Design of Axial Flux Permanent Magnet Generator for Generator Driven Electromagnetic Launcher

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***Abstract*— Coilgun type electromagnetic launchers are driven with capacitor bank or generator. The generator should handle special design procedure since it needs particular specifications. It must produce the power in a short time interval. For this purpose, it requires low inductance and resistance value of stator windings. In addition, in order to increase the projectile speed, it needs high frequency of stator current. Moreover, it requires a compact configuration because of mobility. In consideration of these requirements, coreless axial flux permanent magnet generator is selected and designed.**

Keywords—electromagnetic launcher; axial flux permanent magnet; generator

I. INTRODUCTION

Electromagnetic launchers (EML) convert electric energy stored in a power supply to kinetic energy of a moving projectile. Two types of EML exist: Railgun and Coilgun [1]. A railgun has a pair of parallel conducting rails and a sliding armature (projectile) on these rails [2]. Coilgun or electromagnetic induction launcher has one or more coils arranged along a barrel and produces force at the center of coils [3].

The electromagnetic induction launcher is driven with capacitor bank or generator. Both drive methods have been summarized by He *et al.* [4]. In this work, generator driven systems is handled, so particular generator design is proposed in that most of the works have been investigated performance of the generator driven electromagnetic induction launchers in the literature [1-5].

Practically conventional power generation is low in magnitude and takes a long time to deliver energy. Energy from low-level source has to be provided and stored in a suitable device so that it can be delivered at high level in the short period of time [6]. Therefore, it is suitable for using a flywheel system in the energy source.

The launcher that is to say linear induction launcher (LIL) which driven by generators operate like classical linear induction machines under transient state [5]. Time constant of the electrical currents flowing in the launcher coils is very small because of the transient condition of the LIL [4]. For this reason, the generator should supply the high energy to the launcher in a short time interval.

The generator should have some particular specifications: first, the generator should have very low inductance and resistance of stator winding. Second, it should have the high-frequency stator current to reach higher projectile speed. Last, electrical power should be enough for launching heavier projectiles. In other words, high voltage and current are necessary. These requirements call for a special design generator.

Axial flux permanent magnet (AFPM) generator is suitable for providing all of these requirements mentioned above. Stator of the AFPM machines can be designed in coreless fashion. As a result of coreless windings, it has very low stator inductance and resistance [7]. In order to increase the frequency of stator current, number of poles can be increased. Hence, terminal voltage of windings is raised. In addition, AFPM machines are compact and have better power density compared to conventional induction generators [8].

In this work, a new concept three-phase AFPM generator is designed. Contrary to conventional three phase AFPM machines, each stage consists of one phase winding. As a consequence, terminal voltage and unit power of machine is raised approximately 60 percent for same volume of active material and same windings. In addition, a novel winding shape that improves the inductance and resistance values is presented.

Complete system is an energy source that consists of motor, flywheel system and designed generator for meeting power requirement of the LIL. The system was shown in Fig. 1.

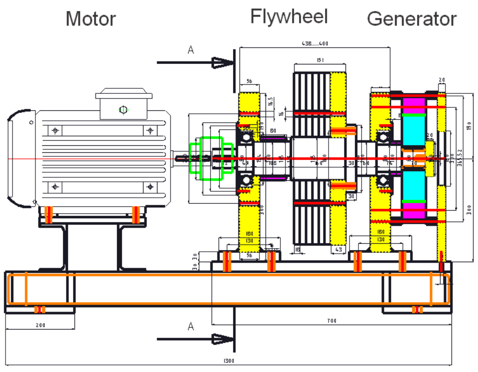


Fig. 1. Energy source for Electromagnetic Launcher

II. FLYWHEEL SYSTEM

Required energy of electromagnetic launcher is related to mass and speed of projectile. Usually, electrical power grid cannot supply this power in a short time period. Furthermore, conventional generators cannot provide that instant power. For these reasons, flywheel system is suggested [9]. Flywheel dimensions are crucial to launch the projectile.

Actual kinetic energy of the disc shaped flywheel is:

$$E_{KA} = \frac{1}{2}J\omega^2 = \frac{1}{2}\frac{\rho\pi r^4 h}{2}(2\pi n)^2 \tag{1}$$

where J is the moment of inertia and ω is the angular velocity of the flywheel. Also, ρ is the density of material, r is the radius of flywheel and h is the length of flywheel.

Required energy storage in the flywheel to accelerate the projectile calculated by [9]:

$$E_{KR} = \frac{0.5mv^2}{\eta \cdot TR \cdot ER} \tag{2}$$

where m and v are the mass and velocity of the projectile respectively, η is the generator efficiency, TR is the energy transfer ratio from barrel to projectile and ER is the energy recovery from flywheel.

Flywheel dimensions, stored energy on the flywheel at 50 rps and required energy for increasing the 0.5 kg projectile speed from zero to 200 m/s are given in Table I.

TABLE I. FLYWHEEL DIMENSIONS, EFFICIENCY AND ENERGY

Radius of Flywheel, (r)	250 mm
Length of Flywheel, (h)	151 mm
Flywheel Material	Steel 1040
TR	0.5
ER	0.2
η	0.5
Stored Energy on Flywheel (E_{KA})	0.35×10^6 joule
Required Energy on Launcher (E_{KR})	0.20×10^6 joule

III. AXIAL FLUX PERMANENT MAGNET MACHINE

AFPM machines have one air gap or more air gaps and air gap flux path is axially orientated. Although main usage of this type machines are low speed and high torque applications, flexible configuration of the topology allows to use them in many different applications [10]. Stator of AFPM machines can be designed without the core that called as coreless AFPM machine. Lack of core in the machine results zero cogging torque. In addition, inductance of stator winding can be very low [13].

The intended coreless AFPM generator should meet the requirements of LIL: high speed of projectile, small time constant of launcher current, high voltage and current i.e. high power.

In order to reach the higher speed of projectile, stator current of the generator should have higher frequency. Pole number of generator and rotational speed of rotor are directly related the frequency of stator current. Mechanical limitations hinder the rotational speed, so number of poles increased to 40 poles for getting high frequency.

Because of the small time constant of LIL, inductance of stator windings should be very small. Coreless fashion of AFPM machine has very low value of inductance. Also the novel stator winding decreases the inductance value and also it has 10 turns of rectangular wire.

Output power of AFPM generators is related to outer diameter of the generator. Analytical calculations of AFPM machines can be easily found in the literature [10-12]. However, outer diameter cannot be increased easily because of the mechanical constraints. This problem is alleviated by multistage design [14]. Output power can be raised via increasing stage number. Contrary to general usage of stator winding, every stage has only one phase winding. Thus, this can be enabled to use the novel stator winding shape. Also the new concept gains 60 percent of terminal voltage and unit power compared to conventional design that has same active material volume and windings. Lateral cross section of the new concept and conventional coreless AFPM generator is seen at Fig. 2.

There are four rotors on the machine and three stator. Rectangular shaped NdFeB magnets are used at rotor that shown at Fig. 3. Leftmost and rightmost rotors have surface mounted magnets and inner rotors have buried magnets. However, to minimize the leakage flux of inner rotors, stainless steel or any strong non-magnetic material can be used. Nevertheless, terminal voltage of the middle stator is lower than outer stators. Decreasing of terminal voltage can be eliminate by increasing thickness of magnets at the middle rotors. Machine dimensions are given in Table II.

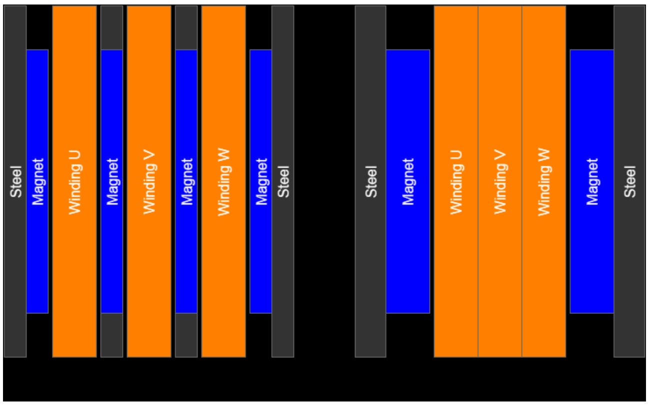


Fig. 2. Lateral cross section of (a) new concept coreless AFPM machine (b) conventional coreless AFPM machine

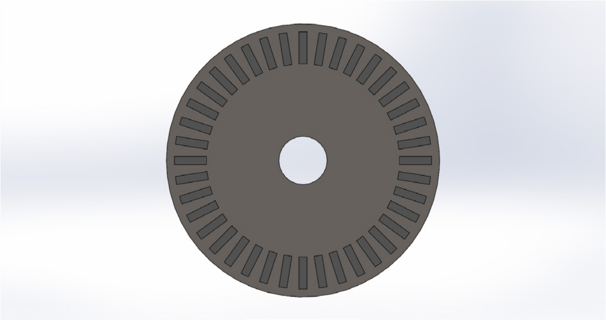


Fig. 3. Rotor of generator

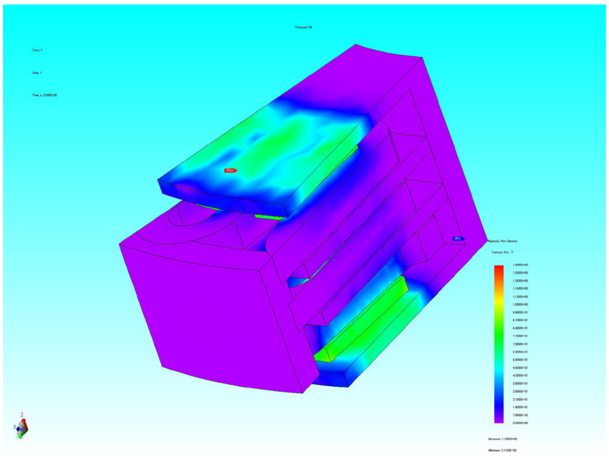


Fig. 4. Magnetic Flux Density of simulation model

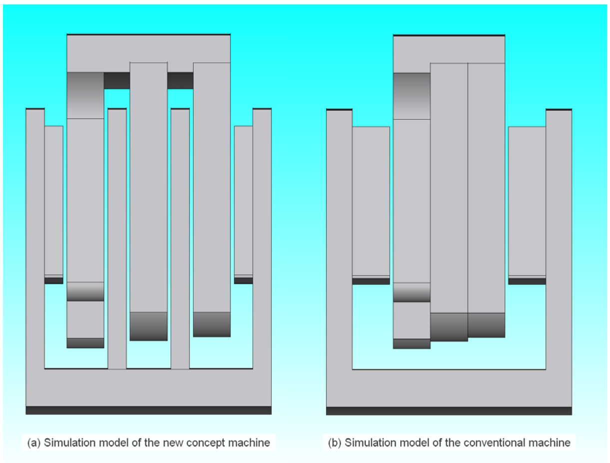
TABLE II. AFPM GENERATOR DIMENSIONS

Radius of Rotor	170 mm
Radius of Stator	205 mm
Rotor Thickness	5 mm
Stator Thickness	10 mm
Air gap (Rotor to Stator)	1 mm
Magnet Shape	Rectangular
Magnet Dimensions	40 x 10 x 5 mm
Wire Dimensions	1 x 10 mm
Number of Turns	10

IV. SIMULATION

Simulations are performed by commercial JMAG software which is used 3D finite elements analysis (FEA). 3D FEA can be time consuming simulations. Therefore, one twentieth of the proposed design is analyzed as seen in Fig. 4. Simulations run under 50 rps (3000 rpm) rotational machine speed.

Two types of machine simulations are done. One type is the new concept coreless AFPM machine and second type is the conventional coreless AFPM machine. Simulation models of machines are shown in Fig. 5.



(a) Simulation model of the new concept machine

(b) Simulation model of the conventional machine

Fig. 5. Simulation models of generators

Both simulations run under no-load condition. Terminal voltages of the concept machine and conventional machine are shown in Fig. 6 and Fig. 7 respectively. Terminal voltage value is higher in the new concept machine than the conventional machine. Moreover, because of the higher air gap in the conventional machine, one of the phase voltage that the lowest one is relatively lower than the lowest phase voltage of concept machine.

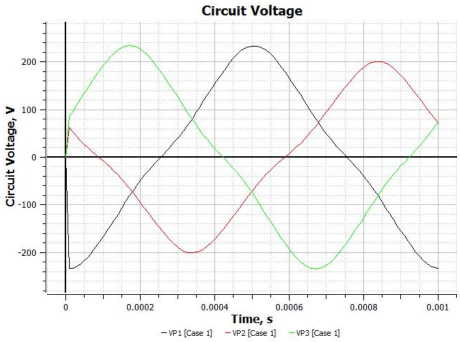


Fig. 6. Terminal voltages of concept machine at 50 rps

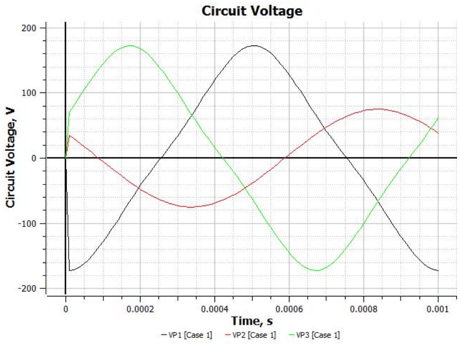


Fig. 7. Terminal voltages of conventional machine at 50 rps

V. CONCLUSIONS

AFPM generators are suitable selection for driving electromagnetic induction launchers. Low inductance and resistance values of stator winding distinguish the combination of AFPM generator and electromagnetic induction launcher. Also the new concept coreless AFPM generator design leads further launcher designs. Simulation results are verified our selection of the AFPM generator for driving electromagnetic induction launcher. Experimental tests and comparison with three stage three phase will be done on future works.

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