results. Special attention is devoted to the external series inductor method which uses a rotary flux compressor. Simulation results indicate an encouraging acceleration ratio of 0.7 for a muzzle energy of 9 MJ. A disk configuration is envisioned for the flux compressor.

INTRODUCTION

The single phase railgun powered by a single phase compulsator [1] has been investigated analytically and experimentally at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) for the past ten years. The CEM-UT compulsator powered 9 MJ railgun system [2] (Task C) has brought to light several limitations of the single phase system. Since the single phase compulsator uses one pulse to launch a projectile, for a given gun length, projectile mass and acceleration profile, the launch time is fixed. The pulse width (approximately launch time) determines the electrical frequency of the compulsator. Therefore, for increasing muzzle energy, the launch time needs to be increased, resulting in an increase in the size and hence the weight of the compulsator. To minimize this effect, the compulsator design is driven toward a two pole configuration, which results in the nonuniform distribution of forces and stresses around the rotor and stator periphery during a discharge. All these factors limit the rotor tip speed for which the compulsator can be designed. Thus single phase compulsators designed to obtain a given pulse width have severe constraints imposed on the number of poles, frequency, and tip speed. These factors remove the machine from the domain of optimum power density.

The multiphase compulsator powered railgun offers solutions to most of the above problems of the single phase system. It removes the strong dependence between the current pulse width necessary for the railgun and the design parameters of the generator (number of poles, rotor diameter and tip speed) thus allowing the compulsator to be designed for optimum power density and electromechanical energy conversion. The polyphase compulsator uses several pulses to drive the projectile, instead of one pulse as in the case of the single phase machine. This also provides for a reduction in the weight of the system, as the increase in stored energy can now be achieved by designing the machine to operate at higher tip speeds. Further weight reduction is again obtained by the increase in power density resulting from the greater number of phases. Also the two pole configuration is no longer required and hence a multipole configuration may be pursued resulting in a more uniform distribution of stresses over the stator and rotor periphery.

MULTIPHASE COMPULSATOR RAILGUN SYSTEM

The two, three, and six phase systems will be examined in the rest of the paper with more emphasis on the two phase system. The three systems are compared on the basis of the same gun bore diameter (90 mm), rail diameter (28 mm), and a gun length of 10 m. A muzzle energy of 9 MJ, with projectile mass of 2 kg, and a constant acceleration of $450,000 \text{ m/s}^2$ is assumed in all three cases.

The three phase railgun has three rails spaced 120° apart and the armature is Y-shaped. The three phases of the compulsator are connected to the three rails of the railgun. No neutral path is required as the balanced three phase currents sum to zero. The rails are assumed to be thin circular conductors (radius of rail is much less than the distance between rails). The rail conductor size is based on an allowable line current density of 40 MA/m and the required force on the projectile to produce a muzzle energy of 9 MJ at a constant acceleration of $450,000 \text{ m/s}^2$.

The three phase currents can be denoted as

$$\begin{aligned} I_a &= I_m \sin(\omega t) \\ I_b &= I_m \sin(\omega t - 120^\circ) \\ I_c &= I_m \sin(\omega t - 240^\circ) \end{aligned}$$

where I_m is the peak current.

The force on the projectile can be computed as

$$F = \frac{1}{2} L' (I_a^2 + I_b^2 + I_c^2) = \frac{3}{4} L' I_m^2$$

Thus one would expect a constant force to act on the projectile giving a constant acceleration profile. The inductance gradient (L') was calculated to be $0.4 \mu\text{H/m}$ and the peak current is 1.73 MA per phase. The compulsator is designed to store 200 MJ and to operate at $1,000 \text{ Hz}$. This frequency was chosen to allow a sufficient number of pulses (at least two to three cycles) within the launch time while keeping a limit on the operating voltage of the machine.

Fig. 1a shows the three phase currents and Fig. 1b shows the acceleration profile of the three phase railgun system. The currents are not sinusoidal with respect to time because of the dc transient in the phases. This dc transient distorts the current waveforms and results in the poor acceleration profile. Further the locus of the centre of force on the armature is a circle. This results in unstable motion of the armature.

One solution to the dc transient problem is to switch in each of the phases at peak voltage, eliminating the dc transient. This, however, does not work very well with the three phase system (Figs. 2a and b) due to the magnetic

coupling between the three phases. However, in the case of a two phase system the above method of eliminating the dc transient works, because the two phase system is decoupled.

TWO PHASE SYSTEM

The two phase system works best in the configuration shown in Fig. 3. The railgun has four rails in the cross-wire configuration, with one phase connected to each pair of diametrically opposite rails. The dc transient affects the sinusoidal current waveform and distorts the acceleration profile in the two phase system also, but it can be eliminated by switching in each phase at peak voltage. Fig. 4a depicts the two phase currents without the dc transient and Fig. 4b the acceleration profile. The force in this system acts through the centre of mass of the armature and is constant in magnitude.

The two phase currents can be described by

$$I_a = I_m \sin(\omega t)$$

$$I_b = I_m \cos(\omega t)$$

6601.0002

Fig. 1a. Three phase railgun currents with all phases switched in at time $t = 0$

6601.0004

Fig. 2a. Three phase currents with each phase switched in at peak voltage

6601.0003

Fig. 1b. Acceleration velocity profile in the three phase gun with all three phases switched in at time $t = 0$

6601.0005

Fig. 2b. Acceleration and velocity profile in the three phase gun with staged switching of the three phases

Fig. 3. Cross section of a two phase, four-rail railgun

Therefore the force is given by

$$F = \frac{1}{2} L' (I_a^2 + I_b^2) = \frac{1}{2} L' I_m^2$$

A 200 Hz, two phase, 200 MJ passive compulsator design is used to examine the performance of the system. For the two phase system the inductance gradient of the gun is 0.82 $\mu\text{H/m}$ and the peak current per phase is 1.5 MA.

An 8 kV, 200 Hz compulsator can deliver a muzzle energy of 9 MJ, but the acceleration profile droops. This problem is also present in the three phase system and is due to the rising back electromotive force of the gun as the projectile moves down the barrel. Railgun projectile designs place a limit on the maximum permissible acceleration. Thus it is necessary to have a high average-to-peak acceleration ratio for best performance. The droop in the acceleration profile must be corrected to make the multiphase gun system attractive.

Improvement of Acceleration Profile

The droop in the acceleration profile is also a feature of the single phase system. The CEM-UT Task C compulsator uses selective passive compensation to get an acceleration ratio of 0.6. The selective passive method [3] allows for the variation in the machine inductance as it rotates through one cycle giving rise to a flat current pulse and hence a flat acceleration profile. However since the polyphase machine uses more than one pulse, the selective passive compensation does not achieve the desired effect.

Once again the force on the armature for the two phase system is given by

$$F = \frac{1}{2} L' I_m^2$$

So to keep the force constant we need to keep

$$L' I_m^2 = \text{constant}$$

Let us consider the different cases

1) L' is fixed: Let us assume a constant L' gun (as in most railguns). This implies that as the armature moves down the gun barrel, the inductance of the gun $L'x$ (x is the position of the armature in the barrel) increases resulting in reduction of the peak current flowing through the gun and the droop in the acceleration profile. A ready solution is to ramp up the field current to increase the generated voltage and hence provide for constant peak current.

A quick calculation shows that this requires a large amount of reactive power.

$$v_m = \text{peak voltage per phase} = I_m (\omega L' x)$$

where

$$\omega = 2\pi f = \text{electrical frequency of compulsator}$$

$$x = \text{position of armature}$$

Fig. 4a. Two phase railgun currents with each phase switched in at peak voltage

Fig. 4b. Acceleration and velocity profile in two phase railgun

$$\frac{dV_m}{dt} = I_m \omega L' \frac{dx}{dt} = I_m \omega L' v$$

assuming constant I_m and ω .

With a peak current of 1.5 MA, $f = 200$ Hz, $v = 1,500$ m/s (average velocity)

$$\frac{dV_m}{dt} = 2.4 \times 10^6 \text{ V/s} \quad (1)$$

Now if we assume a balanced two phase system and ignore resistance

$$V_m = i_f \omega M_{\max}$$

where

i_f = field current

$M_{\max}$ = mutual inductance between the armature and the field windings.

therefore

$$\frac{dV_m}{dt} = \omega M_{\max} \frac{di_f}{dt} \quad (2)$$

$$i_f = \left(\frac{1}{\omega M_{\max}} \right) \times \left(\frac{dV_m}{dt} \right) \times t \quad (3)$$

Also the field voltage V_f is given by

$$V_f = L_f \frac{di_f}{dt}$$

and from (2)

$$= \left(\frac{L_f}{\omega M_{\max}} \right) \times \frac{dV_m}{dt}$$

Therefore the reactive power input to the field coil for a launch duration of 6 ms is given by,

$$V_f i_f = \left(\frac{L_f}{(\omega M_{\max})^2} \right) \times (2.4 \times 10^6)^2 \times t$$

$$\cong 3 \text{ GW from equations 1, 2 and 3.}$$

where

$$M_{\max} = 1.142 \text{ mH}$$

$$L_f = 0.1636 \text{ H for the 14.5 kV, 200 Hz machine used in the analysis}$$

The generator can not have any compensating winding or shield to lower the machine inductance since the ramping of the field current will induce eddy currents in the shield and not produce any effective increase in the generated voltage. Fig. 5 shows the acceleration profile and Fig. 6 the two phase currents and the field current. Fig. 7 depicts the power output per phase and the power input to the field coil. The energy input to the field coil per shot is 18 MJ. For ten shots, a generator storing 180 MJ and running on the same shaft as the compulsator would have to be 0.45 m in radius and 2.0 m long. Also, the rectifier, required for the system would have

to handle the large power input making it large in size. From the above discussion it appears that ramping up the field current is not an attractive option.

Another option is to vary the L' of the gun, i.e. increase or decrease the L' along the gun length. This can be obtained theoretically by varying the diameter of the rails and the distance between the centre of the rails keeping the same bore diameter. However this often leads to impractical designs. Another method is to use a conducting shield of varying thickness over the rails to get the requisite variation in the gun L' . This, however, adds to the total losses in the system. Simulation results for a three fold variation in L' indicate the need for excessive reactive power input to the field coil to keep the force constant.

2) *External variable series inductor method:* Another way of keeping the current constant in a circuit is to keep the impedance of the circuit constant. The gun impedance is low at the start of the launch and high at the end. Now consider an external variable inductance L_c in series with the compulsator. Ignoring resistance and assuming the inductance of compulsator to be negligible in comparison to

Fig. 5. Acceleration and velocity profile in the two phase system with field current ramping

Fig. 6. Two phase currents and field current

Fig. 7. Input power to field coil and output power of each phase

the gun inductance (L_{gun}) and L_c , the single phase circuit equation can be written as

$$(L_{gun} + L_c) \frac{di}{dt} = V_m \sin(\omega t) - iL'v - i \frac{\partial L_c}{\partial t}$$

where

$$\begin{aligned} v &= \text{projectile velocity} \\ \omega &= \text{electrical frequency of the compulsator} \\ L_{gun} &= L'x \end{aligned}$$

Let $I = I_m \cos(\omega t)$, therefore

$$-(I_m \sin(\omega t))\omega = \left(\frac{1}{L_{gun} + L_c}\right) \{V_m \sin(\omega t) - iL'v - i \frac{\partial L_c}{\partial t}\}$$

For constant peak current, we require that

$$\frac{\partial}{\partial t}(L_{gun} + L_c) = 0$$

therefore

$$\frac{\partial L_c}{\partial t} = -\frac{\partial L_{gun}}{\partial t}$$

hence

$$\frac{\partial L_c}{\partial t} = -L'v \quad (4)$$

This means that the external inductance must reduce at a rate given by $L'v$. It is also interesting to note that (4) implies that the speed voltage of the gun is compensated by the $(\partial L_c / \partial t)$ term, i.e.,

$$iL'v = -i \frac{\partial L_c}{\partial t} \quad \therefore iL'v + i \frac{\partial L_c}{\partial t} = 0$$

A rotary flux compressor [4] can be used as the external variable inductor. The rotary flux compressor (rfc) is simply

an actively compensated alternator without the field winding. It has two windings, one on the stator and one on the rotor. The two windings are connected in series. The required inductance of the rfc can be expressed as

$$L_c = L_1 + L_2 + 2M_{\max} \cos(\omega_c t)$$

where

$$\omega_c = \frac{\pi}{T_L} \text{ is the electrical frequency of the rfc}$$

where

$$\begin{aligned} L_1, L_2 &= \text{self inductances of the two windings} \\ M_{\max} &= \text{mutual inductance between them} \\ T_L &= \text{launch duration} \end{aligned}$$

Let $L_1 + L_2 = L$, therefore

$$L_c = L + 2M_{\max} \cos(\omega_c t)$$

Fig. 8 shows the inductance variation of the rfc. As the gun inductance increases, the rfc inductance decreases, thus keeping the net circuit impedance constant. The launch starts with the rfc in the maximum inductance position and by the end of the launch the rfc has reached its minimum inductance position. Thus the rfc delivers energy during the launch. The compression ratio for an rfc is defined as

$$C = \frac{\text{Maximum inductance}}{\text{Minimum inductance}}$$

If we integrate (4) over the launch time we get

$$\int_0^{T_L} \frac{\partial L_c}{\partial t} dt = - \int_0^{T_L} L'v dt$$

$$2M_{\max} \omega_c \int_0^{T_L} \sin(\omega_c t) dt = L'x_{\text{barrel}} = L_T$$

where

$$L_T = \text{total gun inductance}$$

Fig. 8. Inductance variation of the rfc, gun, and the net circuit inductance

therefore

$$2M_{\max} = \frac{L_T}{2}$$

at

$$\begin{aligned} t &= T_L \\ L_c &= 0 \end{aligned}$$

therefore

$$L = 2M_{\max} = \frac{L_T}{2}$$

hence

$$L_c = \frac{L_T}{2} (1 + \cos \omega_c t)$$

therefore

$$L_{c(\max)} = L_T$$

This however requires high operating voltages and compression ratios, hence several iterations are required to arrive at an optimum value for the inductance variation of the rfc.

An expression for the energy released by rfc can be derived by

$$E_c = \frac{1}{2} \int_0^{T_L} i^2 \left(\frac{\partial L_c}{\partial t} \right) dt \quad \text{where } i = I_m \sin(\omega t)$$

$$\cong M_{\max} I_m^2 \text{ per phase}$$

A 14.5 kV, 200 Hz, two pole, 325 MJ, two phase passive compulsator with peak current of 1.8 MA/phase and operating at a tip speed of 610 m/s meets the requirement of delivering 9 MJ muzzle energy. The estimated weight of the compulsator is 6.0 metric tons. The rfc delivers a total energy of 6 MJ per shot. A compact disk configuration is envisioned for the rfc. The rfc dimensions (two pole) are 0.7 m radius and 0.6096 m long, with a compression ratio of nearly 10 and a tip speed of 370 m/s. Fig. 9 shows the acceleration profile for the above railgun system. An acceleration ratio of 0.7 is obtained.

Fig. 9. Acceleration and velocity profile with a variable inductor in series with the compulsator

The weight of the rfc is estimated at 2 metric tons bringing the entire system (two pole compulsator plus rfc) weight to 8 metric tons. However the disk configuration has some inherent problems with regard to shear stress generated during a discharge. The short axial length can also lead to problems with respect to the end turns of the windings. Thus there exists a trade off between achieving the required inductance variation with a particular winding configuration and managing the shear stress and end turns. A cylindrical design for the rfc has none of the problems of the disk machine but leads to a longer machine. The dimensions of such a machine have been calculated to be 0.5 m radius and 1.6 m length, giving the required inductance variation and storing 60 MJ. The estimated weight of the cylindrical rfc is 3.5 metric tons. A four pole (200 Hz, 200 MJ) design of the compulsator results in a weight estimate of 10 metric tons.

SIX PHASE SYSTEM

The six phase system is similar to the three phase system as far as the dc transient problem is concerned. Due the magnetic coupling between the phases of the six phase machine, it is not possible to eliminate the dc transient by switching each of the phases at its peak voltage. However the force acting on the armature is constant and acts along the centre of mass of the armature, leading to stable motion of the armature.

CONCLUSIONS

The polyphase compulsator system alleviates the problem of the single phase system resulting in a low weight power supply with several attractive features. The performance aspects of the system, especially acceleration profile, are particularly impressive. The requirement of the external rfc operating at a different frequency from that of the compulsator may be a drawback. Research is being done to incorporate the inductance variation provided by the rfc within the compulsator, resulting in a single element scheme. The results of this work will be published in a later paper. The three and six phase systems appear to have inherent problems and hence the two phase system is perhaps the most feasible.

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