Research of a Novel Multi-disk Axial Flux Compensated Pulsed Alternator

Wed-Af-Po3.06-14

Xin Liang, Caiyong Ye, Jiangtao Yang, Wei Xu, Fei Xiong, Wenhao Li, Yu Xiang

State Key Laboratory of Advanced Electromagnetic Engineering and Technology (AEET),
School of Electrical and Electronic Engineering (SEEE),
Huazhong University of Science and Technology (HUST), Wuhan, CO 430074, China

HuaZhong University of Science and Technology
Center for Energy Conversion System

Introduction

The design purpose of multi-disk axial flux compensated pulsed alternator (MAFCPA) mainly focus on reducing the subtransient reactance while discharging, which contributes to increasing discharging power. In detail, the compensated shield made in aluminum alloy helps decoupling the mutual-inductance among windings in different disks. By connecting the windings with little mutual-inductance in parallel, the purpose is achieved. In this paper, an equivalent electric circuit model is established to analysis the protective effect of compensated shield to PM and its electric-magnetic shield effect. In an analytical method, the effect of decreasing reactance by connecting windings in parallel is proved. A 0.6MW MAFCPA in Finite Element Method (FEM) is built and simulated.

Objectives

- Establish an equivalent electric circuit model to analysis the protective effect of compensated shield to PM and its electric-magnetic shield effect.
- Prove the effect of decreasing reactance by connecting windings in parallel is proved, in an analytical method.
- Establish models of single-disk and multi-disk axial flux CPA in Finite Element Method (FEM), and compare the performance of them.

Fundamental Theory

Effect of compensated shield

The equivalent electrical circuit model of single winding and single compensated shield is introduced as Fig.2. In the circuit model, L1 and L2 represent the inductance of one phase winding and compensated shield respectively. And M represents the mutual inductance between them. To simulate a common condition in CPA while discharging, current i1 is a half-sinusoid pulse.

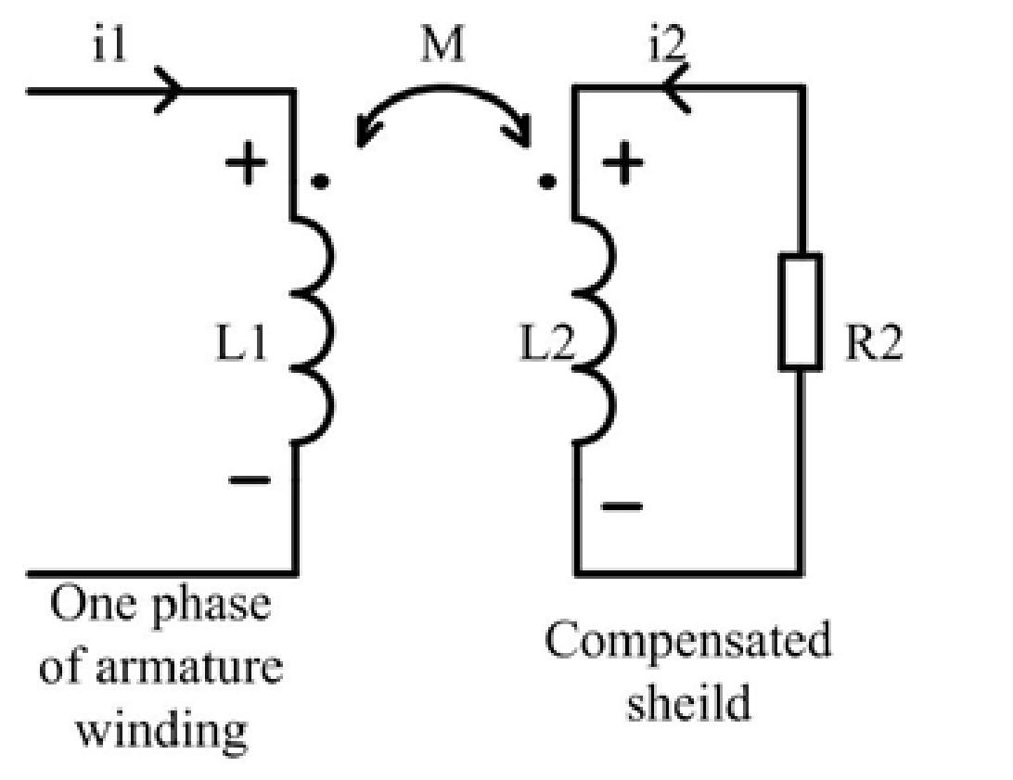

Fig. 2. Equivalent electrical circuit model of single winding and sin; compensated shield

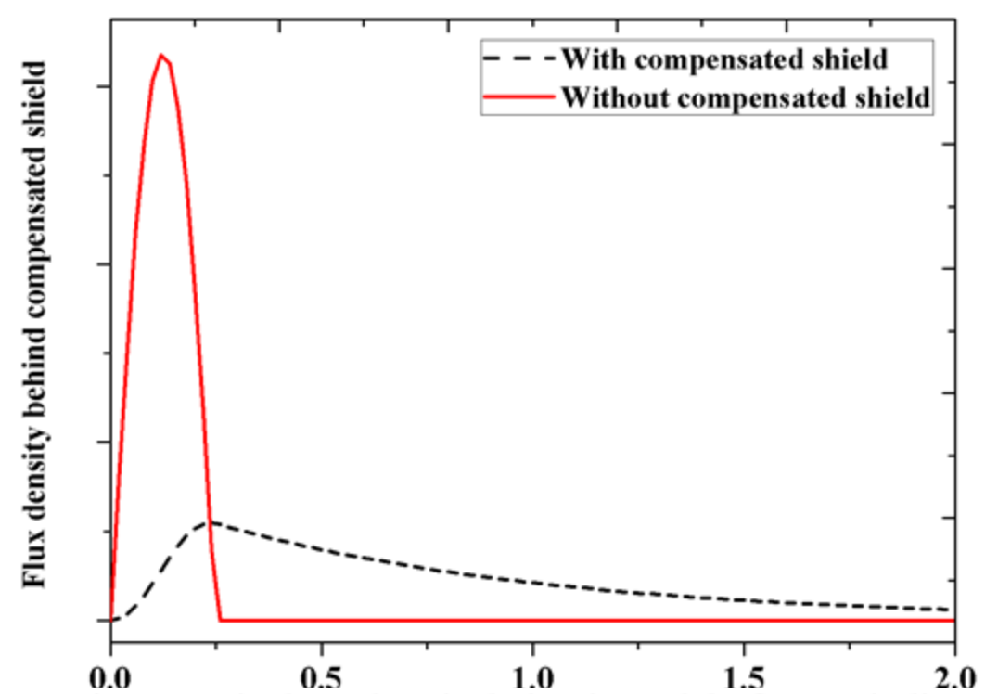

Fig.3. Equivalent electrical circuit model of two windings and one shield between them

Analytical expressions

$$i1=\begin{cases}\sin(\omega t) & 0<t<\dfrac{\pi}{\omega}\\ 0 & t>\dfrac{\pi}{\omega}\end{cases} \quad (1)$$

$$\begin{cases}L_2\dfrac{di_2}{dt}+M\dfrac{di_1}{dt}=-i_2R_2\\ i_2(0)=0\end{cases} \quad (2)$$

$$B=\frac{i_2L_2+i_1M}{S} \quad (4)$$

In Fig.3, it shows the effect on flux density behind compensated shield. The wave of flux density in the condition with the shield consist of a sinusoidal component and an exponential component, which is proved by analytical equations. The differences of flux compensated shield bring can be divided into two effects. The one is that it decreases the slope of flux density, and the other is that it decreases the flux density magnitude.

$$\begin{aligned}B&=\frac{1}{S}\left(\frac{MR_2}{\sqrt{R_2^2+\omega^2L_2{}^2}}\sin(\omega t-\phi)+\frac{\omega L_2MR_2}{R_2^2+\omega^2L_2{}^2}e^{-\frac{R_2}{L_2}t}\right)\\ &<=\frac{1}{S}\left(\frac{MR_2}{\sqrt{R_2^2+\omega^2L_2{}^2}}+\frac{\omega L_2MR_2}{R_2^2+\omega^2L_2{}^2}\right) \quad (5)\\ &\approx\frac{1}{S}\frac{2MR_2}{\omega L_2} \qquad \omega L_2>>R_2\end{aligned}$$

So from equation (5), it can be seen that lower conductance in compensated shield and higher current frequency leads to less demagnetization to PM, while M and L is decided by the shape of the shield which is usually cannot be changed.

Conclusion

- The wave of flux density in the condition with the shield consist of a sinusoidal component and an exponential component.
  The compensated shield decreases the slope and magnitude of flux density in permanent magnet (PM).
  The flux magnitude in PM is related to conductance of compensated shield and discharge current frequency.
- The existence of compensated shield helps decreasing the mutual inductance between the two windings next to the shield, and what extent mutual inductance can be decreased to is decided by the value of k1 and k2, where k1 and k2 is coupling coefficient of the mutual inductances.
- The mean value of discharge current with load is 8.45kA, the peak power is 0.66MW, the width of pulse is 2.7ms and the energy released is 1.04kJ, where the resistance and inductance of load discharged to is 5mΩ, 1μH respectively.

Decreasing inner inductance

Equivalent model

To analysis the effect of compensated shield on decreasing mutual inductance between two armature windings, an equivalent electrical circuit model of two wingdings and one shield sandwiched between them is established, as Fig.4 shows. Symbol La, Lb and Lc represent the inductances of wingding A, winding B and the compensated shield between windings respectively. Symbol M represents the mutual inductance among them.

$$L_a=L_b=L,\ M_{ac}=M_{bc}=M \quad (6)$$

$$\begin{cases}u_b=L_b\dfrac{di_b}{dt}+M_{ab}\dfrac{di_a}{dt}+M_{bc}\dfrac{di_c}{dt}=0\\ u_c=L_c\dfrac{di_c}{dt}+M_{ac}\dfrac{di_a}{dt}+M\dfrac{di_b}{dt}=0\\ i_a(t)=f(t),i_b(0)=0,i_c(0)=0\end{cases} \quad (7)$$

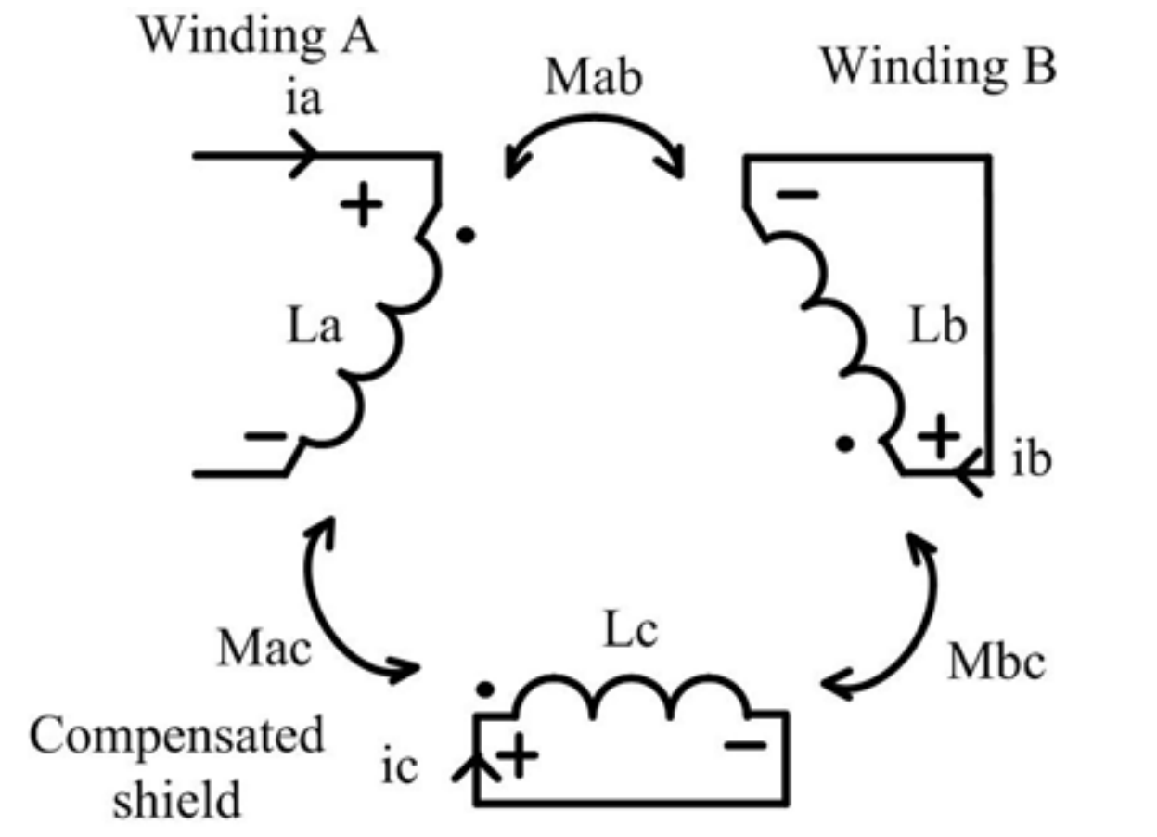

Fig.3. Equivalent electrical circuit model of two windings and one shield between them

Analytical expressions

$$\frac{di_b}{dt}=-\frac{M_{ab}}{L}\frac{di_a}{dt},\ \textit{without shield} \quad (8)$$

$$\begin{aligned}\frac{di_b}{dt}&=-\frac{M^2+L_cM_{ab}}{LL_c-M^2}\frac{di_a}{dt},\ \textit{with shield}\\ &=-\frac{1}{L}\left(\frac{-M^2+L_cM_{ab}}{L_c-\dfrac{M^2}{L}}\right)\frac{di_a}{dt} \quad (9)\end{aligned}$$

$$M_{eq}=\frac{-M^2+L_cM_{ab}}{L_c-\dfrac{M^2}{L}} \quad (10)$$

$$\begin{cases}k_1=k_{ab}=\dfrac{M_{ab}}{L}\\ k_2=k_{bc}=k_{ac}=\dfrac{M}{\sqrt{L_cL}}\end{cases} \quad (11)$$

$$M_{eq}=M_{ab}\frac{1}{k_1}\left(1-\frac{1-k_1}{1-k_2^2}\right) \quad (12)$$

The coupling coefficient of the mutual inductances is introduced, as equations (11) shows. So the equivalent mutual inductance can be simplified to equation (12). The coupling coefficient k1 is decided by armature windings A and B, while the parameter k2 varies with compensated shield.

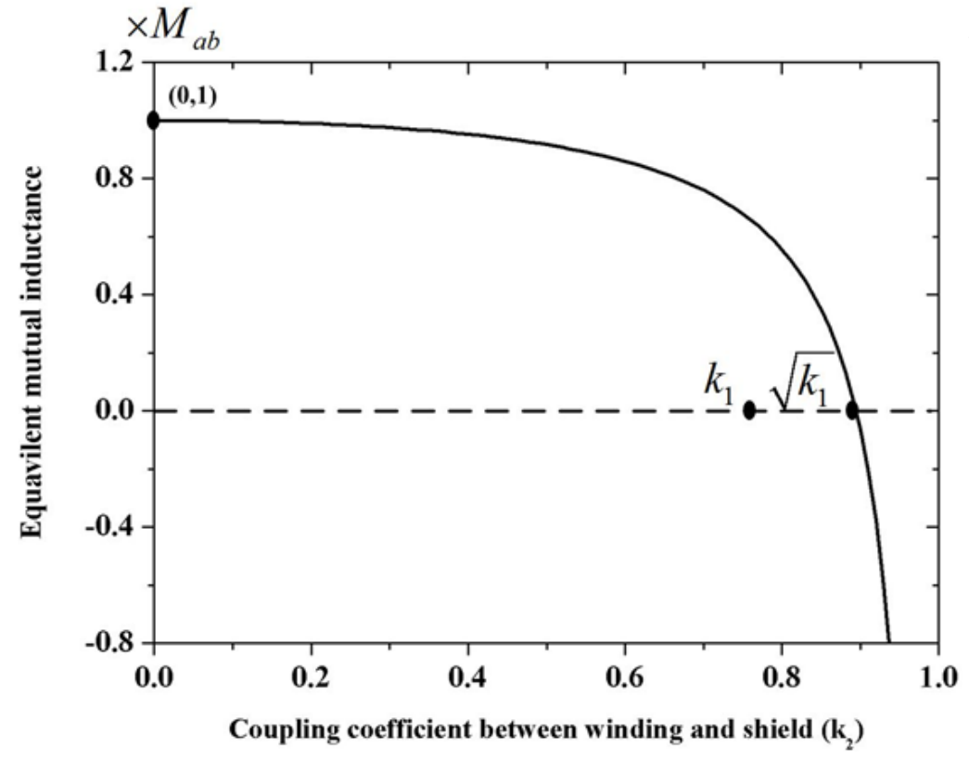

Fig.4. Relationship between equivalent mutual inductance M_{eq} and coupling coefficient k2

The relationship between k2 and Meq is described in Fig.4. The compensated shield helps decreasing the mutual inductance between the two windings next to the shield, and what extent mutual inductance can be decreased to is decided by the value of k1 and k2.

Results

Topology

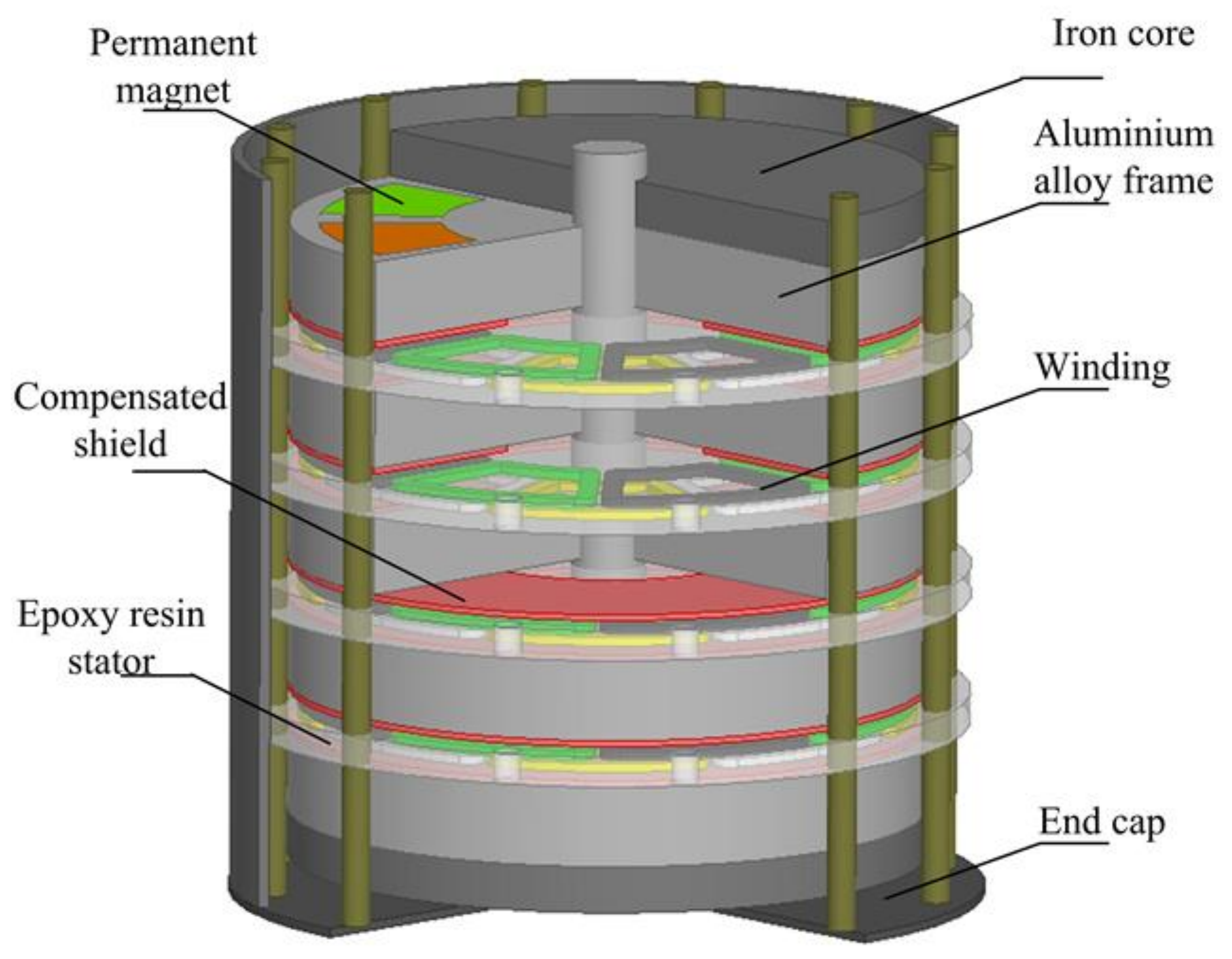

Fig. 1. Topology of MAFCPA.

The structure of MAFCPA is shown in Fig. 1 which mainly consists of four stators and five rotors. The stators, sandwiched between rotors, are made of epoxy resin with armature winding in it. In each stator, the armature winding has 2 layers with 2 phase windings in each layer. The phase winding with the same electrical angle in different stators are connected in parallel. As for rotors, they consist of PM, aluminum alloy frame and compensated shield[4,6]. The compensated shield is also made in aluminum alloy which is used to compensate armature winding while discharging. The PMs, used for establishing airgap field, are magnetized in the direction of shaft. And the magnetization directions of PMs next to each other in a same rotor are in opposite

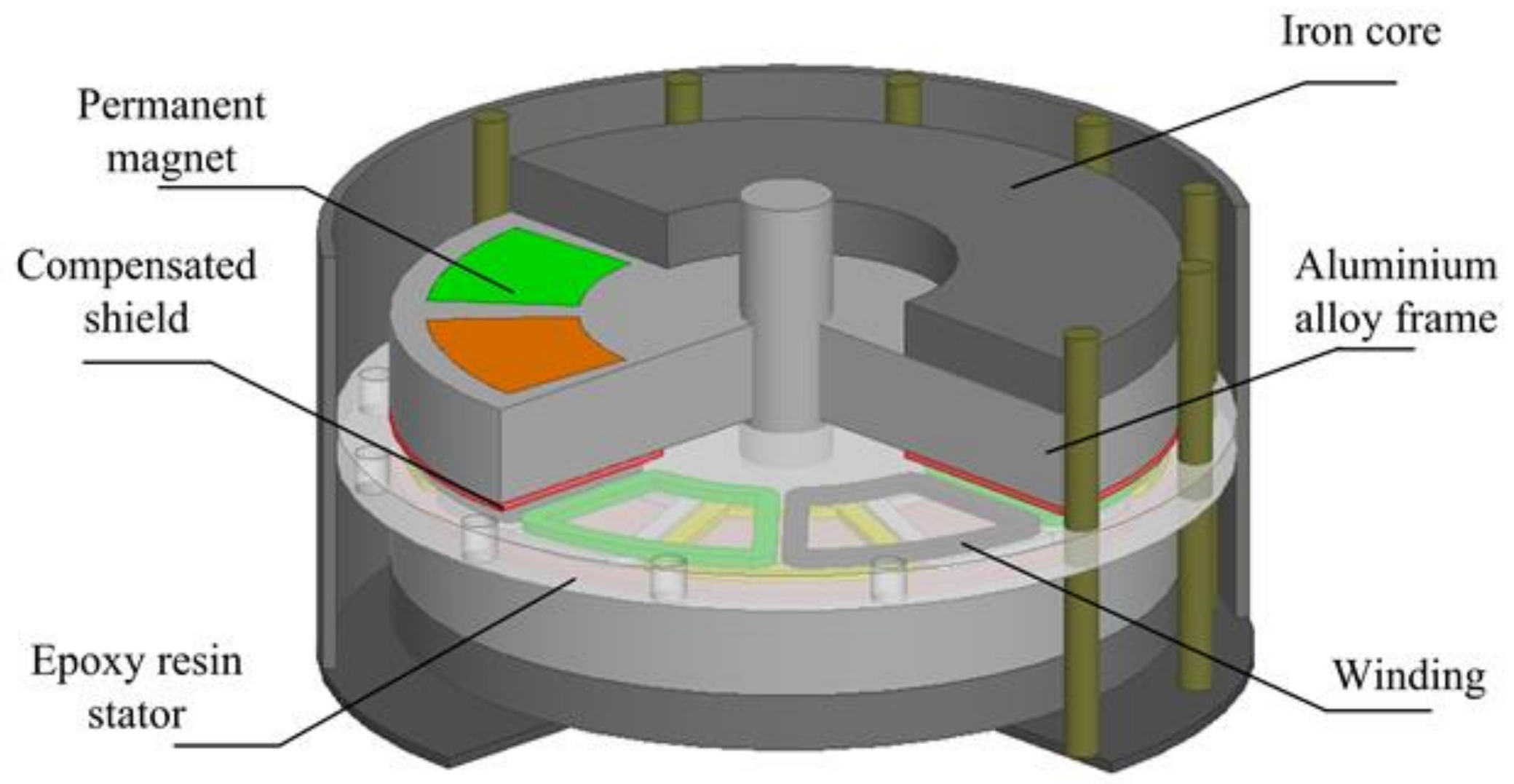

Fig.5. Topology of single disk axial flux compensated pulsed alternator for comparison

TABLE I

PARAMTERS OF SINGLE-DISK AND MULTI-DISK AXIAL FLUX CPA

	Single-disk machine	Multi-disk machine
Outer diameter (mm)	220	220
Axial length (mm)	104	236
Rotational speed (r/min)	20000	20000
Number of stators	1	4
Number of rotors	2	5

Discharge performance

TABLE Ⅱ

PARAMTERS AND PERFORMANCE OF MAFCPA

Outer diameter of PM	200mm	Number of phases	4
Inner diameter of PM	115mm	Rational speed	20000r/min
Axial length of single rotor disk	32mm	Amplitude of airgap flux density	0.79T
Distance between two rotor disks	12mm	Open circuit voltage of one phase	101V
Axial length of single stator disk	9mm	Peak current of discharge current	11.5kA
Number of rotor disks	5	Peak power of discharge current	0.66MW
Number of stator disks	4	Energy released in one shoot procces	1.04kJ
Number of pole pairs	4	Width of pulse	2.7ms

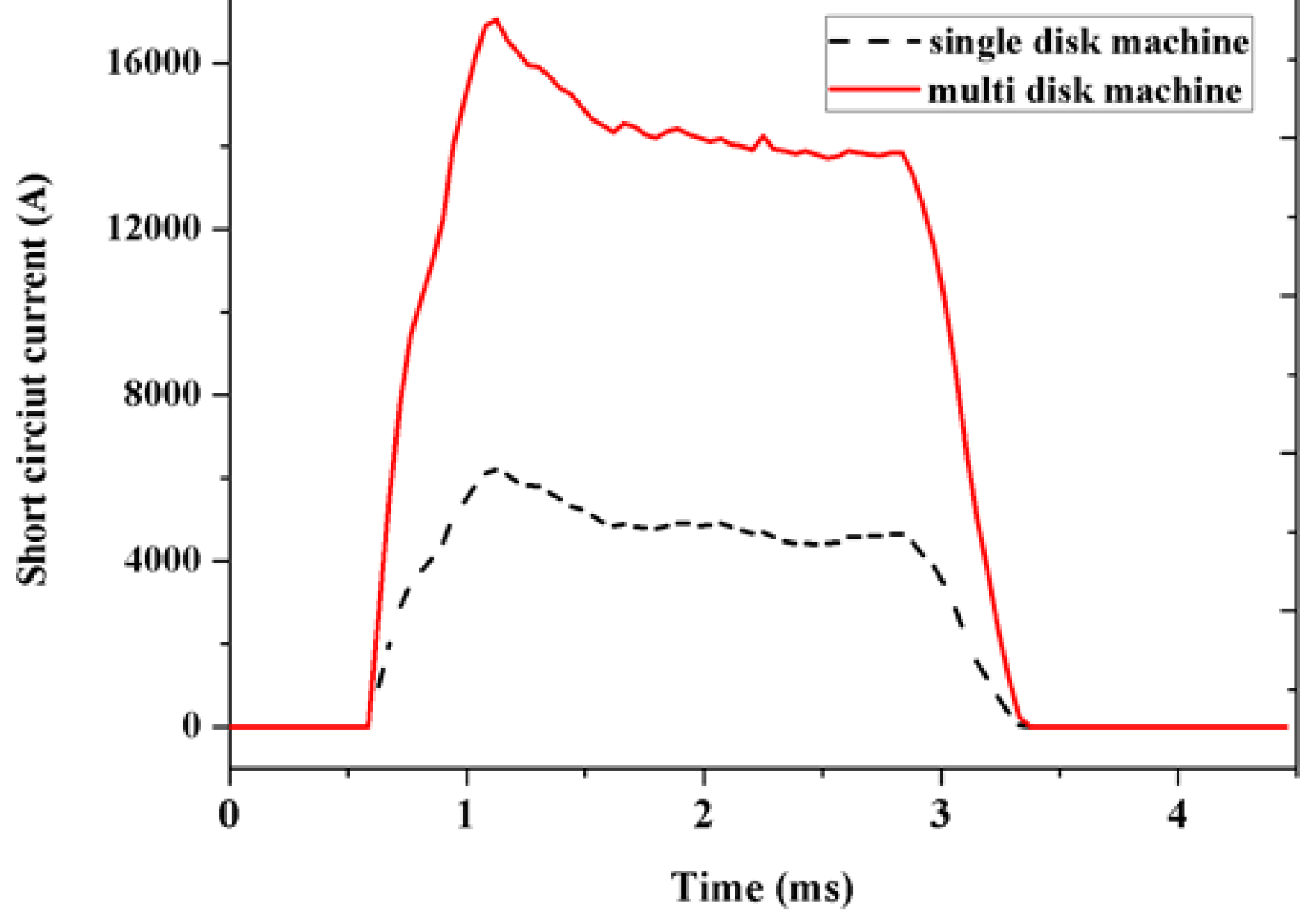

Fig.8. Short circuit current of single-disk machine and multi-disk machine

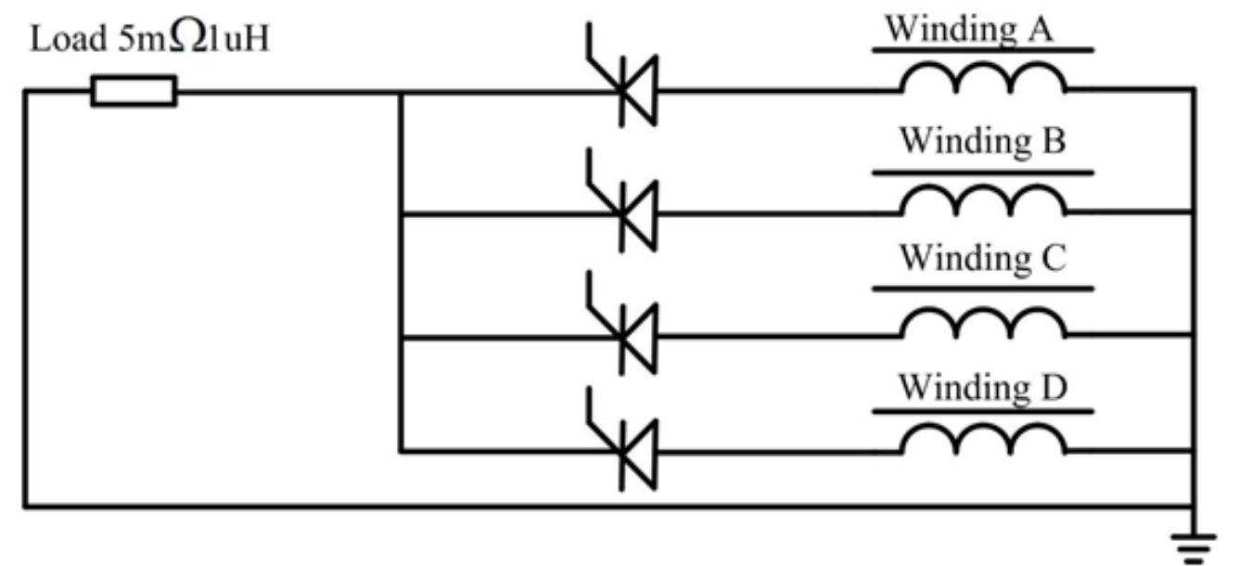

Fig.9. Electrical circuit of discharge process

The inner subtransient reactance are 29mΩ and 10mΩ for single-disk machine and multi-disk machine respectively. In addition, the volume of multi-disk machine is 2.3 time larger than the single-disk one, while the short discharging current is 3 time lager.

The detail parameters and performance of MAFCPA are listed in TABLE Ⅱ. The discharging current on load is shown in Fig.10, from which it can be seen that the mean value of current is 8.45kA, the peak power is 0.66MW, the width of pulse is 2.7ms and the energy released is 1.04kJ.

Presented at Applied Superconductivity Conference, 2017 Aug. 21 – Sep.1, Amsterdam, Netherland; Session: 25th International Conference on Magnet Technology