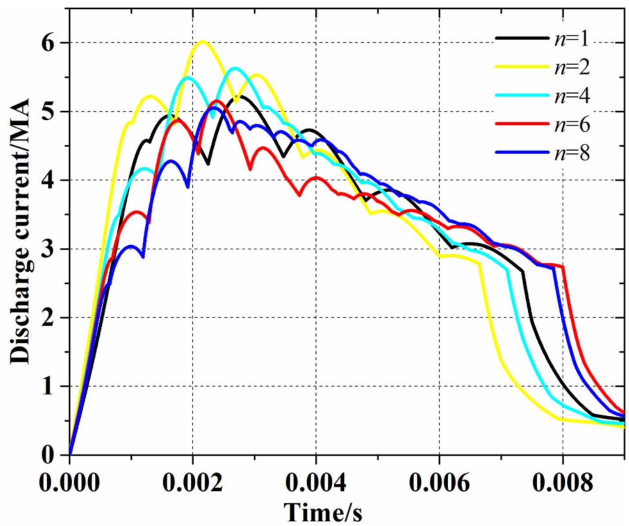

Fig. 5. Discharge current in the designs of the different number of modules.

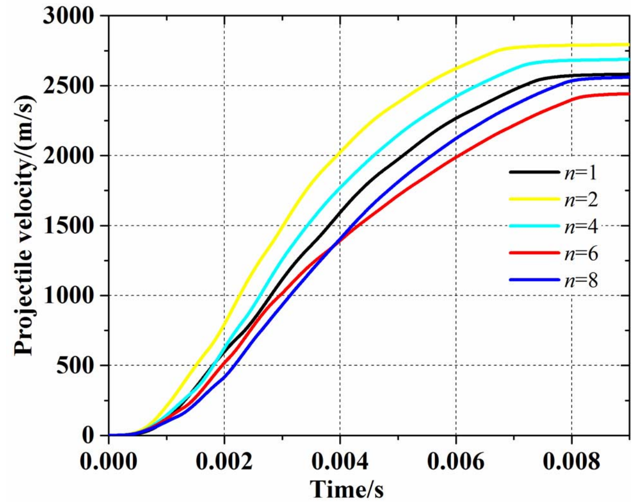

Fig. 6. Projectile velocity in the designs of the different number of module.

energy such as shipboard. The reduction in specific energy is insignificant.

D. Reliability and Complexity

Reliability and complexity are difficult to be quantitatively analyzed. The more modules can provide redundancy and the associated fault tolerance to improve the system reliability. However, with the increasing of the number of modules, system complexity increases, and synchronization control is complicated. Therefore, the candidate number of modules is 4 and 6.

E. Output Current Pulse-shape Flexibility

The ideal current pulse shape for the railgun load is a flat-topped shape to achieve the best performance of average-to-peak acceleration ratio. The load impedance increase as the projectile moving down the barrel, so a single pulsed alternator cannot generate this desired current pulsed shape due to impedance mismatch. An alternate approach is the integration of separate pulsed alternators that discharge sequentially into the load on a specified firing schedule [12].

Figs. 5 and 6 show the output current shape and the resulting projectile velocity in the different MPAPS designs using this approach. MPAPS composed of one module generates the available current shape that exceeds the expectations but has no potential for optimization due to a single module. MPAPS composed of two modules and the one composed of four modules generate the bad current shapes with the high current peak resulting in the high acceleration. This will damage railgun. MPAPS composed of six modules and the one composed of eight modules generate the potential current shapes to be optimized for the ideal flat-topped shape. Thus, the candidate number of modules is 6 and 8.

Finally, based on the above analyses, the proper number of modules is 6 to drive railgun with the muzzle energy of 32 MJ.

V. Optimization

The MPAPS design is optimized by adjusting the firing time and voltage of each module according to Table IV.

TABLE IV
PARAMETERS OF MPAPS WITH THE DIFFERENT NUMBER OF MODULES

Module number	1 and 2	3 and 4	5 and 6
Firing Time/ms	0	2	4
Voltage/kV	7.5	8.5	8.5

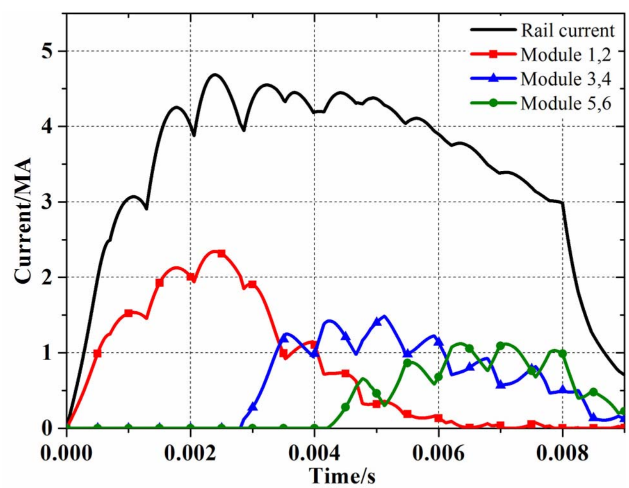

Fig. 7. Optimized rail current and the discharge current of each module.

Fig. 7 shows the optimized current shape. The optimized MPAPS generates a relatively flat-topped current shape with the peak current of 4.7 MA. The rail current consists of the three segment currents discharged from the three pairs of pulsed alternators at different times. It is noted that the segment current is two times the discharge current of each module because of modules in parallel. The discharge current of each module has different shapes and amplitudes due to the varying circuit impedances and the different voltage.

Fig. 8 shows the projectile velocity curve. The average-to-peak acceleration ratio of railgun reaches 0.67. The muzzle velocity is 2531 m/s, so the muzzle energy is 33 MJ. The rotor speed of each pair of alternators is 8790, 8250, and 9000, respectively, after the projectile exits the barrel. Thus, the system consumes the kinetic energy of 142 MJ and system efficiency is 0.244.

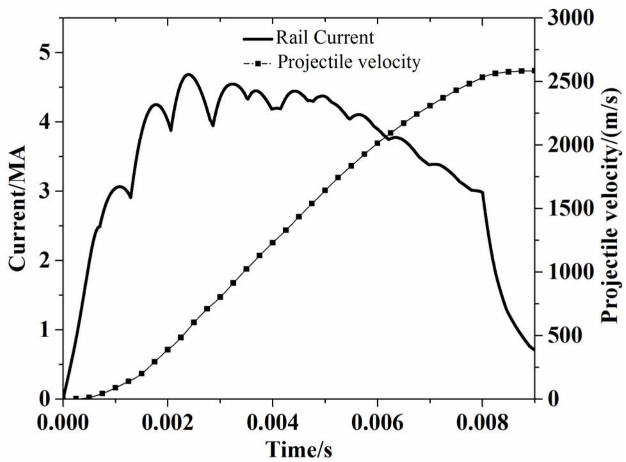

Fig. 8. Optimized rail current and the resulting projectile velocity.

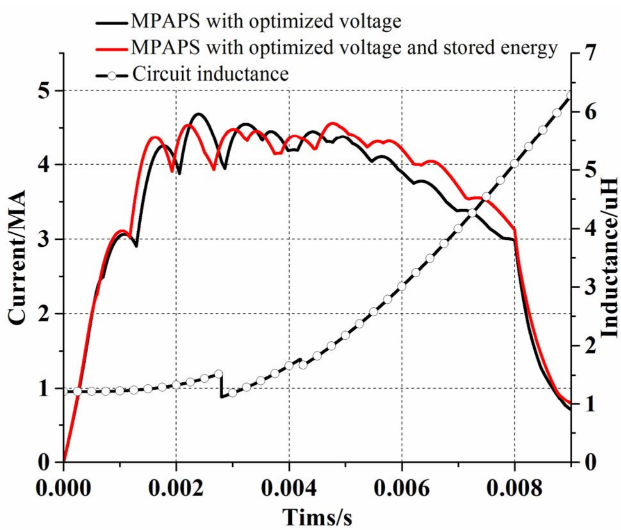

Fig. 9. Comparison of rail current between the two optimized designs and the circuit inductance variation.

VI. Discussion

We have obtained a relatively ideal current shape by the optimization of adjusting the firing times and voltage. However, it must be noted that the relatively constant current of flat-topped shape lasts only about 2.5 ms and then drops. A longer time of constant current is desired, so the higher voltage of the third fired pulsed alternator pair may be needed against the current drop.

It must also be noted each pair of pulsed alternators has the different remaining rotor speed after discharge is complete. This suggests that the different kinetic energy in each module is delivered to the railgun. The first pair of pulsed alternators consumes the least kinetic energy and makes a small contribution to the muzzle energy. Therefore, the stored energy of the first pair of pulsed alternators needs to be reduced for better utilization.

Thus, the voltage of the third pair of pulsed alternators is increased to 12 kV and the stored energy of the first pair of pulsed alternators is reduced to 50 MJ. Fig. 9 shows the current shape comparison between the two optimized designs. A longer time of constant current about 3.5 ms is achieved. This optimized MPAPS generates a more ideal flat-topped current shape.

However, the optimized voltage of 12 kV is 1.6 times the original voltage exceeding the machine design margin. Namely, the third pair of pulsed alternators must be redesigned. Considering the redesigned first pair of pulsed alternators with the energy of 50 MJ, MPAPS consists of three completely different designs of modules to the disadvantage of modular design: the replaceability of modules is lost; the cost of module manufacturing is increased; the augmentability of power supply for the new railgun is reduced. Therefore, this optimization is not recommended.

In addition, Fig. 9 shows the circuit inductance variation which grows slowly within 4.5 ms and then grows rapidly. The circuit inductance includes the pulsed power supply inductance and the railgun inductance. The pulsed power supply inductance decreases from 0.7 μH to near zero because the modules are connected successively to load. The rail inductance increases from 0.4 to 4.9 μH. Due to the inductance variation mismatch, the relatively constant circuit impedance is difficult to be kept for a long time. To achieve the ideal flat-topped shape, the modules with the high voltage must be connected to load after 4.5 ms. According to the previous analysis, 12 kV or even higher voltage may be required resulting in the increasing difficulty of machine manufacturing. Therefore, the ideal flat-topped current shape is almost impossible to obtain.

VII. Conclusion

This paper designs and analyzes the MPAPS composed of six pulsed alternators to drive the railgun with the muzzle of 32 MJ. The six modules are divided into three pairs of matched contra-rotating pulsed alternators. They are sequentially triggered to discharge into the load on a specified timing. By optimized the voltage and the firing time of each pair, a relatively flat-topped current pulse is obtained. The average-to-peak acceleration ratio of railgun reaches 0.67. The estimated mass of the system is less than 50 000 kg. Therefore, this type of MPAPS is an option for a long-range railgun.

References

[1] I. R. McNab, "Large-scale pulsed power opportunities and challenges," *IEEE Trans. Plasma Sci.*, vol. 42, no. 5, pp. 1118–1127, May 2014.

[2] I. R. McNab, "Pulsed power options for large EM launchers," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1352–1357, May 2015.

[3] S. K. Murthy and W. F. Weldon, "A single element multiphase compulsator powered railgun system," *IEEE Trans. Magn.*, vol. 30, no. 1, pp. 145–154, Jan. 1994.

[4] D. Eccleshall and S. B. Pratap, "Comparison of a single pulsed alternator with two or more in parallel for driving a railgun," *IEEE Trans. Magn.*, vol. 37, no. 1, pp. 473–475, Jan. 2001.

[5] S. Cui, W. Zhao, S. Wang, and T. Wang, "Investigation of multiphase compulsator systems using a co-simulation method of FEM-circuit analysis," *IEEE Trans. Plasma Sci.*, vol. 41, no. 5, pp. 1247–1253, May 2013.

[6] S. Pratap, R. Zowarka, T. Hotz, S. Pish, and B. Murphy, "Synchronization of multiple pulsed alternators discharging into an EM launcher," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1421–1426, May 2015.

[7] X. Li, S. Wu, S. Cui, and X. Zhao, "A flexible waveform conditioning strategy of an air-core pulsed alternator," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1398–1404, May 2015.

[8] J. S. Bernardes, M. F. Stumborg, and T. E. Jean, "Analysis of a capacitor-based pulsed-power system for driving long-range electromagnetic guns," *IEEE Trans. Magn.*, vol. 39, no. 1, pp. 486–490, Jan. 2003.

[9] J. D. Herbst, B. Rech, R. F. Thelen, and R. C. Thompson, "Status of the 9 MJ range gun system," *IEEE Trans. Magn.*, vol. 31, no. 1, pp. 540–545, Jan. 1995.

[10] W. A. Walls, "Advanced compulsator topologies and technologies," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. Texas, Austin, TX, USA, May 2002.

[11] D. A. Howey, P. R. N. Childs, and A. S. Holmes, "Air-gap convection in rotating electrical machines," *IEEE Trans. Ind. Electron.*, vol. 59, no. 3, pp. 1367–1375, Mar. 2012.

[12] W. C. Nunnally, S. M. Huenefeldt, and T. G. Engel, "Performance and scalability of MJ sequentially fired pulse forming networks for linear and nonlinear loads," *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 484–490, Apr. 2007.

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