INDUCTIVELY COMMUTATED COILGUNS

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Abstract

The concept and relevance of power factor is presented in regards to high performance launchers. As the scale of launchers grows and as efforts to improve efficiency continue power factor considerations will become crucial in engineering design and ultimate launcher performance limits. The use of motion induced commutation to improve the power factor are discussed. Various approaches to inductive commutation are presented, including: the brush-commutated 9 MJ Coilgun, the solid state-switched coilgun and the quenchgun.

Coilgun Introduction

The name "coilgun" was coined about 5 years ago to describe the class of coaxial launchers that were being studied as alternatives to the more prevalent railgun launchers of the day. The motivation to do so was the promise of higher efficiency and lower current operation. At the time, coilgun was predominantly used to describe what is now referred to as coaxial brush-commutated launchers. The term coilgun has since expanded to include virtually all alternative EM launchers where higher efficiency and lower current operation, as compared to railguns, are still goals.

Although launcher electrical efficiency can ultimately be reduced to the total integrated I^2R losses in the windings, the overall efficiency can be attributed to several underlying design considerations.

Coupling: The magnetic coupling of the launcher's windings to the projectile's has a great impact on the overall efficiency. In general, this is a function of the radial build and width of the involved coils. A certain amount of flux coupling to the projectile is necessary to accomplish the magnetic work in the launcher. However, not all of the flux generated by the stator coils is coupled to the projectile. This uncoupled flux is exactly analogous to the leakage flux referred to in rotating machines. Being predominantly air-core, the flux leakage in high performance launchers can be commensurate with the coupled flux terms and in some cases many times larger. Clearly the reduction of leakage flux is pivotal for minimizing losses as well as keeping coil heating and stresses in check. In coaxial geometries leakage flux can be reduced by utilizing minimum coil radial builds and widths and gaps. However, this guideline has to be traded off against unacceptably high coil stresses and heating for a given application.

Localization of Flux/Excitation: In rotating machines all of the rotor and stator windings can be used continuously throughout the rotation cycle. In linear launchers, unfortunately, the projectile windings are necessarily localized to a finite length corresponding to a small fraction of the total launcher length. In coaxial geometries the region of useful coupling extends about one bore diameter from the projectile's instantaneous axial position. Excitation beyond this simply produces additional leakage flux without any significant useful mutual flux. As a result, some means of confining the excitation of the stator windings to the local position of the projectile coils as it moves down the launcher length is required.

This process is referred to as commutation and usually involves two key aspects: the use of switching to control the physical extent of excitation, and some flux transfer mechanism to get the combined flux (leakage and mutual) into or out of the launcher. These two mechanisms are inter-dependent in that a sharply defined excitation length requires a high rate of flux transfer for commutation. A broad excitation region, on the other hand, requires a larger total flux transfer due to a greater leakage flux component, albeit at a lower transfer rate.

Energy Recovery: Commutation can also be thought of as the recovery of the magnetic energy associated with the leakage flux (see figure 1). The energy recovery can be a local event which happens continuously as the leakage flux energy is recovered from the trailing edge of the moving excitation region of the stator windings. Energy recovery can also be a global event such as when the magnetic field energy of the excitation region is recovered at the end of the launch.

Local commutation is then the process whereby magnetic energy is recovered from the moving region of excitation continuously during the launch interval. Lack of local commutation will result in an arbitrarily long excitation region with the resistive losses and efficiency scaling accordingly.

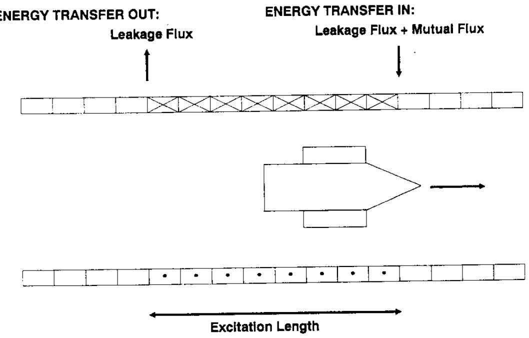

Figure 1 Commutation Energy Transfer

Global commutation is then the process whereby magnetic energy is recovered from the launcher at the end of the launch. Lack of global commutation will result in the loss of this energy. For example, in a conventional brush commutated coilgun like the 9 MJ Coilgun, local commutation is used to limit the excitation length to roughly 1-2 diameters. The energy associated with this region is about 200 kJ. Because the 9 MJ Coilgun does not incorporate global commutation this energy is lost at the end of the shot. However, this term is almost insignificant as compared to the total muzzle energy of 9 MJ.

By way of comparison, a compulsator driven railgun does not permit local commutation but does incorporate the potential of global commutation by forcing the railgun field energy to transfer back into the compulsator's inertia at the end of the launch. The energy transfer back can be on the same order as the muzzle kinetic energy. In both launcher examples roughly the same amount of energy is commutated out of the gun. In the coilgun's case this happens continuously during the launch while in the railgun's case it occurs predominantly at the end of the launch. The use of local commutation in the coilgun is also what allows the excitation losses to be limited to a much shorter length.

Scale Size and Speed: In general, a launcher's perceived efficiency will improve as the launcher's scale size or speed is increased. The larger size allows better coupling to be established for the same heating or stress limitations. The higher speed translates to a shorter launch interval with proportionally lower excitation losses as a result. Another way to think of this is to relate the efficiency to the ratio of the natural launcher time constant (L/R) to the launch time. This ratio is clearly a direct function of the launch velocity and scale size. This is one reason why many large scale, high velocity launcher concepts such as those for earth-to-orbit all seem to have a high efficiency seemingly independent of launcher type. Claims of

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"solving the armature heating problem" are more a result of large scale size than optimum launcher design.

As discussed above, high launcher efficiency is generally only possible through some combination of local and global commutation to limit excitation losses and wasted field energy. While the benefits of this capability are readily apparent, the penalties, commonly, are not fully appreciated. Aside from the specific details involved, all the various commutation schemes involve the transfer of magnetic field energy over and above that associated with the projectile's kinetic energy. This involves the application of voltage and current to the launcher's windings, the product of which can be many times the mechanical power associated with the launcher's muzzle energy. The ratio of these two terms is introduced as the power factor and has many similarities to the same concept conventionally used for AC magnetic devices such as alternators or transformers.

Power Factor Considerations

The power factor is commonly used to describe the ratio of the real power to the complex or apparent power:

$$PF = \frac{P}{[P^2 + Q^2]^{1/2}} \qquad (1)$$

where P is the real power and Q is the reactive power (capacitive or inductive). The PF is unity for ideal machines and less than unity depending on the degree of reactive power associated with the magnetics. This concept can be expanded to characterize launchers using the following expression:

$$PF = \frac{Fv}{I_{peak} + V_{peak}} \qquad (2)$$

Fv = force x velocity product
I_{peak} = peak coil current
V_{peak} = peak coil voltage

A low power factor implies that the voltage and current applied to the windings can be well in excess of what would be normally associated with the launcher mechanical power. Aside from heating issues, coil design is limited mostly by the maximum current and the maximum voltage that the windings must withstand. Current affects the peak stresses in the coil and voltage affects the insulation requirements. It does not matter whether these peak values occur at the same time or shifted in time. As a result coils are constrained by the peak volt-ampere product and hence the importance of the power factor for a given launcher. Notice that this product is independent of the number of turns and is strictly a function of the coil geometry and the commutation scheme. A low power factor can be directly related to the amount of leakage flux relative to the mutual flux, independent of whether it is locally or globally commutated.

It should also be noted that power factor considerations are, for the most part, independent of efficiency. It is quite possible to have a very efficient launcher in excess of 90% with a very poor power factor of 0.1. Although the launcher has proportionately low losses, its windings must withstand ten times the volt-ampere product associated with the mechanical power. In large scale applications, such as earth-to-orbit, for instance, power factor constraints can be more of a concern than overall losses.

For transient devices, such as launchers, the power factor concept needs to be expanded to include the effects of non-uniform power delivery. A uniform acceleration launcher, for instance, has a peak power at the muzzle that is roughly twice the average power integrated over the launch cycle. Power factor can also be used to incorporate the impact on winding voltage-current product of the payload fraction, where only a fraction of the muzzle kinetic energy is useful payload. The total launcher power factor might then be described as:

$$PF = \underbrace{\frac{M_{payload}}{M_{projectile}}}_{\text{payload mass fraction}} \times \underbrace{\frac{\text{average acceleration}}{\text{peak acceleration}}}_{\text{non-uniform power delivery}} \times \underbrace{\frac{\text{mutual flux}}{\text{mutual flux + leakage flux}}}_{\text{coupling}} \qquad (3)$$

The above expression is presented not as a rigorous equation but more as an underlying concept to consider when evaluating a launcher's performance. Notice that nothing in the above equations are intrinsically tied to losses or efficiency. Even the projectile parasitic mass can, in principal, be recovered through global commutation of the sabot's kinetic energy. However, the size and mass of equipment external to the launcher, that allows it to operate efficiently, are greatly dependent on the peak power they must handle.

Coilgun research at EML Research has always been concerned with high efficiency operation starting from the early mass drivers and including pulsed induction, brush commutated, solid state switched and now, most recently, the superconducting quenchgun. These launchers all incorporate some form of local commutation to limit the extent of excitation and thereby promote high efficiency. Throughout these efforts the price that local commutation places on the power factor has been quite evident. Having incorporated local commutation, it has been our observation that the mass, size, cost and losses of the commutation equipment can exceed that of the launcher, itself. Moreover, much of the engineering attention has to be paid to the leads, insulation, switches, etc. due to power factor considerations. This perspective has led to an appreciation of the unique features of inductive commutation.

Inductive Commutation

Inductive commutation is the use of the motion of the projectile coil's magnetic field to provide the reactive power necessary to accomplish local commutation. As discussed above, local commutation requires sufficient reactive power to commutate the leakage flux into and out of the launcher windings. By the appropriate choice of projectile coil excitation the change in mutual flux and leakage flux can be made equal. As a result, the motion of the projectile can deinduce current at the trailing edge of excitation with suitable switching. The advantage of this type of commutation is that no external reactive power conditioning components are required. From an external viewpoint the launcher can be said to approach a power factor of unity. In this ideal case the power flow to the launcher approaches that of the mechanical power.

The price paid for this capability is that the projectile coil must be sized to handle the stresses and heating associated with the current level required to satisfy the inductive commutation conditions. The penalty for this is extremely diameter dependent and must be reviewed on a case-by-case basis. However, the penalties associated with operating at low power factors do not depend on diameter and in the author's opinion dominate the overall system design.

At EML Research the power factor penalties on power conditioning components, switchgear and coil design has been appreciated since the beginning days of mass drivers [1] and pulse induction launchers [2], where capacitors provided the necessary reactive power. Since then most of the high velocity coilgun research at EML has focused on inductively commutated coilguns. The following sections on brush-commutation coilguns, solid-state switched coilguns and quenchguns differ only in respect to how the switching functions are accomplished; they all use virtually the same sequence of coil shorting, projectile motion and coil opening to accomplish commutation.

Reference Brush-Commutated Coilgun: 9 MJ Coilgun

Brush commutated coilguns use projectile mounted brushes sliding on the inside of continuous barrel windings which acts as a linear segmented commutator (see figure 2). A common misconception of brush commutated coilguns is that the sliding brushes commutate the field energy through arc dissipation. In reality the projectile current is sized to deinduce the barrel currents in the distance it takes for the brushes to traverse each shorted turn [3]. This commutation process has been carefully analyzed where we can now predict coilgun performance to the accuracy of the instrumentation, including velocity, voltages, currents and coupling terms.

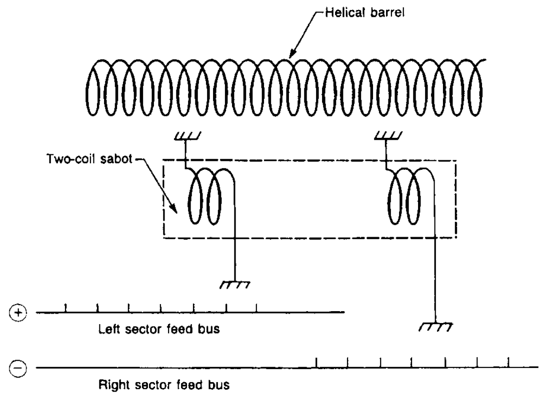

Figure 2 Brush Commutated Coilgun Schematic

The largest brush-commutated coilgun is the 9 MJ system which has been under development for the last 4 years. This system (figure 3) is designed to deliver nine, 9 MJ shots repetitively in 3 minutes. The 9 MJ coilgun program combines major development efforts in pulse power engineering including pulse disk alternator, 300 MW rectifier, modular Brooks coil and rep-rated firing switch.

Because of the tactical nature and size and mass objectives of the 9 MJ coilgun program, brush commutation was selected. While some of the more advanced switching schemes discussed below are appealing they still have a long way to go before they can handle the multi-gigawatt power necessary for the 9 MJ coilgun.

Prior to the 9 MJ coilgun program brush commutated coilguns had been operated at speeds approaching 200 m/s and several thousand gee's acceleration. While this level of performance is about an order of magnitude greater than that found in conventional brush commutated machines it still was an order of magnitude away from the performance goals of 2.5 km/sec and tens of kilogee's.

To reach these goals required an engineering development of the barrel and projectile structures to handle the high level of stresses, voltages and thermal loads while still maintaining the efficient inductively commutated mode of operation. The barrel is required to handle 20 kV at up to 250 kA turn per inch of barrel length and a equivalent bursting pressure of 50 ksi. Figure 4 shows a full bore 6 foot section length that is being used for preliminary testing. The barrel incorporates composite reinforced coil modules with an external tension housing to provide the axial preload. This barrel section has been statically stressed, hipotted and inductively verified to meet design parameters.

One of the most challenging aspects of the launcher was the development of the projectile coils. These coils had to be designed to handle up to 2 MA-turns for 10 ms, with a mass goal of under 2 kg. The coils developed incorporated integral graphite reinforcement of litz-wound aluminum conductors. Figure 5 shows a prototype coil and traveling wave coil pair assembly, respectively. These coils are designed for 70% conductor packing factor with a 100 ksi average overall strength. They have been tested up to 200 ksi total stress and up to 600 C temperature in the windings with no degradation of the resin-composite insulation.

A disadvantage of inductively commutated coilguns is their projectile parasitic mass penalty. This is mostly a result of attempting to incorporate local commutation (traveling wave mode operation) in a bore diameter that is unfavorable to the scaling of coilguns. Expanding front projectile designs, where only one coil rather than two coils are used in the projectile, do offer greatly decreased coil mass but still suffer the same power factor penalties of a railgun. In addition, all coilgun mass penalties tend to improve substantially as the bore is increased. If, for instance, the 9 MJ bore was increased to 155 mm from 120 mm the parasitic coil mass could be reduced on the order of 50%. As a result, coilguns tend to favor telescoping type projectiles rather than base pushed types to take advantage of the benefits of large bore without the associated sabot mass penalties.

At present the major development hurdles of the 9 MJ coilgun system have been overcome. The power conditioning system is built and awaiting testing. A coilgun barrel section of 6 feet has been built and assembled with additional modules for 10 more feet available. The manufacturing processing for high strength, high conductivity composite coils has been perfected with a lightweight projectile in hand. The 9 MJ coilgun program awaits final funding to finish the remaining assembly and test phases. If the program proceeds, test efforts will provide the first quantitative evaluated coilguns and related power conditioning at the multi-megajoule level.

Solid State Switched Coilgun

In place of brushes, external switches can be used to accomplish the required switching functions. In an inductively commutated coilgun the switching functions can be reduced to closing and then opening at zero current crossing. This is an ideal match for silicon controlled rectifiers, which represent the highest power solid state devices available. An inductively commutated, solid state switched coilgun was first developed in 1984 at EML Research [4]. This system consisted of 10 discrete coils individually switched with SCR's and diodes (see schematic in figure 6). The benefit of external switching, of course, is the elimination of sliding brushes and the internal commutator bore. Launcher coils can now be designed specifically for high strength and power factor considerations without concern for an internal brush surface.

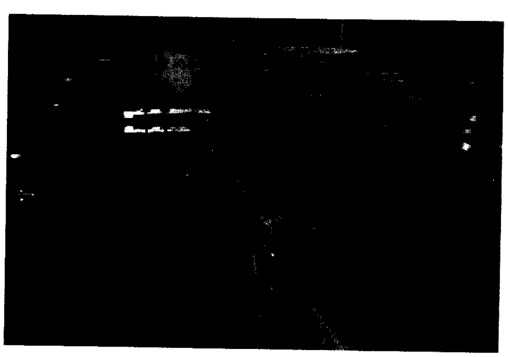

Figure 3a 9 MJ Single Shot Test Facility

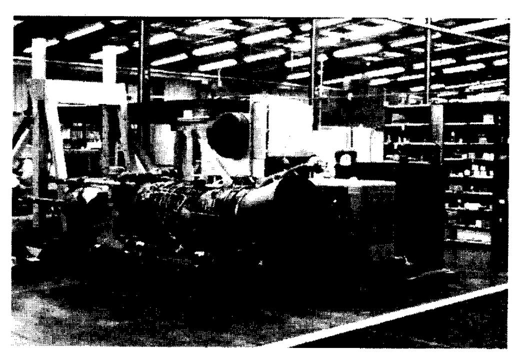

Figure 3b 9 MJ Rep-Rated Stand Alone Sled

Figure 4 Coilgun Barrel

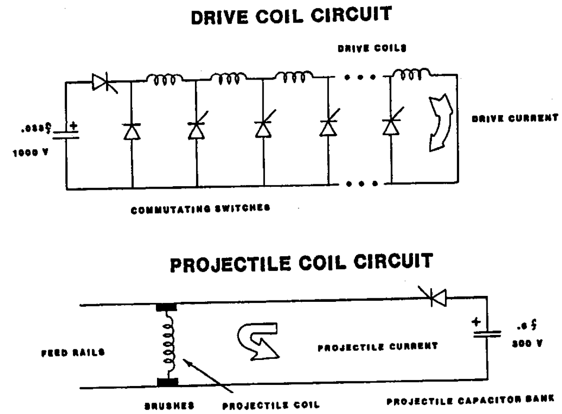

Figure 6 Solid State Switched Coilgun

The great appeal of solid state switching is the controllability, reliablity, long lifetime and low losses. At present, solid state devices, even under pulse conditions, do not have the power density to be practical in most high energy launcher applications. Although their peak discharge current is adequate, their current and voltage recovery rate (dI/dt and dV/dt) are not fast enough for high power inductive commutation. However, the rate of growth of power semiconductor performance is rapid and merits close monitoring.

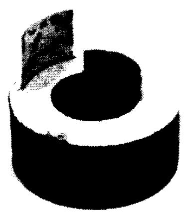

Figure 5a Composite Projectile Coil

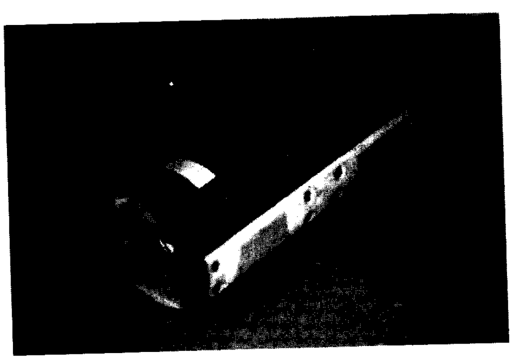

Figure 5b Assembled Traveling Wave Coilgun Projectile

Quenchgun

If by way of scale size or material selection the launcher's time constant can be made very large, it is possible to integrate the pulse power source into the launcher itself. This is accomplished by utilizing the barrel windings as a storage inductor where all of the launch energy is stored in the barrel field prior to the launch. Inductive commutation is still accomplished by the motion of the projectile. The benefit of this approach, is that the pulse power source only has to provide the relatively low-level charging power. As the barrel time constant approaches infinity this power supply can become vanishingly small. This mode of operation was first conceived by the EML Research group while at MIT in the context of using superconducting barrel windings. In this case it was considered that the switching could be accomplished by the synchronized phase change of the windings from superconducting to normal or quenching, and hence the name quenchgun. However, the concept can be expanded to include all launchers which store the launch energy in the barrel and have the current commutated by the motion of the projectle.

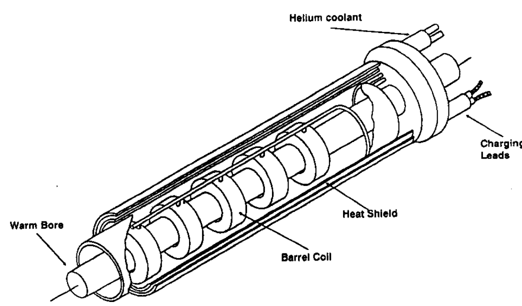

Figure 7 Quenchgun Prototype

The first effort to develop a working quenchgun is now under contract at EML Research. This effort will not only establish the underlying analysis and engineering of quenchgun operation but will address some of the practical hardware considerations as well. The system design (see figure 7) features a modular barrel coil with forced flow capillary rather than pool immersion helium cooling. The cryostat features an open warm bore and demountable thermally isolated barrel structure for experimental flexibility.

Conclusions

High efficiency launcher operation requires some form of commutation to limit the extent of excitation in the barrel and to recover residual leakage flux energy left in the barrel. The impact of commutation can be expressed in terms of reduced launcher power factor in direct analogy to the use of the term in conventional AC machines. A low power factor can be related directly to the combined voltage-current product that the windings must experience that can be several times that of the launcher kinetic power. Although the apparent or complex power, in and of itself, does not imply low efficiency, it does require some source of reactive power. Inductive commutation is unique in that the reactive power is derived from the projectile's motion, and does not require auxilliary power conditioning components. Three examples of inductively commutated coilguns (brush-commutated 9 MJ coilgun, solid state switched coilgun and the quenchgun) are being developed to explore the limits and practicality of high performance coilguns.

Acknowledgements

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