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A Fractional Slot Multiphase Air-Core Compulsator With Concentrated Winding

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***Abstract*— Compulsator is a specially designed generator capable of delivering high current pulses to a low-impedance load, such as the electromagnetic railgun. In order to increase the tip speed of the rotor, advanced composite materials have been used in the recent compulsator prototype, which is mentioned as air core instead of the traditional iron core. For typical air-core compulsators, there are no slots and steel teeth to place the armature windings due to the nonmachinability of composite materials. Therefore, concentric windings in racetrack style are often adopted instead of traditional lap winding in most cases, since it is more convenient to be fixed by composite materials. However, overlap occurs at the end winding part for multiphase compulsators, which are not easy to be formed during the manufacture process. In this paper, a fractional slot multiphase air-core compulsator with concentrated windings is proposed and analyzed. The main advantage of fractional slot configuration is that it can offer a concentrated winding structure under certain conditions, which means each coil only spans one "tooth," and will not cause any intersection between each phase at the end winding. Two referenced fractional slot air-core compulsators with two phases, six poles, and four "slots" or eight "slots" (q = 1/3 and q = 2/3, q is the "slot" per pole per phase) are analyzed and compared with the performance of a traditional integral slot machine. The results indicated that the output voltage and self-excitation performance of a fractional slot compulsator can reach the same level with an integral slot one, and the discharging performance can reach an acceptable level. Thus, the fractional slot multiphase concept can be further used to improve the manufacture process of the winding in the future.**

***Index Terms*— Compulsators, electromagnetic launch, fractional slot windings, multiphase, railguns.**

I. Introduction

As PULSED power supply, compensated pulsed alternator (compulsator) is a specially designed generator capable of delivering high current pulses to a low-impedance load [1]. It can be used in various electromagnetic launch applications, especially, for the electromagnetic railguns, which require high-power, high-energy pulsed power in compact form [2]. In order to increase the power density of the machine, lots of efforts have been made during the last two decades. One is to increase the tip speed of the rotor: advanced composite materials have been used in the recent compulsator prototype, which is mentioned as air core instead of the traditional iron core [3]. Then, the other one is to use multiphase configuration instead of the single phase system, since it decouples the machine speed from the railgun requirements, which enables a higher tip speed and reduction in machine mass [4], [5].

However, these two technologies also bring out some manufacturing problems, especially for the multiphase armature windings. Since the composite materials of the stator, such as the carbon fiber and glass fiber, are wound and best not to be machined, there are no slots and teeth to place the armature windings like the traditional iron-core motor. The concentric windings in racetrack style are often used, and the fixations are achieved by pretightening force between two composite material wound cylinders. For multiphase compulsators with common integral slot windings, the end windings will be overlapped between the different phases, which are not easy to be formed and fixed on the stator. Such as the two-phase two-axis-compensated (2P2AC) compulsator shown in Fig. 1, the straight line part of phase A and phase B armature windings were located on the same cylinder surface, but the end turns region of the Ph.B was bent outward to avoid cross with the end turns of Ph.A [6]. Moreover, even 3-D geometric modeling of the overlapping end winding is not an easy work. In [7], the UT-CEM group developed a specialized technique for creating the accurate geometric models of racetrack style electrical windings, as well as a means of using these models to perform 3-D electromagnetic load analysis of the windings.

The number of slots per pole per phase q is a key parameter for a motor design. If q is an integer, the winding is called integral slot winding; if q is a fraction, it is known as a fractional slot winding. The fractional slot topology was often used in the stator winding of large scale hydro-generator with lower speed. Currently, it is more popularly used in the permanent magnet brushless dc motor or permanent magnet synchronous motor, especially for those with the higher number of poles, because this topology can decouple the constrains between the higher number of poles and the lower slot numbers [8]. One main advantage of fractional slot winding is that it can offer a proper

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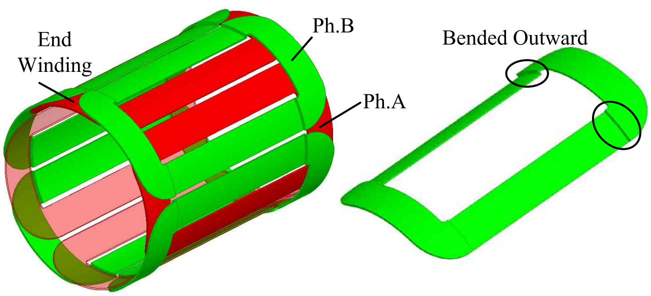

Fig. 1. Overlap happens at the end winding of the integral slot topology.

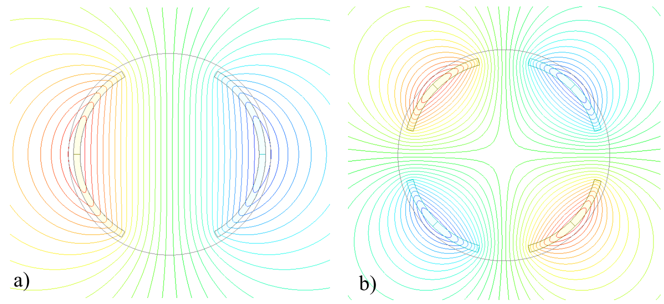

Fig. 2. Effects of the number of poles on flux distribution of the air-core compulsator. (a) $2p = 2$. (b) $2p = 4$.

winding design with coil pitch $y = 1$ (concentrated windings) under certain conditions of slot and pole combination. Since each coil only spans one "tooth," the end winding length will be reduced significantly, and there is no overlap between each winding. Therefore, the fractional slot winding is also known as the nonoverlapping winding.

In the view of this background, a multiphase air-core compulsator with fractional slot windings is proposed and analyzed in this paper. The condition of slot and pole combination to obtain a concentrated winding is discussed in the first place, and then, a referenced fractional slot winding compulsator is analyzed and compared with the performance of a traditional integral slot machine.

II. Design of Fractional-Slot Concentrated Windings

A. Discussion of the Number of Phases

Compulsators can be designed as single phase or multiphase. By using the positive half period of the output voltage, a single-phase compulsator can only discharge a single current pulse. The machine structure is simple, such as no overlapping problem for armature windings, and the requirements of the discharging switch are also not high. However, the pulsewidth of a single-phase system is limited by the machine speed, and is only suitable for small caliber and short railgun if high energy density is required.

The multiphase compulsator can combine multiple short current pulses into a wide pulse, by controlling the trigger time of each phase. Since the multiphase configuration decouples the machine speed from the pulsewidth, it can provide more flexibility in current waveform and higher energy density. Compared with the three phases topology in common motor, two phases topology with electrical orthogonal displacement are more attractive, because there is no magnetic coupling between phases, and the free component of discharge current can be controlled to be zero, thus obtain a flat-topped output current [9]. Some compulsator also used the four phases topology [10] with double layer configuration of armature windings (Layer 1: Ph.A and Ph.B; Layer 2: Ph.C and Ph.D), but their four phases also have 90° electrical phase difference as the two phases. Four discharge switches can be eliminated by this topology.

B. Discussion of the Number of Poles

When discussing the number of poles ($2p$), flux density distribution in the air-core compulsator must be understood first. A similar analytical method as the air-core superconductor electrical machine can be used in this paper [11], [12]. Since the current i flows in the axial direction, the magnetic vector potential only has an axial component A_z. Assume that currents are concentrated on the center line of the winding ($\rho = r_0$), then the solution of the Laplace's equation under the cylindrical coordinate system can be given as

$$A_z(\rho,\phi) = \begin{cases} \frac{\mu_0 K_m}{2p}\rho\left(\frac{\rho}{r_0}\right)^{p-1}\sin(p\phi) & \rho < r_0 \\ \frac{\mu_0 K_m}{2p}\rho\left(\frac{r_0}{\rho}\right)^{p+1}\sin(p\phi) & \rho \geq r_0 \end{cases} \tag{1}$$

where μ_0 is the permeability of vacuum; K_m is the amplitude of the linear current density, given as

$$K_m = \frac{2Nk_w i}{\pi r_0} \tag{2}$$

where N is the total serial number of turns of windings; k_w is the fundamental winding factor.

According to the definition of the magnetic vector potential A_z, the radial and tangential flux density of any point in the air-core compulsator can be solved as

$$\begin{aligned} B_\rho(\rho,\phi) &= \frac{1}{\rho}\frac{\partial A_z(\rho,\phi)}{\partial\phi} \\ &= \begin{cases} \frac{\mu_0 K_m}{2}\left(\frac{\rho}{r_0}\right)^{p-1}\cos(p_0\phi) & \rho < r_0 \\ \frac{\mu_0 K_m}{2}\left(\frac{r_0}{\rho}\right)^{p+1}\cos(p_0\phi) & \rho \geq r_0 \end{cases} \end{aligned} \tag{3}$$

$$\begin{aligned} B_\phi(\rho,\phi) &= -\frac{\partial A_z(\rho,\phi)}{\partial\rho} \\ &= \begin{cases} -\frac{\mu_0 K_m}{2}\left(\frac{\rho}{r_0}\right)^{p-1}\sin(p_0\phi) & \rho < r_0 \\ \frac{\mu_0 K_m}{2}\left(\frac{r_0}{\rho}\right)^{p+1}\sin(p_0\phi) & \rho \geq r_0. \end{cases} \end{aligned} \tag{4}$$

Equations (3) and (4) can represent any winding with current, including the field winding, the armature winding, and the compensation winding. The flux density distribution under no load condition can be clearly seen from these two equations, by using r_0 as the field winding radius. It can be seen that both the radial and tangential flux density decreases with the increase of the number of poles p exponentially.

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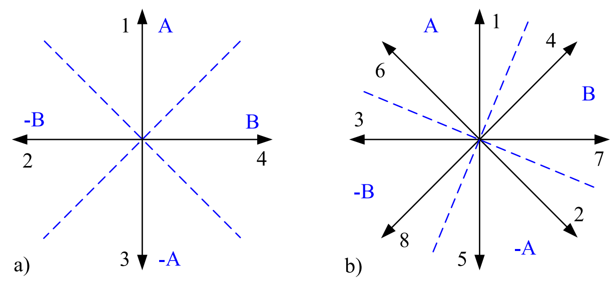

Fig. 3. EMF phasor diagram for two-phase compulsators. (a) $Z = 4$ and $2p = 6$ $(q = 1/3)$. (b) $Z = 8$ and $2p = 6(q = 2/3)$.

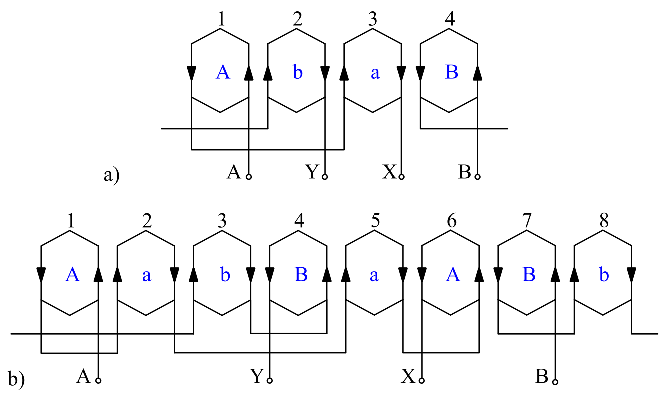

Fig. 4. Coil group diagrams for two-phase compulsators. (a) $Z = 4$ and $2p = 6$ $(q = 1/3)$. (b) $Z = 8$ and $2p = 6(q = 2/3)$.

The outside part decreases faster due to the exponent of $p+1$, whereas the inside part decreases slower since the exponent is $p - 1$. Therefore, the compulsator has the smaller of the number of poles, the better magnetic coupling between the field and armature windings will be obtained.

Two poles topology seems to be a good choice according to the above-mentioned analysis. However, if a two poles topology $(2p = 2)$ is adopted, according to (3) and (4), the flux density inside the field winding will be constant without any attenuation. The flux will go through the shaft, as shown in Fig. 2, and then ,an extra shield of the shaft must be used, due to the alternating flux during the self-excitation process. Moreover, the two poles topology may also cause some uneven distribution of the loading and stress concentration problem [13]. Therefore, the two poles topology is not adopted in the air-core compulsator in most cases.

From the above-mentioned discussions, the multiphase compulsator is better to use a four poles and six poles topology, to obtain higher magnetic coupling, shorter flux path, and more uniform distribution of stress.

C. Discussions of the Slot and Pole Combination

A fractional slot winding is used when the stator has a nonintegral number of slots per pole per phase. There is no winding with identical groups of coils disposed symmetrically with respect to the poles. As discussed earlier, multiphase compulsators often use two-phase instead of common three-phase machine. Therefore, the conditions of the slot and pole

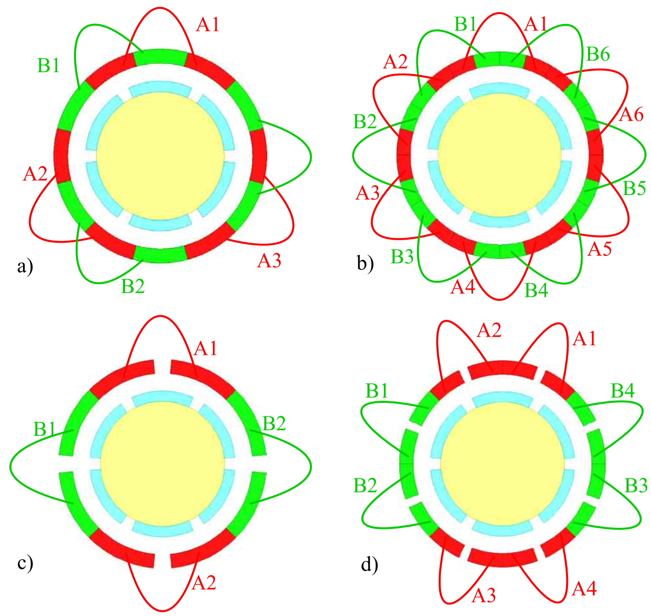

Fig. 5. Winding diagram for two-phase compulsators. (a) Half-coiled with $Z = 12$ and $2p = 6$ $(q = 1)$. (b) Whole coiled with $Z = 12$ and $2p = 6$ $(q = 1)$. (c) Fractional slot with $Z = 4$ and $2p = 6$ $(q = 1/3)$. (d) Fractional slot with $Z_0 = 8$ and $2p_0 = 6$ $(q = 2/3)$.

combination to achieve the concentrated winding are also different, and must be discussed first.

To obtain a symmetrical winding for m phase, the ratio of Z_0/m must be an integral number, where Z_0 is the slot number for the unit machine. In our case, the slot number Z_0 must be an even number due to $m = 2$.

Due to the definition of the unit machine, the slot number Z_0 and the number of pole pairs p_0 should not have the divisor. Since Z_0 is an even number, then p_0 must be an odd number $(p_0 = 1, 3, 5 \ldots)$. Therefore, the best choice of number of pole pairs for a two-phase compulsator is $p = p_0 = 3$ (namely six poles topology), according to the above-mentioned discussion.

As p has been selected, then Z should be 4, 8, 16, 20, and so on. Since increasing the number of slots will also bring out some manufacturing problem, finally $Z = 4$ and $Z = 8$ are selected to be analyzed in this paper, which gives the slot per pole per phase $q = 1/3$ and $q = 2/3(q = Z/2\text{pm})$, respectively.

D. Phasor and Winding Diagram for Concentrated Windings

As the traditional iron-core motor, slot EMF phasor diagram can be used to analyze the winding connections of each phase. For the concentrated winding configuration with $y = 1$, the number 1 phasor is on $+y$-axis and represent the EMF of one conductor of a coil. The other conductor of the same coil strides α degree as the number 2 EMF phasor. The angle between these two phasors is the slot pitch angle (electrical degree), which is given as

$$\alpha = \frac{360^\circ p}{Z}. \tag{5}$$

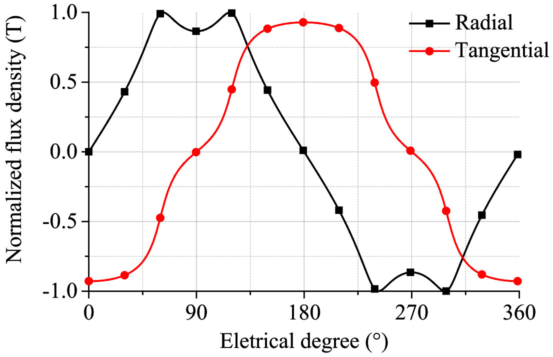

Fig. 6. Normalized flux density of the airgap.

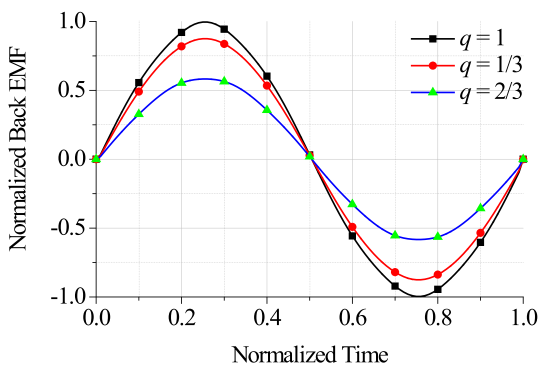

Fig. 7. No-load back EMF for different kinds of winding configurations.

Follow the same rules and draw the rest EMF phasor, the EMF phasor diagrams for the two fractional slot windings can be obtained as shown in Fig. 3. The phase belt for each phase is divided to make the composite EMF largest.

According to the phasor diagram, coil group diagrams of these two fractional slot concentrated windings are shown in Fig. 4. Each coil is connected in series for clarity in Fig. 4, and it can also be connected in parallel or in series–parallel to reduce the impendence of the winding, at the expense of reducing the output voltage. This tradeoff needs to be considered between the performance of discharge ability and self-excitation efficiency.

For comparison, an integral slot winding compulsator with $Z = 12(q = 1)$ is introduced. Each design has the same rotor structure, and the winding diagram is shown in Fig. 5. No matter a half-coiled or a whole-coiled winding structure is adopted, overlap happens at the end of each coil, whereas there is no overlap on each "tooth" for these two fractional slot designs. The winding structure and connection of the last two fractional slot concentrated windings are much simpler than the integral slot windings, which will be beneficial from the manufacture point of view.

It can also be seen from Fig. 5, due to the absence of teeth for air-core compulsators, the conductors can be placed all over the periphery for integral-slot windings, leading a higher cross-sectional area. Besides, the conductors of coil B can be placed in the "salient-pole" of coil A, which means that the coil span is also larger than the fractional slot concentrated windings, and leading a higher distributed winding factor.

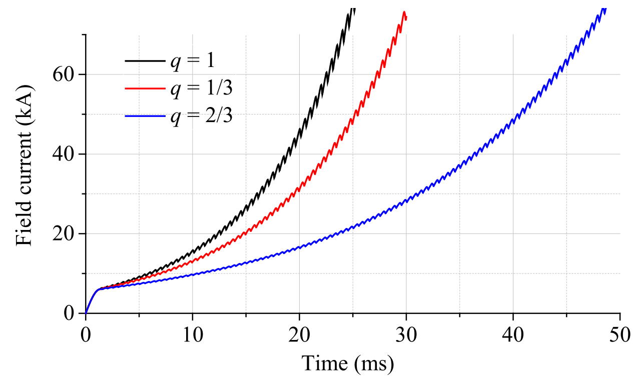

Fig. 8. Field currents during self-excitation process.

TABLE I
SELF-EXCITATION PERFORMANCE COMPARISONS

Description	$q = 1$	$q = 1/3$	$q = 2/3$
T (ms)	23.36	28.18	45.64
I_{rms} (kA)	28.78	28.93	29.47
Losses (kJ)	251.46	306.55	515.44
η_f (%)	85.66	83.05	74.45

According to the above-mentioned analysis, we can see that manufacturing benefits can be gained at a cost of decreasing electromagnetic performance by using fractional slot concentrated windings. The reduction of the performance of the machine above-mentioned is discussed in Section III.

III. PERFORMANCE OF FRACTIONAL SLOT COMPULSATORS

A. Back EMF Comparisons

Since the rotor structure and field windings are not changed, the same flux density of the air gap can be obtained as shown in Fig. 6. The radial and tangential flux density has nearly the same value, which is the unique character of the air-core machine, and consistent with the analytical solution (3) and (4).

When making comparative studies, all the integral slot winding designs and fractional slot winding designs with the different slots have the same total serial number of turns of windings ($N = 4$). Therefore, the only differences of the no-load back EMF between these designs are the winding factors.

Based on a finite-element model (FEM), the normalized no-load back EMF was compared and plotted in Fig. 7. It can be clearly seen that the back EMF decreases for designs with fractional slots concentrated windings. By using Fourier transform, the fundamental EMF can be calculated as the decrease of 13% for $Z = 4$ and 42% for $Z = 8$, respectively.

The winding factors for the integral slot windings are easier to be calculated. In this case, the short pitch winding factor $k_p = 1$, since the single layer concentric winding is used. The distributed winding factor k_d can be calculated as

$$k_d = \lim_{\substack{\alpha \to 0 \\ q\alpha \to \beta}} \frac{\sin \frac{q\alpha}{2}}{q \sin \frac{\alpha}{2}} = \frac{\sin \frac{\beta}{2}}{\frac{\beta}{2}} \tag{6}$$

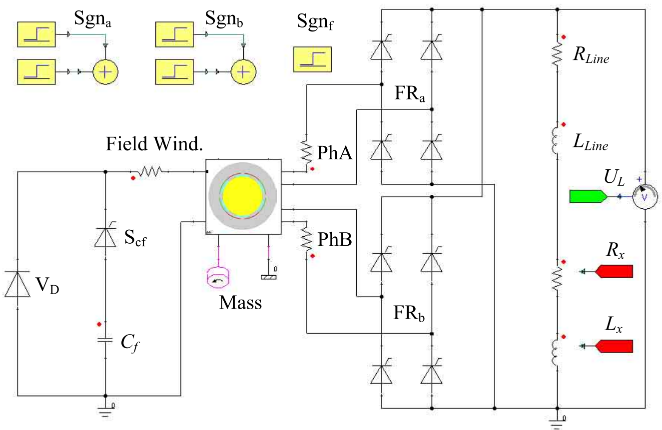

Fig. 9. Fast cosimulation model of compulsators based on capacitor field.

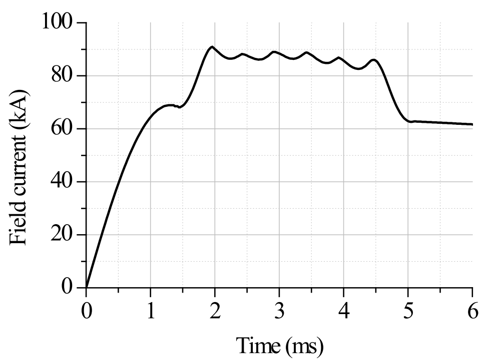

Fig. 10. Currents in the field windings.

where β is the electrical degree per pole per phase occupied by the armature windings. Since phase A and phase B are distributed evenly on the stator inner surface, namely, $\beta = 90°$, the distributed winding factor can be calculated as $k_d = 0.9$. Then the fundamental winding factor for the integral slot design is $k_w = 0.9$.

According to FEM simulation results, the winding factor for $q = 1/3$ $(Z = 4)$ is 0.783, whereas only 0.522 for $q = 2/3$ $(Z = 8)$. Due to the small coil span, the winding factor is too low for $q = 2/3$ and cannot be adopted in any air-core compulsator. But it only decrease 13% for $q = 1/3$ design, which is not a significant gap comparing with an integral slot winding.

B. Self-Excitation Comparisons

A reference compulsator with nearly the same parameters of 2P2AC is used in this paper [6]. Only the slot and pole combination have been changed as shown in Fig. 5. By using a cosimulation model [14], the compulsator driving railgun system can be simulated simultaneously. The self-excitation process can also be simulated by this cosimulation model, when the main discharge switch is not triggered. The comparison results are plotted in Fig. 8.

The target field current I_F is 65 kA, and the required time to accomplish the self-excitation process is also different due to the different winding factors. As summarized in Table I, the

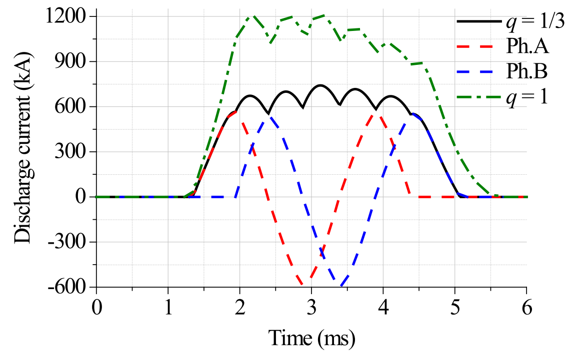

Fig. 11. Discharge current of the compulsator.

self-excitation loss increases 22% and 105%, and the efficiency η_f decreases 2.6% and 11.2%, which is defined as

$$\eta_f = \frac{\frac{1}{2}L_f I_F^2}{I_{\mathrm{rms}}^2 R_f T + \frac{1}{2}L_f I_F^2} \tag{7}$$

where L_f and R_f is the inductance and resistance of the field winding, $L_f = 711$ μH and $R_f = 13$ mΩ in the reference compulsator; I_{rms} is the rms current of field windings; T is the duration to accomplish the self-excitation process.

The comparison results indicate that $q = 1/3$ design only extend a few self-excitation periods to get the same voltage as the integral slot windings, and the self-excitation efficiency does not drop too much as well, whereas $q = 2/3$ design cannot be accepted due to the more than 100% increase of self-excitation loss.

Since self-excitation is adopted in most air-core compulsators, and the field current level (10–100 kA) are similar with the reference compulsator in this paper, the conclusion can also be suitable for other air-core compulsator designs. Besides, the increase of resistance of armature windings due to reduction of the cross-sectional area will be eliminated by the reduction of the resistance and inductance of end windings.

Consequently, the back EMF magnitude and self-excitation efficiency are within expectation for $2p = 6$ and $Z = 4(q = 1/3)$ configuration. The output performance of an air-core compulsator with fractional slot concentrated windings will be analyzed and discussed in the following.

C. Output Performance Comparisons

Since this section only focuses on the discharging performance, a fast cosimulation model was adopted to reduce the simulation time, by using the discharging current from an ideal large pulsed capacitor C_f as the field current, instead of the relatively long self-excitation process, as shown in Fig. 9.

The field capacitor can provide an initial field current of 65 kA, and then, the field current freewheels via the diode V_D. The two-phase armature windings are connected to the railgun load through the discharge rectifier FR_a and FR_b, and output pulsed power according to the trigger angle. The railgun launcher is modeled as a variable resistance and inductance in our cosimulation model, and the variation is governed by circuit and physical equations calculated in the Simplorer platform. During the discharge process as plotted in Fig. 10, field windings will induce currents and provide the

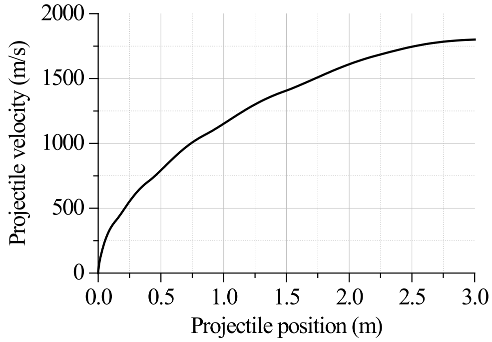

Fig. 12. Velocity variation as a function of projectile position.

direct-axis compensation to reduce the effective inductance of the armature windings.

By controlling the firing angle of each phase individually, the compulsator can discharge a preferred flat-topped current pulse to a railgun load. In this paper, a 3-m railgun with an inductance gradient of $L' = 0.5$ μH/m and resistance gradient of $R' = 0.1$ mΩ/m is used. The discharge current for the fractional slot design is plotted in Fig. 11, compared with the integral slot design.

It can be seen that the peak discharge current is 741 kA with pulsewidth of 3.76 ms for the $q = 1/3$ design, whereas 1212 kA and 4.24 ms for the $q = 1$ design. The decrease of the peak current is more than 38%, which is much higher than the 13% decrease of the back EMF. This is mainly because the effective inductance L_{aef} is also increased for the fractional slot design, which is a key parameter to represent the compensation ability, defined as [15]

$$L_{\text{aef}} = L_a - \frac{M_{\text{af}}^2}{L_f} \quad (8)$$

where L_a is the self-inductance of armature windings, which is 4.28 and 2.34 μH; M_{af} is the mutual inductance between the armature and field windings, which is 29.14 and 32.83 μH; L_f is the self-inductance of armature windings, as mentioned earlier, 711 μH for both designs.

Due to the direct-axis compensation, the internal inductance of the air-core compulsator is a sinusoidal wave between the maximum value of L_a and the minimum value of L_{aef}. The effective inductance can be calculated as 3.09 μH for $q = 1/3$ design and 1.33 μH for $q = 1$ design. Since the railgun load has the same or even less impedance compared with the internal inductance of the compulsator, the discharge current is reduced a lot in our fractional slot design. If an augmented railgun with longer barrel is used as the load, namely, higher inductance and resistance, the output performance must be better for the fractional slot concentrated winding design.

Even the discharge current is not as high as the integral slot design, it can still launch a projectile of 175 g to 1800 m/s, with muzzle energy of 284 kJ. The velocity versus position curve is plotted in Fig. 12; it shows that the velocity stopped growth at the position of 3 m, indicating the current has dropped to zero before the projectile exits the gun, which may alleviate problems associated with current removal prior to exit.

IV. Conclusion

A novel multiphase air-core compulsator with fractional-slot concentrated windings has been proposed and analyzed in this paper. Without any overlap at the end region, concentrated windings with coil pitch of 1 ($y = 1$) can be obtained by using the topology of two phases, six poles, and four "slots" or eight "slots," which is a reasonable selection according to the discussion of the number of phases and poles, and the slot and pole combination in the first place. Then, the performance of the fractional slot winding compulsator is compared with a traditional integer slot machine. The results indicated that the output voltage and self-excitation performance of the fractional slot compulsator with $q = 1/3$ can reach the same level with the integral slot one. Although the output performance has some differences, it can still reach an acceptable level under large impedance load. Therefore, the fractional slot multiphase concept can be further used to improve the manufacturing process of the winding in the future.

References

[1] M. L. Spann, S. B. Pratap, M. D. Werst, A. W. Walls, and W. G. Fulcher, "Compulsator research at the University of Texas at Austin-an overview," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 529–537, Jan. 1989.

[2] J. R. Kitzmiller, S. B. Pratap, and M. D. Driga, "An application guide for compulsators," *IEEE Trans. Magn.*, vol. 39, no. 1, pp. 285–288, Jan. 2003.

[3] D. E. Perkins, S. B. Pratap, M. L. Spann, R. F. Thelen, and M. D. Werst, "The CEM-UT rapid-fire compulsator railgun system recent performance and development milestones," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 74–79, Jan. 1991.

[4] 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.

[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] W. Zhao, S. Wu, L. Song, and S. Cui, "Design and analysis of a two-phase two-axis-compensated compulsator," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1434–1440, May 2015.

[7] G. A. Wedeking, "Geometric modeling and electromagnetic analysis of electrical windings for pulsed alternators," *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 404–407, Jan. 2005.

[8] D. Ishak, Z. Q. Zhu, and D. Howe, "Eddy-current loss in the rotor magnets of permanent-magnet brushless machines having a fractional number of slots per pole," *IEEE Trans. Magn.*, vol. 41, no. 9, pp. 2462–2469, Sep. 2005.

[9] J. R. Kitzmiller, J. A. Pappas, S. B. Pratap, and M. D. Driga, "Single and multiphase compulsator system architectures: A practical comparison," *IEEE Trans. Magn.*, vol. 37, no. 1, pp. 61–66, Jan. 2001.

[10] J. A. Mallick and M. Crawford, "Determining pulsed alternator thyristor converter firing angles to produce a desired launcher current," *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 322–325, Jan. 2005.

[11] A. Hughes and T. J. E. Miller, "Analysis of fields and inductances in air-cored and iron-cored synchronous machines," *Proc. IEE*, vol. 124, no. 2, pp. 121–126, Feb. 1977.

[12] C. Ye, K. Yu, H. Zhang, L. Tang, and X. Xie, "Optimized design and simulation of an air-core pulsed alternator," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1405–1409, May 2015.

[13] J. R. Kitmiller *et al.*, "Optimization and critical design issues of the air core compulsator for the cannon caliber electromagnetic launcher system (CCEML)," *IEEE Trans. Magn.*, vol. 31, no. 1, pp. 61–66, Jan. 1995.

[14] W. Zhao, D. Cheng, Q. Liu, and S. Cui, "Sensitivity analysis and regulation strategy of current waveform for two-axis-compensated compulsators," *IEEE Trans. Plasma Sci.*, vol. 41, no. 5, pp. 1254–1259, May 2013.

[15] S. B. Pratap and M. D. Driga, "Compensation in pulsed alternators," *IEEE Trans. Magn.*, vol. 35, no. 1, pp. 372–377, Jan. 1999.

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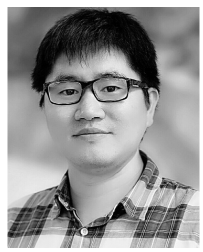

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