ARMATURE DESIGN FOR COAXIAL INDUCTION LAUNCHERS

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Abstract: The armature design for a coaxial induction launcher is influenced by a large set of highly coupled parameters. The assumptions often employed in coaxial accelerator analysis, such as a uniform or sinusoidal axial distribution of the azimuthal armature current, are unrealistic in induction launchers with monolithic single-turn armatures. In order to better understand the true dynamic behavior of coaxial accelerators, the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has developed a series of computer codes based on the current filament method. By utilizing these performance codes in conjunction with electromagnetic (EM) and mechanical finite element programs, it is now possible to design high performance induction launchers with armatures that can withstand the considerable mechanical and thermal loads inherent in a coaxial accelerator launch.

Simulations of induction launchers with single-turn armatures indicate that the induced current tends to concentrate at the back of the armature, causing excessive heating and typically limiting efficiencies to 10% or less. When the armature geometry is changed to a multiturn configuration, forcing a uniform axial distribution of current, the temperature rise can be reduced by over an order of magnitude. An optimization algorithm has identified several launchers with multiturn armatures that have high stage efficiencies (over 40%) and low armature temperature rises (less than 15 K per stage), which makes a cascaded multistage launcher very attractive.

Once the performance of the accelerator has been defined, the body forces in the armature windings can be determined with TEXMAP, a CEM-UT EM finite element code. This force history influences the geometry and material selection for both the armature winding and its support structure. The current armature package consists of a helical aluminum litz winding, potted in epoxy, and wrapped around a solid 7075 aluminum support cylinder. Preliminary analysis performed with ABAQUS, a mechanical finite element code, indicate that this package will survive a typical launch.

Monolithic vs. Multiturn Armatures

Historically, most attempts at designing a high velocity induction accelerator have incorporated a single turn, monolithic conductive sleeve for an armature. In

order to simplify the analysis of such a design, it is common to assume that the axial distribution of current is either uniform or varies as a half sinusoid along the length of the armature. In addition, the radial distribution of current is often assumed to be uniform throughout the sleeve, or uniform throughout one skin depth at the frequency of interest and zero elsewhere. Detailed analysis of several proposed coaxial accelerators at CEM-UT (using the current filament codes AXICOIL and COILGUN) indicate that both of the above assumptions are incorrect, and can lead to a substantial errors in the predicted performance of induction launchers. Both codes have been verified against existing accelerators built at CEM-UT and the David Taylor Naval Research Center (DTRC).

The set of equations that these codes solve can be derived by considering the induction acceleration of a circular filament, driven in a repulsion mode by another concentric circular filament subjected to an arbitrarily varying voltage [1,2]. The two coupled ordinary differential equations that govern the "stator" and "armature" currents are expressed with Kirchhoff's law:

$$V_s = I_s R_s + L_s \frac{dI_s}{dt} + M_{sa} \frac{dI_a}{dt} + I_a v \frac{dM_{sa}}{dz}$$

$$0 = I_a R_a + L_a \frac{dI_a}{dt} + M_{as} \frac{dI_s}{dt} + I_s v \frac{dM_{as}}{dz}$$

where

- V_s = voltage applied to stator
- I_s, I_a = stator and armature currents
- R_s, R_a = stator and armature resistances
- L_s, L_a = stator and armature self inductances
- M_{sa} = stator/armature mutual inductance
- M_{as} = armature/stator mutual inductance
(= M_{sa})
- v = velocity

The mutual inductance and its gradient are functions of elliptic integrals [3]. Knowing the currents and armature/stator separation allows direct calculation of the force on the armature:

$$F = I_s I_a \frac{dM_{sa}}{dz}$$

Newton's law then becomes a third differential equation:

$$m \frac{dv}{dt} = I_s I_a \frac{dM_{sa}}{dz}$$

where

$$m = \text{launch mass}$$

If this set of equations is extended from two to "N" filaments, one obtains a very powerful model of a generic coaxial accelerator. A suitable numerical technique (Runge-Kutta, etc.) can be employed to solve these coupled equations, subject to a prescribed voltage waveform and a set of initial conditions (stator and armature currents and temperatures, armature position and velocity). COILGUN is quite extensive, and allows the specification of a winding packing factor, power supply impedance, and temperature dependent material properties. The temperature rise is calculated by assuming that the I^2R losses are dissipated adiabatically in the windings. To demonstrate the errors that can occur by assuming uniform current distribution in a monolithic armature, consider the following single stage system driven by a high voltage capacitor that is crowbarred at zero voltage:

Stator

Inner radius = 1.5 cm
Outer radius = 2.0 cm
Length = 5.0 cm
N = 10 turns
Material = copper litz wire (60% packing)
Resistivity = $1.72 \times 10^{-8} \Omega \cdot m$

Armature

Inner radius = 1.1 cm
Outer radius = 1.4 cm
Length = 5.0 cm
Material = solid aluminum
Resistivity = $2.80 \times 10^{-8} \Omega \cdot m$
Density = 2,700 kg/m³
Conductor mass = 0.0318 kg
Total launch mass = 0.1 kg

Power supply

V = -20,000 V (peak)
C = 125 μF

Initial conditions

Stator current = 0 A
Stator temperature = 293 K
Armature current = 0 A
Armature temperature = 293 K
Armature velocity = 0 m/s
Armature position = 1.0 cm

To force uniform current distribution in the armature, it is modeled as a multiturn winding with 100% packing, having a thickness equal to that of the annular monolithic armature. Alternatively, it can be modeled as a similar winding with a thickness of one skin depth (approximately 0.66 mm at this discharge rate). These results can be compared to more accurate, yet computationally intensive, solutions that model nonuniform current diffusion effects with many parallel coaxial current filaments (table 1).

Table 1. Simulation results for various monolithic armature models

	Current Distribution	Thermal Effects	Peak Stator Temperature (K)	Peak Armature Temperature (K)	Peak Velocity (m/s)
1	Uniform (thick)	No	556.8	394.5	382.5
2	Uniform (thick)	Yes	561.2	415.4	365.5
3	Uniform (thin)	No	529.5	1,543.1*	282.0
4	Uniform (thin)	Yes	522.0	1,984.4*	110.6
5	Nonuniform (9 filaments)	No	552.1	914.8**	327.8
6	Nonuniform (9 filaments)	Yes	553.1	1,105.6**	271.5
7	Nonuniform (19 filaments)	No	551.3	1,220.4**	324.9
8	Nonuniform (19 filaments)	Yes	551.7	1,289.9**	270.2

* exceeds melting temperature of aluminum (750 K)

** exceeds melting temperature of aluminum at trailing edge

These results demonstrate that it is incorrect to assume that the currents in a monolithic armature are uniformly distributed throughout the entire armature. The most detailed model (#8) shows considerable heating at the rear of the armature, due to high current densities. The nonuniform current density and temperature distributions in the armature are shown in figures 1 and 2 for $t = 15.5 \mu s$ and $t = 134.6 \mu s$. Armature velocity is shown in figure 3. Note the fairly significant deceleration that occurs after the armature reaches peak velocity, a phenomenon known as "armature capture". Results from the EM finite element analysis indicate that the peak magnetic field in this launch is over 55 T, and occurs in the air gap between the armature and stator. In a coaxial accelerator armature, this large axial (z) field interacts with the azimuthal (θ) current, and produces a large radial (r) crushing force. It would be extremely difficult, if not impossible, to design an armature that could sustain such a high magnetic field for any significant length of time.

(a) Current distribution (kA)

(b) Temperature distribution (K)

Figure 1. Current and temperature distribution at $t = 15.5 \times 10^{-6}$

(a) Current distribution (kA)

(b) Temperature distribution (K)

Figure 2. Current and temperature distribution at $t = 134.6 \times 10^{-6}$

2604.0066

Figure 3. Armature velocity vs. time (simulation 8)

Even though the results of these and many other simulations show that one cannot always analyze a simple launcher with a simple model, they do point to an alternative armature design, in which the current is induced in a helical winding rather than a solid conductive sleeve. A multiturn armature is certainly a more difficult device to fabricate, since it must be shorted on itself, and the windings must withstand tremendous forces in a high velocity shot. Nevertheless, the benefits are tremendous. In the past year, CEM-UT has developed and verified an optimization code (OPTJA2) that has pinpointed many launcher designs with efficiencies over 40%. Construction has begun on a 60 stage 45 mm diameter launcher, which is expected to accelerate a 340 g, multiturn armature to 2,000 m/s, using a switched 1.5 MJ capacitor bank as a power supply. Each stator stage is optimized for its particular set

of initial conditions, such as armature temperature and velocity. Typical stage efficiencies (kinetic energy increase over initial capacitive energy) are over 48%, but power supply losses are expected to bring the whole system efficiency down to around 45%. The armature temperature rise will be about 8 K per stage, with peak magnetic fields less than 25 T. Details about this launcher are discussed by Ingram, et. al., in these proceedings.

Mechanical Design and Fabrication of Multiturn Armatures

The primary difference between a multiturn stator and a multiturn armature lies in the fact that the armature must be shorted on itself in order for current to flow. This can be accomplished in at least two different ways. The armature can be wound with long leads that are routed down the centerline and connected to each other (fig. 4), or it can be wound in two layers from one continuous winding, the ends of which are connected together on the armature surface (fig. 5).

In addition to large acceleration forces that may try to shear the windings from the support structure, an induction launcher armature is subjected to a large crushing force that arises from the axial magnetic field in the air gap. This crushing force can be approximated as a magnetic pressure [4]

$$p = \frac{B_z^2}{2\mu_0}$$

where

B_z = axial magnetic field

μ_0 = magnetic permeability of free space

This load closely matches more detailed calculations of the EM body forces in TEXMAP, as long as the armature winding is relatively thin.

2604.0067

Figure 4. Multiturn armature shorted at center line

2604.0068

Figure 5. Multiturn armature shorted on surface

If the armature support structure is annular to allow the winding leads space in which they can be joined, the structure is weakened. The stress distribution in cylinders subject to an external pressure is well documented [5]:

Solid cylinder: $\sigma_{\text{mises}} = p$

Annular cylinder: $\sigma_{\text{mises}} \geq 2p$ ($= 2p$ as $r_i \rightarrow 0$)

The von Mises stress invariant is compared directly to the yield stress of the support material to determine if yield has occurred. The minimum von Mises stress of $2p$ in an annular cylinder can be thought of as a stress concentration effect, and reduces the allowable magnetic field by at least 41% for a given material. For this reason, it is desirable to wind a two-layer armature and solder the ends together on the surface.

At this time, the winding material of choice is aluminum litz potted in epoxy. Unconstrained uniaxial compression tests (transverse to the litz wire) show that this material typically fails at loads around 10 ksi, but has repeatedly survived loads of over 60 ksi when constrained in a steel jacket. The constraining jacket causes the litz sample to be stressed in a "hydrostatic" state, which results in a low von Mises stress. This is encouraging, because a well-constructed armature will provide stiff support to the winding on all sides, and the winding should be stressed in a similar "hydrostatic" state by the magnetic pressure. It appears that most efficient designs in the 45 mm regime have peak axial magnetic fields in the 25 to 30 T range, which corresponds to compressive loads in the 36 to 52 ksi range.

Fabrication of these armatures is considerably more time consuming than fabrication of a monolithic sleeve. In order to provide stiff support to the helical winding (aluminum litz wire), a spool with helical end plates is required (7075 aluminum). The litz wire is wrapped with insulating tape (fiberglass) and wound on the spool, after

which the ends are compressed in crimp joints that are then soldered to each other. The whole assembly is then placed in a vacuum-rated mold, and degassed at around 2 torr for several hours, preferably over a day. This whole mold is then vacuum impregnated with epoxy and baked in a 24 hour cure cycle.

Conclusions

It has been demonstrated that, in a coaxial induction accelerator, multiturn armatures offer significant advantages over monolithic solid sleeves. The overall armature temperature rise can be reduced by over an order of magnitude, and efficiency can be increased from around 10% to over 40%. Solid armature support structures appear to offer more promise than annular designs, since they can tolerate 41% more magnetic field. However, solid structures require shorting the armature leads to each other on the armature surface, rather than on the centerline.

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