Design and Analysis of a Modular Pulsed Alternator Power System for Driving 32-MJ Muzzle Energy Railgun

Shumei Cui, Shaofei Wang, Shaopeng Wu, *Member, IEEE*, Ostanin Sergei Yurievich, and Igor M. Milyaev

***Abstract*— This paper explores the use of pulsed alternators driving a railgun with 32-MJ muzzle energy. A series of modular pulsed alternator power system (MPAPS) with the different number of modules is designed and analyzed based on the scaling laws. The system performances are simulated using MATLAB. Taking into account all system performances, especially the output current pulse-shape flexibility, the MPAPS composed of six alternators is selected. The six modules are divided into three pairs of matched contra-rotating pulsed alternators; each pair has the independent firing time. By optimizing the voltage and the firing time of each pair, a relatively flat-topped current pulse is produced. The average-to-peak acceleration ratio of railgun reaches 0.67. Therefore, this design of MPAPS is an option for a long-range railgun.**

***Index Terms*— Modular, pulsed alternators, pulsed power supply, railgun.**

I. Introduction

In RECENT years, some institutions have been developing a long-range electromagnetic railgun. The largest one is the railgun with the muzzle energy of 32 MJ powered by capacitors by U.S. Navy [1]. Capacitors are used widely in pulsed power application. However, due to a low energy density (2 MJ/m^3), the pulsed power supply is heavy. Compared to capacitors, pulsed alternators have a higher energy density (60 MJ/m^3) [2]. Thus, the pulsed power supply based on pulsed alternators is compact and lightweight, especially for the long-range railgun application.

To achieve a high average-to-peak acceleration ratio and get the maximum use out of the barrel, the ideal current pulse would be the flat-topped current shape. A single pulsed alternator cannot provide the required current to drive the railgun because of the increasing impedance and back electromotive force of the railgun when the projectile moves down the barrel [3]. Therefore, the modular design is adopted as for capacitor banks [4]. This design is defined as modular pulsed alternator system (MPAPS).

This paper designs and analyzes a series of MPAPS with the different number of modules to drive a railgun with 32-MJ muzzle energy. An electric circuit model for a railgun system is built to simulate the system performances. The proper number of modules is determined, and this design is optimized.

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S. Cui, S. Wang, and S. Wu are with the Institute of Electromagnetic and Electronic Technology, Department of Electrical Engineering, Harbin Institute of Technology,Harbin150080, China (e-mail: cuism@hit.edu.cn; wsf200901@163.com; wushaopeng@ hit.edu.cn).

O. S. Yurievich is with the Department of Electro technical Complexes of Autonomous Objects and Electric Transport, Institute of Electrical Engineering, Moscow Power Engineering Institute, Moscow 111250, Russia (e-mail: OstaninSY@mpei.ru).

I. M. Milyaev is with the A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences, Moscow 119994, Russia (e-mail: imilyaev@mail.ru).

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TABLE I
Railgun Parameters

Projectile mass	10.3 kg
Muzzle velocity	2,500 m/s
Rail length	10 m
Muzzle energy	32 MJ

II. Pulsed Power Supply Requirements

The parameters of the railgun with 32-MJ muzzle energy are listed in Table I.

It is assumed that the projectile has a constant acceleration in railgun until the muzzle. According to (1),the average acceleration is 312 500 m/s^2. The acceleration time is approximately 8 ms

$$v^2 = 2\bar{a}l \tag{1}$$

where v is the muzzle velocity, $\bar{a}$ is the average acceleration, and l is the rail length. The average-to-peak acceleration ratio of 0.7 is estimated. Then, the peak acceleration a is 446 428 m/s^2.

The electromagnetic force F is given by

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

where L' is the inductance gradient with the typical value of 0.45 μH/m and $I$is the rail current. A peak current of 4.5 MA is need considering the peak acceleration requirement.

The back electromotive force across the rails V_b is expressed by (3). When the projectile reaches the muzzle of the railgun, the back electromotive force reaches a maximum value of 5 kV. The required voltage of pulsed power supply is 1.5 times the value of breech voltage. Therefore, the required voltage of pulsed power supply is 7.5 kV

$$V_b = IL'v. \tag{3}$$

TABLE II
PARAMETERS OF THE PULSED POWER SUPPLY

Stored energy	400 MJ
Voltage	7.5 kV
Current	4.3 MA
Pulse width	8 ms

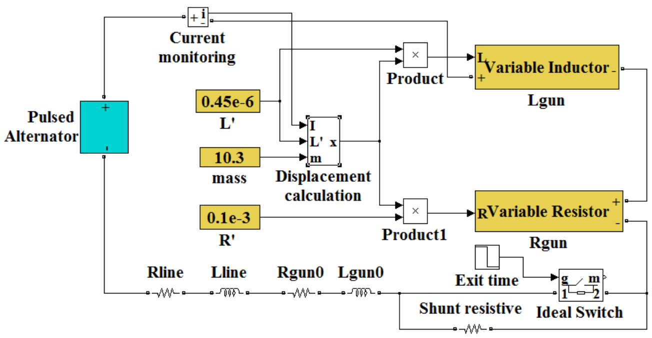

Fig. 1. Model of a pulsed alternator driving the railgun.

The estimated system energy conversion efficiency is 0.2. If the 40% of the rotor kinetic energy is used to drive the railgun, a total stored energy of 400 MJ is needed. Therefore, the parameters of pulsed power supply are listed in Table II.

III. MODEL DESCRIPTION

Our team has developed a co-simulation model of a pulsed alternator driving the railgun based on an FEM combined with the circuit analysis method [5]. However, this simulation can be time-consuming especially for the use of multiple alternators. We build the electrical circuit model using MATLAB shown in Fig. 1 to fast calculation and optimization. This model just shows a single pulsed alternator driving the railgun. Since multiple pulsed alternators connect in parallel [6], a model of MPAPS is achieved by incorporating the pulsed alternator models.

A. Model of the Pulsed Alternator

Based on the basic electromagnetic relationship of the pulsed alternator, the model is built using MATLAB. The model is detailed in [7]. The parameters of pulsed alternators, such as inductance, mutual inductance, and resistance, are measured by finite element model [5].

B. Model of the Railgun

It is assumed that the effects of friction, wind drag and ablation are ignored, so railgun is modeled as a variable resistance and a variable inductance. As the projectile is being accelerated to move down the barrel, this resistance and inductance will cause large variations. The model of projectile displacement x is shown in Fig. 2 according to (4). This model monitors the rail current and calculates the velocity and displacement of the projectile

$$x = \int v dt = \iint \text{adt} = \iint \frac{F}{m} dt. \quad (4)$$

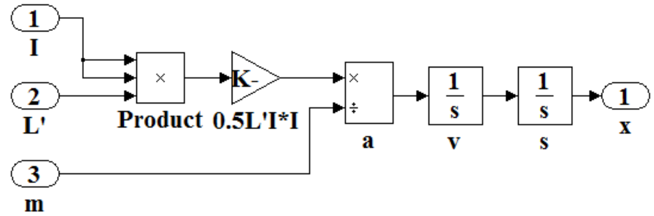

Fig. 2. Model of projectile displacement and velocity.

The variable inductance is equal to $R' \cdot x$, where R' is the resistance gradient of railgun and 0.1 mΩ/m is used in this paper. The product of projectile displacement and resistance gradient is transmitted to a model of controlled voltage source to simulate the characteristics of variable resistors as shown in Fig. 1. The variable inductance is equal to $L' \cdot x$. The same method is used to build the variable inductance model.

In addition, the inherent resistance and inductance of railgun are also considered in the model.

C. Model of Auxiliaries

The auxiliaries consist of the converters, the connecting cables, and the muzzle shunt. The converters are integrated into the model of the pulsed alternator. The converters use the compact lightweight 125-mm thyristor with the thyristor resistance of 75 $\mu\Omega$ [8]. The equivalent resistance of converters is decreased depending on the number of thyristors in parallel.

The cable with a resistance of 240 $\mu\Omega$/m and inductance of 120 nH/m is used. The connection between pulsed alternators and railgun uses 40 cables with a length of 10 m in parallel [8].

When the projectile exits the barrel, large current remains that causes damage to the ends of the rails. Muzzle shunts are designed to manage the current to reduce damage. This paper uses resistive muzzle shunt. Once the projectile exits the barrel, the rail current will flow through the shunt resistive. The value of shunt resistance is 10 mΩ.

IV. PRELIMINARY DESIGN OF MPAPS

This paper uses a four-pole, four-phase, self-excited, drum-type, and air-cored pulsed alternator as a basic model. The shot frequency of six rounds-per-minute is assumed. A series of MPAPS with the different number of modules is designed to meet the railgun requirements based on the scaling laws. The parameters of MPAPS are listed in Table III. We need to take into account these parameters to determine the optimal number of modules.

A. Machine Manufacturing

From the perspective of machine manufacturing including alternator and motor, the small size machine is easier to manufacture. In the nineties of last century, UT-CEM attempted to construct the pulsed alternator with stored energy of 255 MJ to drive a 9-MJ range gun. Unfortunately, the rotor failed [9]. Based on experience and technical level, the pulsed alternator with the stored energy of less than 100 MJ and the motor of a few megawatts is appropriate for manufacturing.

TABLE III
OPTIMIZED FIRING TIME AND VOLTAGE OF EACH MODULE

	Number of modules	1	2	4	6	8
Alternator	Total energy/MJ	400	400	400	400	400
	Energy of each alternator/MJ	400	200	100	66.67	50
	Rotor speed/(r/min)	6000	7559	9524	10902	12000
	Rotor radius/m	0.8	0.635	0.503	0.44	0.4
	Rotor length/m	1.3	1.03	0.82	0.715	0.65
	Voltage/kV	7.5	7.5	7.5	7.5	7.5
	Exciting current/kA	260	206	163	143	130
	Mass of each alternator/kg	16400	8200	4100	2733	2050
	Total mass/kg	16400	16400	16400	16400	16400
Motor	Power of each motor/MW	20	10	5	3.3	2.5
	Mass of each motor	1336	1778	2665	5353	10690
	Total Mass/kg	10688	10688	10660	10706	10690
Converter	Number of thyristors in self-excited	96	128	192	256	256
	Number of thyristors in discharge	736	784	1312	1728	1920
	Total number	832	912	1504	1984	2176
	Total Mass/kg	416	456	752	992	1088
Mass		27504	27544	27840	28080	28176

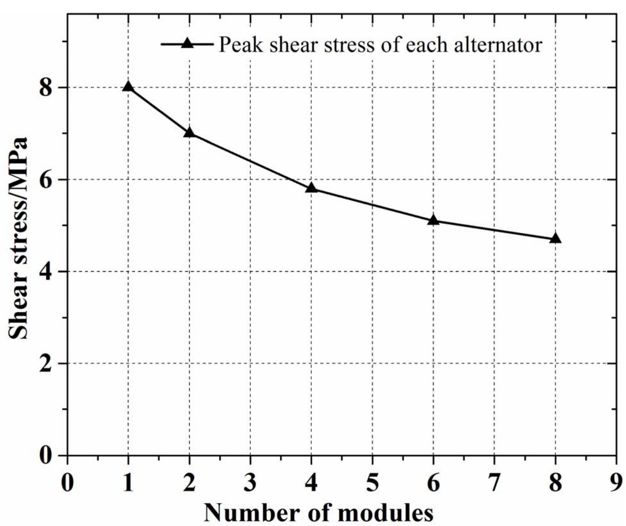

Fig. 3. Shear stress of pulsed alternators in the designs of the different number of module.

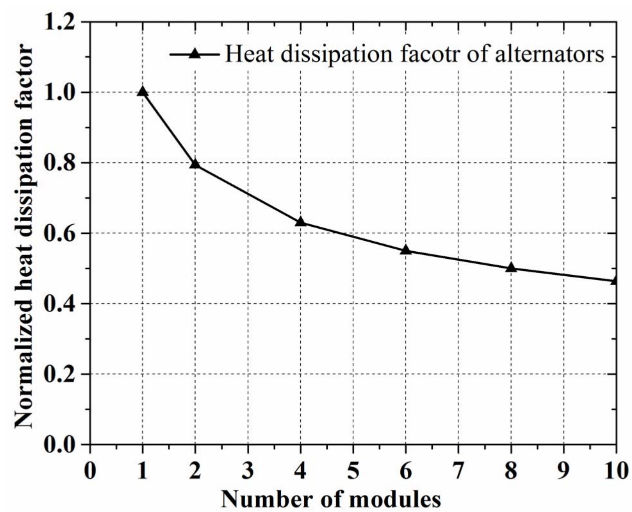

Fig. 4. Heat dissipation factor of pulsed alternators in the designs of the different number of modules.

According to Table III, the number of modules should be greater than four.

Since armature windings of pulsed alternators are mounted on the stator inner surface by epoxy bonding, the shear stress produced by discharge torques limits the alternator size. Fig. 3 shows the shear stress of alternators for the different MPAPS designs. Practical design limits shear stress to about 13.8 MPa based on epoxy bonding techniques [10]. Considering a safety factor of two, the shear stress should be less than 6.9 MPa. Therefore, the candidate number of modules is 6 and 8.

B. Thermal Management

Thermal management is the key technology to the repetitive operation. Fig. 4 shows the heat dissipation factor of alternators in the different MPAPS indicating that heat per unit area required to be dissipated is little in small size alternators. In addition, the faster alternators have higher convective heat transfer coefficients in the air gap [11]. As shown in Table III, the rotor speed increases with the increasing number of modules. Therefore, the heat dissipation of small size alternator is easy. The cooling system with low heat transfer coefficient is used. From the perspective of thermal management, the candidate number of modules is 4, 6, and 8.

C. Specific Energy of System

Table III shows that the system mass increases with the increasing of the number of modules resulting in a maximum reduction of 3% in the specific energy considering the mass of the main components. However, if the mass of the neglected components is considered in detail, such as the extra end connections on the windings in machines, the snubber and trigger in the converter, and the cables, a more reduction of specific energy is produced. (The estimated mass of the system is less than 50 000 kg.) A 20% reduction is estimated if MPAPS composed of eight modules. Thus, the optimal number of modules is 1 from the perspective of specific energy. It also is noted that some applications are insensitive to specific