INDUCTION LAUNCHER DESIGNS CONSIDERATIONS

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Abstract: Research, prompted by increased interest in induction accelerators for space and for military applications has shown that their advantages (contactless armature, high theoretical efficiency) with respect to their railgun counter parts are balanced by strong requirements on their power supply characteristics. In fact at each moment, the stator barrel, the projectile and the power supply must form a carefully tuned system, capable of achieving a uniform and efficient electromechanical energy conversion with no contacts or feedback control.

The tuning of the system changes during the launch since the parameters are changing in order to achieve an almost constant acceleration and uniformly distributed force and heating in the moving armature as a means of surviving the mechanical and thermal stresses.

In the recent period, the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has introduced new concepts in the design of induction accelerators and their power supplies in order to improve the performance levels and the feasibility of such devices: The Distributed Energy Store for Induction Launchers (DESIL) introduces a piecewise rising frequency power supply in which each elementary generator (normal compulsator or rising frequency generator, RFG) has a different base frequency.

Introduction

In a previous paper on induction launchers[1] two essential features affecting the design of such accelerators were emphasized:

a) The traveling stator field produced by the stator winding must accelerate at nearly the same rate at the projectile, maintaining the slip at a preferably constant value, in order to maintain a high efficiency. An accelerated wave is obtained if the power supply energizing the stator has a continuously increasing frequency from the beginning to the end of the launch, or if the polar pitch is continuously increasing, or by using a combination of both frequency and polar pitch variation.

b) The analytical tool of equivalent circuits and the theory and methodology of design, related to such tools must undergo significant modifications for the induction accelerator which is ironless and "of long stator" (short secondary) construction.

This means that even in the case of a launcher with accelerated traveling magnetic wave, the efficiency will remain low since the electromechanical energy conversion process takes place only in the small part of the barrel which contains the projectile at that moment of time--while the entire stator is being excited.

As remedy to such effect a Distributed Energy Store for induction launchers has been proposed elsewhere [2] such that power supplies with different frequency range, supply definite modules of the stator, only for the time interval when the stator contains the armature. The paper will exemplify such principle

outlining the design of a coaxial accelerator for use in a Hypersonic Real Gas Facility which was performed by CEM-UT for NASA.

In space and military applications very severe constraints are imposed on the length of the barrel while the performance parameters such as muzzle velocity and specific energies stored in the projectile are considerably increased in comparison to solid propellant guns. The electromagnetic launcher can counterbalance such effects by evenly distributing the mechanical and thermal stresses. The frequency and voltage profiles in time and along the barrel are paramount in achieving the desired force and stress distribution. Electrical machines which can perform this task (such as Rising Frequency Generator in its variants "mechanical" and "electrical" RFG) are discussed in this paper.

Accelerated Traveling Fields

The synchronous speed (VTF) of a traveling (linearly advancing) field is given by the relation

$$V_{TF} = 2\tau f \quad (1)$$

where

τ = polar pitch of winding (m)
 f = frequency of the power supply (Hz)

In a previous paper published by the authors [1] as well as in [2] is shown in detail the necessity of continuously increasing the synchronous speed as the projectile accelerates, otherwise, for a constant speed of the traveling field the losses in projectile are superior to the kinetic energy stored in the armature for the entire launch period.

$$W_{PJ1} = \int_0^{v_{rg}} m_p (v_{TF} - v) dv = m_p (v_{TF} \cdot v_M - \frac{v_{rg}^2}{2}) \quad (2)$$

where

W_{PJ1} = losses in the projectile (J)
 m_p = projectile mass (kg)
 v_M = projectile output velocity
(at the muzzle of the launcher, m/s)
 v = instantaneous projectile speed (m/s)

Assuming that the frequency is increased stepwise, only two stage still produce a substantial improvement in efficiency. For a two-stage system (fig. 1)

$$W_{PJ2} = \int_0^{v_1} m_p (v_{TF1} - v) dv + \int_{v_1}^{v_{rg}} m_p (v_{TF2} - v) dv \quad (3)$$

where

W_{PJ2} = losses in the projectile for a two-stage system (J)
 v_{TF1}, v_{TF2} = velocities of the traveling field (m/s)

v_1 = intermediary speed (m/s)

Assuming that the intermediary speed $v_1 = \frac{v_{rg}}{2}$
and $v_{TF2} = 2v_{TF1}$

Figure 1. Two-stage acceleration

$$W_{PJ2} = \frac{m v_{rg}}{2} \left(\frac{3}{2} v_{TF2} - v_{rg} \right) \quad (3a)$$

The losses will continue to decrease with the increase in the number of stages, being minimal when the frequency increases continuously during the launch.[3,4]

However, the coaxial induction accelerator represents a strong inductive load and even if a power supply will energize it with the exact frequency time profile, the efficiency and the utilization of the power supply will remain low, despite of minimization of losses in the secondary. In other words, the power supply is poorly utilized once it has to energize the entire stator barrel at the time of the launch and has to be sized for the highest voltage, which is actually necessary only for the last six coils of the stator barrel (assuming a three-phase system). The voltage applied to the stator barrel is in phasorial notation

$$\underline{V}_S = R_S \underline{I} + j X_S \underline{I} + \underline{E}'_b \quad (\text{per phase}) \quad (4)$$

where

- $\underline{I}$ = the current phasor, assumed to have constant rms value during the launch (A)
- R_S = the active resistance of the stator (Ω)
- $X_S = \omega L_S$ the inductive reactance of the entire stator phase (Ω)
- $\underline{E}'_b$ = the back (motional) electromotive force, referred to the primary winding

The reactance of the stator barrel, varies proportional to the frequency of the power supply

$$X_S = \omega L_S = 2\pi f L_S \quad (5)$$

being $X_{Smin} = 2\pi f_{min} L_S$ at the beginning of the acceleration and reaching its maximum value $X_{Smax} = 2\pi f_{max} L_S$. In the same manner, the back electromotive force E_b , varies linearly from zero to the maximum value E_{bmax} , corresponding to the muzzle velocity at the end of the launch. The back EMF is being seen by

the power supply as referred from the secondary to the primary by multiplication with the ratio of the corresponding number of turns.

A segmented design of the stator in which each, galvanically independent, module is energized by an independent ac power supply for only the time interval in which the projectile passes through the respective module -- is strongly suggested by the relations (4) and (5) and by the equivalent circuit shown in fig. 2.

Figure 2. Equivalent circuit of the linear induction accelerator (long stator variant)

This segmentation, as a distributed energy store induction launcher DESIL was proposed by authors in [2] and permits an important reduction in the reactive power oscillating between the launcher barrel and the power supply, a reduction in total size of the power supplies necessary to feed the launcher, and a reduction in mechanical structure and insulation requirements in the system.

In the same time the rising frequency necessary in order to satisfy the relation [1] in order to reduce the slip losses in the secondary is satisfied stepwise, the consecutive generators having different frequencies $f_1 < f_2 < \dots < f_n$, where f_n corresponds to the first and f_2 corresponds to the last power supply.

Assuming that the stator is divided in n equal segments, and the acceleration of the projectile is nearly constant along the barrel, the reactive energy per segment will increase as the sequence:

$$\frac{1}{n^2}; \frac{1}{n(n-1)}; \frac{1}{n(n-2)}; \dots \frac{1}{n(n-n+1)} \quad (6)$$

In this way, the reduction in comparison with the case when the whole stator is energized during the entire launch, can be characterized by the reduction factor ϵ

$$\epsilon = \frac{1}{\frac{1}{n^2} + \frac{1}{n(n-1)} + \frac{1}{n(n-2)} + \dots + \frac{1}{n}} \quad (7)$$

The reduction factor is 1.64 for a division of the stator in three parts, increasing to 2.2 for a divi-

sion in five parts, assuming that the base frequency of the generators is linearly increasing.

Figure 3 is an illustration of the distributed energy store induction accelerator approach. In it, the voltage and the frequency are varying stepwise, from segment to segment, and decrease in time along every individual segment. Such decrease has to be compensated by change in the polar pitch. For this coaxial accelerator, the solution to using four compulsators as the power supply was chosen, each of them powering a fourth of the stator. The machines discharge sequentially when the projectile is passing through the respective accelerator segment, but only half of the stored energy is transmitted to the stator at the moment when the projectile exits the segment. The frequency and voltage of the power supply drop, at this moment at 70% of their initial value. The stator winding (the barrel) is designed to sustain the heating due to the joule losses in case that the whole energy stored in the power supply is discharged in it. The magnitude of the inductive reactance of the barrel segment and internal reactance of the generator are diminishing during discharge, thus allowing the current to remain nearly constant. However, the variation of the polar pitch decreases the effectiveness of the design. Thus, a further improvement is the use of a more complex power supply, the rising frequency generator (RFG).

Figure 3. Sequential discharge of staged high frequency compulsator, as power supply or the induction coaxial accelerator

The Rising Frequency Generator (RFG)

A novel machine concept in which the voltage and the output frequency are increasing during discharge, thus satisfying the requirements of the coaxial accelerator has been proposed by CEM-UT. Such a machine will power a segment of the barrel (in order to reduce the reactive power); but, its voltage and frequency increasing (see dotted lines in fig. 3), the barrel can be made with equal polar pitch, assuring an optimal design for the system.[5]

The RFG is actually a cascade of two generators having a common shaft: one is a compulsator which supplies the excitation, the other is the RFG proper (see fig. 4) which in its "mechanical variant" has an outer rotor of higher inertia (J_S) rotating initially at a velocity ω_S slightly higher than that at the inner rotor ω_R , which has a lower moment of inertia (J_R) -- both rotors spinning in the same direction.

Figure 4. Rising frequency generator

At the beginning of the cycle, the compulsator discharges into the RFG excitation winding while, the RFG output is connected to the load (accelerator barrel). As the two common shaft rotors are slowing down (due mainly to the compulsator pulse into the excitation winding) the differential speed ($\omega_S - \omega_R$) is increasing. Then the frequency and the voltage applied to the load are increasing, achieving the desired effect.[6]

In a design example, performed at CEM-UT, the initial frequency produced by RFG was 433 Hz increasing to 2,700 Hz at the end of the discharge cycle, while the output voltage increased from 4.3 kV to 27.5 kV.

The initial frequency seems higher than desirable at the beginning of the launch, but the resulting low efficiency occurs only at the very beginning of the acceleration and plays an almost negligible role in the overall efficiency. The basic machine frequency is high (4.335 kHz) and requires special consideration of the armature conductor construction, shielding, etc. The influence on the design of a large number of poles has been offset by the large diameter and the resulting polar pitch, $\tau = 9.24$ cm or $2\tau = 18.48$ cm, which is manageable. The machine has a "slim" construction--the active length being only 0.36 m for the machine and 0.36 m for the auxiliary alternator (self-excited synchronous machine operating in pulsed mode) necessary to provide the excitation for the RFG. The presence of the rotor of the auxiliary alternator on the same shaft as the inner rotor of the RFG is essential in assuring the desired cycle of the operation and the desired power flow for the system. The inertia of the rotor of the auxiliary alternator counts in the discharge pulse. The self-excited alternator has both three-phase and single-phase armature winding, electromagnetically decoupled. A schematic representation of the general circuit is shown in figure 5. This circuit functions as follows: the power supply on the left-hand side of the circuit provides a pulse of current to the self-excited alternator excitation (stator) winding. As this initial current produces flux in the alternator air gap, the three-phase alternator rotor winding, begins to generate an alternating voltage which is rectified by the stationary self-excitation rectifier and the current I_a is supplied to the alternator stator winding causing the alternator to self-excite (fig. 6b). As the alternator self-excites, the voltage produced by the single-phase armature winding (V_A) rises as shown in figure 6a. As V_A reaches a peak value after 220 ms, it is connected to the RFG rotor winding through a making switch producing the current shown in figure 7a.

Figure 5. Schematic of a rising frequency generator excited compulsator excitation mounted on a common shaft ("mechanical" variant)

Figure 6. a) compensated alternator voltage V_A
b) excitation current

After allowing 1 ms for the excitation current in the RFG, to rise, the RFG output is connected into the stator of the induction accelerator providing the required voltage frequency and current for the load (fig. 7b and c).

An "electrical" variant of the Rising Frequency Generator can be built by replacing the outer rotor by a rotating field, produced by an "exciter" machine. The same general principle applies, the system is a

Figure 7. RFG performance in driving a coaxial induction accelerator (excitation current, RFG output voltage, and RFG output current)

cascade of electrical machines, on a common shaft (fig. 8). The two rotors are slowing down due to the excitation train of pulses in the RFG, the frequency, and the voltage applied to the load are increasing.

In order to diminish the effect of the slowing down on the exciter frequency, the direction of rotation of its traveling field is opposite to the direction of the rotor.

$$f_{ex} = \frac{P_{ex}(n_{stex} + n_{roter})}{120}$$

Figure 8. Three-phase rising frequency generator (RFG)
"electrical variant"

where

f_{ex} = exciter frequency
 P_{ex} = number of exciter poles
 n_{stex} = rpm for the exciter stator field
 n_{roex} = rpm of the exciter rotor

Coaxial Accelerator for Space Applications

An illustration of the above considerations is a preliminary design performed by CEM-UT for NASA, Langley, of a coaxial induction accelerator for a hypersonic real gas facility. Important in this design were the velocities at which the secondary has to be accelerated 6 km/s and 11 km/s, representing the low earth orbit launch velocity and respectively the escape velocity. Of significance is the large energy transferred to the projectile 252 MJ for the 6 km/s launch and 897 MJ for the 11 km/s launch.

This design has led to a passive, nonfree, modular coaxial accelerator, 188-m long, capable of launching a load of 14 kg at 6 km/s at a nearly constant acceleration of 10,000 G. Provisions have been made so that the same accelerator can also launch the same 16 kg load at 11 km/s at a constant acceleration of 33,000 G by changing a few connections in the accelerator barrel dividing the stator in a larger number of modules and increasing the number and sizes of electrical machines used as pulsed power supplies for the system.

Figure 9 shows the induction accelerator (starter, stator barrel and power supply) as well as a diagram of frequency variation during the sequential discharge of the four power supplies. The starter coil represents a 0.2-m long preliminary stage of the accelerator inducing the initial secondary current in 0.066 s, acting both as a pulse transformer and a slow (10 m/s) injector of the projectile. Special synchronization is required between the injection, and the position of the traveling magnetic wave. The launcher proper is divided into four electrically independent but magnetically series connected segments. Each part is 48-m long and has 14, 8, 7, and 7 segments, each segment having a different pole pitch in order to match the power supply instantaneous frequency with

the velocity of the armature passing through the respective segment.

Finally, an end coil, 6-m long performs the "smoothing" of the magnetic end effects of the traveling wave. Then, the real length of the accelerator is approaching 200 m. The standard unit coil which forms the base for the modular construction is 0.15-m long. The power supply is configured using the principle of stepwise frequency increase, as in relations (6) and (7).

Four compulsators are used, storing 179, 211, 242 and 274 MJ. While the projectile is passing through an individual segment only half of the stored energy is used. The frequency and voltage of the alternators drops to 70% of the initial value (for instance, in the last stage the frequency drops from 480 to 340 Hz). The initial voltage (runs) of the electrical machines varies from 8.75 kV for the first generator to 30 kV for the fourth one. Table I shows the characteristics of the four compulsators used as distributed power supply. The maximum apparent power seems very high for comparison. We mention that CEM is under contract with the U.S. Army to build a self-excited compulsator with a voltage of 8,000 V and a current equal to 3.6×10^6 A, storing 236 MJ of kinetic energy. The apparent power of the machine is

$$S = 8.5 \times 10^3 \times 3.6 \times 10^6 = 28.8 \times 10^9 \text{ VA} = 28.8 \text{ GVA}$$

which is in the range of values required for the four compulsators used as power supply for this project.

For the 11 km/s variant the same coaxial accelerator will be split in eight parts of 24 m each and several connections will be modified. Eight compulsators, of increased frequency will be used. Table 2 gives the characteristics of these generators.

If RFGs are to be used, the frequency curve (see fig. 8b, the broken line characteristic) is continuous, and the barrel winding has a uniform polar pitch, leading to a better design.

The question which arises is the trade-off between a more complex machine (RFG) versus increase in the efficiency of the launch, almost uniform acceleration, and uniformity of the launcher construction.

Figure 9. a) induction accelerator: starter, stator barrel and power supplies
 b) frequency variation during discharge for compensated pulsed alternators

This problem needs a careful evaluation which is being performed presently at CEM-UT.

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