Comparison of a Single Pulsed Alternator with Two or More in Parallel for Driving a Railgun

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Abstract

Pulsed alternators, particularly multipole, multiphase machines incorporating a flexible rectifier/inverter subsystem, can be used for powering large dc railguns [1]. Such machines are able to store energy for several shots; presently, these designs generally lead to much lighter and smaller systems than those designed with other pulsed power options. For large caliber railguns that are designed to accelerate projectiles to 10 MJ or more, however, the reaction torque associated with a pulse discharge from a single alternator can be excessive. If two (or any even number) of counter-rotating alternators are used, the torque on the overall structure can be virtually eliminated. Use of two identical counter-rotating machines also overcomes some of the gyroscopic effects on the vehicle.

Most practical systems, therefore, utilize an even number of multipole machines. This raises several questions that must be answered. How does this mode of operation affect the energy density of the system? How must the machines be connected together, in series or parallel? What are the issues involved in each configuration? Must the field coils of the two or more machines be connected in series or in parallel? If the machines must operate in parallel, at what location must they be linked? This paper attempts to define the issues involved in answering these questions.

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Pulsed alternators, particularly multipole, multiphase machines incorporating a flexible rectifier/inverter subsystem, can be used for powering large dc railguns [1]. Such machines are able to store energy for several shots; presently, these designs generally lead to much lighter and smaller systems than those designed with other pulsed power options. For large caliber railguns that are designed to accelerate projectiles to 10 MJ or more, however, the reaction torque associated with a pulse discharge from a single alternator can be excessive. If two (or any even number) of counter-rotating alternators are used, the torque on the overall structure can be virtually eliminated. Use of two identical counter-rotating machines also overcomes some of the gyroscopic effects on the vehicle.

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Introduction

For a given load, it is clear that the total maximum power required by the load must remain the same, independent of the connection alternatives shown in Fig. 1. Therefore, each of the dual machines must generate half the total power that the single machine generates. This can be accomplished by either halving the current (as in the parallel connection) or by halving the voltage (as in the series connection). The internal structure of the machine will vary in response to the connection choice.

Penalties and other ramifications are associated with the dual or multi-alternator configurations, and will be discussed later in this paper. First, however, it is instructive to examine the pertinent scaling properties using simple models for the railgun, busbars and alternators.

Fig. 1: Two connection schemes for a dual machine system

Simple Models

Consider a railgun with a performance comparable to a very large tank-mounted 120 mm gun that is designed to fire a projectile with a kinetic energy of 32 MJ. The gun is taken to be 7 m long and so must be fed with a relatively constant current of $I = 4.3$ MA (approximately, the projectile energy $E_p = 0.5I^2L'l$, where $L' = 0.5$ $\mu\text{h/m}$ and $l = 7$ m). The current of 4.3 MA can be

established within the first millisecond while the projectile is near the muzzle, using a relatively modest source voltage. This is because the effective load at this point is just the internal inductance of the alternator and converter in series with the inductance of the busbars and the almost-shortened railgun. For a relatively constant acceleration of the projectile to a velocity of $v = 2,500$ m/s, a source voltage is required that increases from a few hundred volts to 6.7 kV at muzzle exit within 5 ms. Of the muzzle-exit voltage, 5.4 kV is the “speed” voltage ($iL'v$) which is needed to drive the projectile and increment the magnetic energy from the rail current behind the projectile. The remaining 1.3 kV is the electromagnetic force (EMF) associated with the impedance in the circuit. (Actually, the peak voltage must be slightly higher than 6.7 kV in order to facilitate control of the source voltage, but in practice, the constant current requirement can be relaxed a little in favor of a lower muzzle velocity or final peak voltage.)

Impact on Energy Density

For the purpose of this analysis a single, self-excited, drum-type alternator is assumed. It is designed to achieve the best performance allowed by state-of-the-art and available materials. Many validated simulations have shown that it is possible to design complete drum-type machines (including rectifiers, switches and auxiliaries that allow self-excitation of the field and recovery of magnetic energy after each discharge) having a delivered projectile energy density (DED_p) of 10 J/g. The DED_p is defined in this case as the kinetic energy delivered at the muzzle divided by the total mass of the machine. (This is generally about a factor of two smaller than the more commonly defined DED, which features energy delivered to the *breech* rather than to the *projectile*.) These machines can store enough energy to fire two shots before the rotor speed decreases to the point where there is insufficient source voltage to maintain an efficient charge-up of the field coil and a subsequent gun discharge.

This single-machine design is presumed to be operating at the limits dictated by the thermomechanical properties of the materials used. These limitations are retained in the design for a dual machine, in which each of two machines has the same rotor radius and angular speed as the

single machine, but only half the length. Each small machine now has (neglecting the extra end connections on the windings and the auxiliaries) approximately half the mass of the larger one. In a drum machine, the EMF is derived mainly from the axial armature conductors crossing the radial magnetic field; therefore, the source voltage from each half-machine is only half that of a single machine. Two configurations are possible:

- A. The two machines can be connected in series to retain the original voltage.
- B. Each individual machine can be rewound to double the voltage and halve the current output.

For the purpose of the discussion on the energy density, it is assumed that the machines are connected in parallel.

Within the state-of-the-art for insulation, the machine described in option B is created by increasing the number of axial conductors and turns in the armature winding by a factor of two. In order to retain the same thermal and mechanical behavior, the area of the armature conductors is reduced by a factor of two. Apart from end effects, the smaller machines now have the same mass per unit length as the large single machine. The resistance of the small-machine armature is now twice that for the large machine; in the parallel configuration, however, it only contributes half the current to the load. Also, the ohmic losses are proportional to i^2R , so the thermal losses in each half-machine are just one half of the losses experienced in the large single machine.

A pair of counter-rotating half-length drum-type machines, with their armature turns modified in the way described, will provide the same current to the railgun and accelerate the projectile to the same energy as would the single, full-length machine. Furthermore, the thermal and mechanical features of the pair are identical to those of the single machine, apart from end effects. In addition, each of the dual machines can be halved again (length halved, armature windings doubled) to create a four-machine system that (apart from end effects and insulation-driven detail) will deliver the same current and energy to the railgun. It will also be subject to the same thermal and mechanical stresses as the single large machine, so that the delivered energy densities

(DED_p) are nominally the same for the specified single, dual and four-alternator systems (see Table 1, rows 1 through 6).

When one of the dual machines alone is connected to a 7 m railgun, it is able to deliver only half the current due to thermal limitations, and thereby only a quarter of the energy to a projectile (8 MJ - see Table 1, row 7). The DED_p for a lone half-length machine is therefore half that for the dual system, or 5 J/g. But this single configuration has excess voltage and enough stored energy to fire twice as many shots, as shown in row 8 of Table 1. The excess voltage could be used, in principle, to fire a lighter projectile to the same energy (8 MJ) but at a velocity up to 5,000 m/s. Rows 7, 8, and 9 of Table 1 (last column) show similarly expanded results for a four-machine system.

Table 1: Nominal single and multiple machine performance characteristics

1	No. of alternators	1	2	4
2	Muzzle energy per shot, E_s (MJ)	32	32	32
3	Mass of system (kg)	3,200	3,200	3,200
4	Delivered energy density, DED_p (J/g)	10	10	10
5	Energy stored per machine (MJ)	240	120	60
6	Current per machine, I_M (MA)	5	2.5	1.25
7	Muzzle energy per shot for individual machine, $E_{s,m}$ (MJ)	32	8	2
8	No. of shots for individual machine	2	4	8
9	Muzzle velocity capability of each machine (m/s)	2,500	5,000	7,500

This analysis, as stated earlier, discounts the end effects of the mechanical construction of the multiple machine, such as additional mass from added bearings and changes to the structure and auxiliaries. In order to quantify the impact of these factors, specific designs must be examined. If the single, base machine is relatively long (1.5 m), a 10% reduction in DED_p is estimated for the dual machine, relative to the corresponding single machine. As the number of parallel machines increase, the end effects very rapidly become increasingly important.

Similar considerations will apply to disk-type alternators, and similar results may be expected. In this case, the end effects involve the amount of axial space and material that has to be added to accommodate the magnetic circuit, as opposed to the completion of the electrical windings. Also, depending on details of the design, there may be changes to the mutual coupling of the field and armature windings. In the case of the disk machines, a better starting point is probably a single-disk module. Multiple modules can be added in parallel, with benefits to the overall DED_p comparable to those for the drum topology.

Choice of Series or Parallel Connection

Fig. 1 shows two possible ways to connect an even number of machines. The series connection has the advantage that if the two machines are slightly out of phase during the synchronization process, there are no circulating currents between the machines. The total voltage available in that case may be slightly lower, a condition which can be compensated by an appropriate adjustment in the field coil current. The total gun current must pass through each machine; therefore, the buswork may be more massive and the terminations may occupy more space on the machine. The armature winding of the series machine (which must provide half the total voltage) has fewer turns per pole and a larger cross section in order to accommodate the full gun current. Since these armature windings are made from litz wire, there may be difficulty encountered in fabricating these wires once the cross-section gets too large.

With the parallel operating scheme, there is an additional question that must be answered: where must the connection between the two machines be made? If the connection is made at the terminals of the machine, a slight phase difference between the two machines may result in circulating currents between them. The armature windings in each machine must generate the full gun voltage but carry only half the gun current. This requires more turns in the armature winding and higher voltage within each machine, and impacts the insulation. The armature windings are lower in cross sectional area and are therefore easier to fabricate.

Field Coil Connections for Multiple Machines

There are two aspects to the operation of a pulsed alternator, i.e., charging the field coil and discharge into the gun. The charging of the field coil can be accomplished independently for each machine. In this case, the field coil is optimized for the most efficient charging with each machine, be it designed for series or parallel discharge into the gun. The drawback of this scheme is that the individual machines may attain the required current levels at slightly different times, and the faster machines would have to wait for the slower ones to catch up. This is a source of some inefficiency, besides causing differentials in speed between the various machines. A more reliable approach would be to connect the various field coils in series and optimize the charging process for this mode of operation. The various armature windings can then be connected in series or parallel at the rectifier to charge the field coil as shown in Fig. 2.

Fig. 2. Connection schemes for the rectifiers of the dual machine system

Synchronization

Running two/several machines in parallel has been very well documented and implemented in utility as well as industry. There are several ways of accomplishing the parallel operation.

ation of the two machines synchronously. The traditional means is to use power selsyns wherein the induction motors driving the two machines are connected in parallel to the same supply and the wound rotors of the induction motors are connected in series to form a synchro-tie configuration. More modern methods can also be employed using vector control techniques [2] or phase locked loops [3] to lock the speed and phase of the two induction motors being driven by variable- frequency drives. The second method has the advantage of not needing the synchro-tie on the rotor windings of the induction motor.

Conclusions

Machine configurations are driven by the need to manage gyroscopic effects and high discharge torques, such that an even number of machines are required for EM gun applications. There is a penalty associated with this scheme, as compared to a single machine, regarding energy density. Table 1 forms an important link in establishing the performance degradation obtained when operating only one machine of a multiple machine system.

Synchronization becomes an important issue when multiple-machine configurations are used. The network topology, motoring scheme, and control system must be chosen carefully so as to facilitate the operation of the multiple machines.

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