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Temperature rises characteristics of modern double sided flat permanent magnet linear generator for free piston engines for hybrid vehicles

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Abstract

This paper presents the development of a thermal model for a novel flat, double-sided linear generator designed for use in free-piston engines. The study conducted in this paper examines the influence of temperature on the performance of the permeant magnet linear generator, an integral and pivotal component within the system. This research places particular emphasis on the Neodymium Iron Boron (NdFeB) permanent magnet, which serves as a source of magnetic field for the linear generator. In this study, an internal combustion engine that tends to produce heat is connected to a generator. Considering the temperatures rise from both the combustion process and the thermal contributions of current-carrying conductors and frictional forces. Utilizing Computational Fluid Dynamics (CFD) method, a thermal model of the (NdFeB) magnet within the linear generator is constructed and analyzed. Furthermore, the temperature field is examined to ensure that the linear generator operates under stable conditions without the risk of demagnetization.

Keywords:Free piston engine, permanent magnet, linear generator, demagnetization, simulation.

1. Introduction

The rapid exploitation of fossil fuels due to their indiscriminate use has brought us to a point where we cannot continue to use gasoline and diesel beyond the next three decades. Transportation is accountable for a substantial amount of global utilization of energy. The low efficiency of conventional vehicle power systems leads to significant emissions of NO_x and CO_2, thus contributing to the greenhouse impact[1]. Authorities and energy corporations internationally are on the quest for alternative propulsion methods for vehicles. Given the potential advantages of elevated efficiency, diminished emissions, and adaptable fueling, the free-piston linear generator (FPLG) emerges as a promising contender for powering hybrid electric vehicles within a hybrid powertrain configuration (HEVs)[2].

The Free Piston Linear Generator (FPLG) is an electromagnetic device that converts reciprocating mechanical motion into electrical energy through the oscillation of a piston within a cylinder. This innovative device is capable of increasing the driving range and functioning as a secondary power converter in hybrid vehicles, particularly during instances when battery charging infrastructure is inaccessible. The free-piston engine involves a compression stroke and a power stroke within its combustion cycle. In the compression stroke, the piston is driven by an air spring to move from the bottom dead center (BDC) position. When the piston reaches the top dead center (TDC), it initiates the power stroke. The expansion of the fuel within the combustion chamber generates mechanical work, producing a force on the piston in a direction opposed to its initial position. The linear generator's piston and mover are linked through a piston rod. The reciprocating motion of

the piston propels the mover, which leads to the changing of a magnetic field within the linear generator to produce electrical energy. By adjusting the piston's stroke length, the compression ratio and thermal efficiency can be raised.[3].
Variable compression ratios, however, can also lead to various fuel sources and combustion modes, which can result in a range of clean energy applications[4]. The Linear generator is an integral part of the FPLG system and is directly connected to the free piston. As depicted in Figure 1, Consequent to the elimination of the crankshaft and connecting rod assembly, the conventional combustion engine's camshaft has been substituted by electromagnetic valves[5].

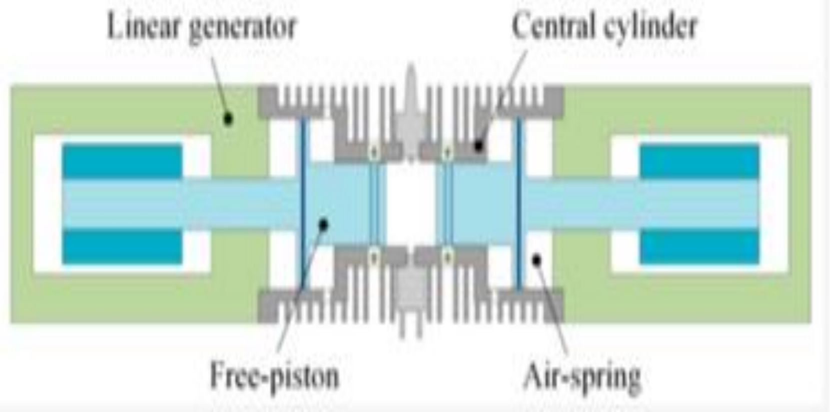

Figure 1: Free piston engine linear generator

This research focuses on the permanent magnet linear generator due to its significant susceptibility to demagnetization from heat generated by the free piston engine, stator coils, and frictional forces. Nowadays, a great effort is being made regarding available energy conversion with the development of rare-earth permanent magnets. The maximum energy density(products) of neodymium iron boron (NdFeB) magnets is approximately 500 kJ/m^3, as shown in Figure 1. However, PM can generate high overall efficiency and reasonable force density at low speed, and as a result, it is widely used in a variety of applications, including home appliances, aerospace, wind power generation, and electric/hybrid electric vehicles [6], etc.

The performance of PMs in linear generators depends on temperature stability, and the thermal impact is an essential element that imposes limitations on the enhancement of power/torque density[7]. However, the thermal degradation has greater significance in the case of permanent magnet (PM) generators due to the vulnerability of the frequently used high-energy rare-earth PM material, such as NdFeB, to thermal overheating. The temperature rise in permanent magnets (PM) leads to decreased remnant flux density and reduced knee points of PM demagnetization characteristics. Consequently, this results in a decrease in both output torque capacity and efficiency. Moreover, when the temperature at localized hotspots of the permanent magnet (PM) exceeds the maximum allowable operating temperature and the operational points surpass the knee points on the PM demagnetization curve, it leads to partial and irrevocable demagnetization of the PM. Furthermore, once the permanent magnet (PM) temperature is above the Curie point, the PMs will experience complete demagnetization.

Many researchers worldwide are concerned about how linear generators can contribute to clean energy. The research and enhancement of novel energy vehicles and high-performance power units has emerged as an important topic of interest within the automobile sector. To improve the performance of the linear generator

prototype, a comprehensive analysis of prior research has been conducted. On the basis of previous research conducted at West Virginia University and the Sandia National Laboratories in California, the fundamentals of designing a free-piston generator have been analyzed.[8, 9].
In [10], A linear generator design for the wave energy conversion system was suggested, aimed at augmenting system stability through the reduction of cogging force. Comparing the flat and tubular linear electric machines, Li et al. [11] from Shanghai Jiao Tong University found that the flat-type alternator has superior efficiency, specific power, output voltage, and current.

Xu developed a tubular permanent magnet linear generator that incorporated both I-shaped and rectangular configurations. Notably, the I-shaped PMLG demonstrated superior output power and efficiency in comparison to the rectangular model[12].

Mahadi designed a linear generator designed specifically for hybrid vehicles applications. This study investigates the impact of heat generated from various sources such as combustion engines, current-carrying conductors, and friction, on the performance of NdFeB magnets. The investigation is conducted both with and without the presence of cooling fins [13].
Sun ye [5] investigated and modeled the maximum operating temperature without accounting for the heat source derived from combustion engine exhaust.

The purpose of this research is to simulate and study the thermal characteristics of a novel of double-sided flat permanent magnet linear generator for FPEG. The temperature field of the flat moving-magnet will be analyzed utilizing computational fluid dynamics (CFD) modeling techniques. The investigation will concentrate on examining the temperature rise characteristics of the flat moving-magnet. Finally, It is important to adhere to the specified maximum operating temperature for the permanent magnet in order to sustain its physical, mechanical, and magnetic characteristics [14].

2. The design structure of linear generator

The Permanent Magnet Linear Generator contains a foundational structure as shown in fig.2., two stationary assemblies known as stators, and a moving assembly referred to as the mover. The mover assembly is consisting of two permanent magnets and a support structure that houses the mover. As depicted in the image(figure), the magnetization direction of the two permanent magnets (PMs) is oriented perpendicular to the shaft, with their polarities reversed and directed towards different stator components. The base is equipped with two non-magnetic shafts, into which the entire mover assembly is securely mounted. This configuration enables the mover assembly to reciprocate at rapid pace, facilitated by the inclusion of sliding bearings.
The mover assembly is encompassed by two stator assemblies characterized by symmetrical specifications. The stator assembly has two coil bobbins, two stator supports, a coil, and a core. The bobbin serves the dual purpose of securing the core and insulating the winding against abrasion caused by the core. The winding is positioned within two slots located on the iron core. To ensure a consistent gap between the stator and the mover, the stator supports are securely fastened to the base. The stator assembly and mover assembly are separated by an air gap. The PMs and the core determine the magnetic attraction between the stator and mover components. The stator core is made by laminating silicon steel sheets perpendicular to the shafts, which reduces eddy current loss effectively. Thus, it is possible to reduce the amount of heat produced by the generator and increase its efficacy. As a component of the stator, the coil can be actively cooled [15].

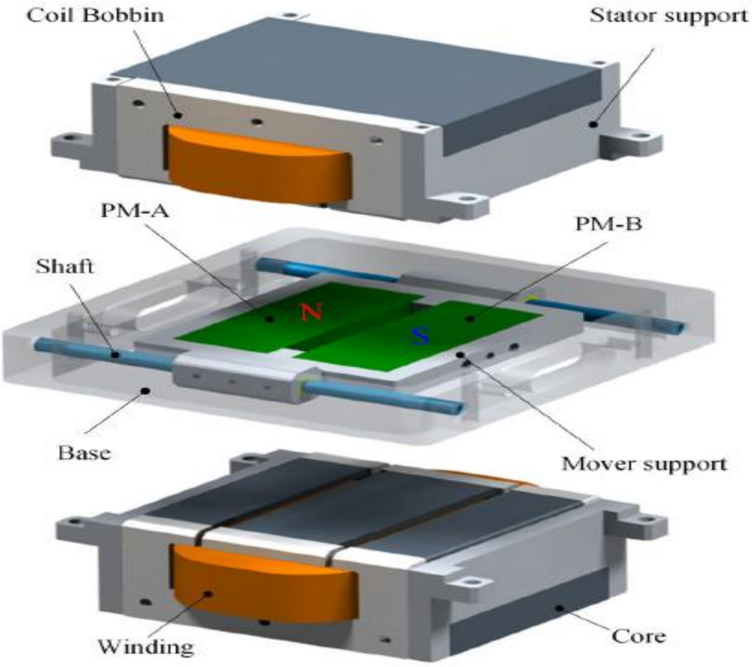

Figure 2: Double sided flat linear generator

Table 1. Main parameters of permanent magnet

Name	Parameters
Generating power (KW)	2
efficiency	95
volume	4.5
Rated frequency (Hz)	50
Rated stroke(mm)	40
Average force(N)	15.8
Power density(W/kg)	183
Moving mass (kg)	1.4
Max cogging force(N)	58
Outer dimension	180*188*132 mm
PM	100*40*12 mm
PM material	N42SH
Max working temperature of PM	423K

Stator material	47F240
Max stroke	40 mm +2 mm

3. Permanent magnet for linear generator design

A neodymium iron boron (NdFeB) permanent magnet, which is a type of rare earth magnet is an excellent option for a linear generator. Compared to other permanent magnets due to its highest energy output. Therefore, N42SH has been chosen as the material for the permanent magnet generator design, as it possesses the highest magnetic property among other permanent magnets, having a maximum operating temperature of 423 K. While this meets the design specifications for the generator, it is essential to maintain the permanent magnet's optimal operating temperature to preserve its physical, mechanical, and magnetic characteristics.

4. Simulation of thermal analysisof flat double sided linear generator

Taking into account the thermal effect is a critical factor that must be considered throughout the design phase of a linear generator. There are three main methods [16]: The methods for analyzing the thermal performance of a linear generator include the simplified formula approach, the equivalent thermal circuit technique, and the temperature field analysis. Among these, the temperature field method employs modern numerical techniques such as Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) to accurately solve complex thermal equations, The finite element method is a versatile and adaptable technique that combines the advantages of traditional finite difference methods with those of analytical computations. On the other hand, CFD is a computer simulation technique used for heat transfer and fluid flow modeling.

Numerical methods, including Finite Element Method (FEM) and Computational Fluid Dynamics (CFD), have been developed within software platforms to become among the most effective analytical tools available. [17, 18]. Based on Highly proficient computer resources, therefore the software can be applied to solve complex conjugate heat transfer problems.

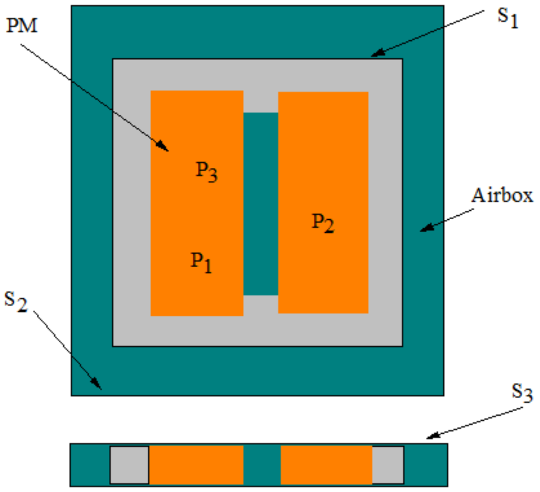

Figure 3: Permanent magnet temperature field model

By using numerical simulation, the temperature field of PM is analyzed throughout the CFD method, using ANSYS Fluent.

To evaluate the temperature gradients of the FPLG components, numerical analyses were performed [19]. The resulting temperature distributions from the combustion chamber to the linear generator and the resulting heat flux distribution in the area which connected directly to the linear generator by translator are 345 K and 47612 W/m^2 respectively. This information will have applied as thermal load into the linear generator model.

The model consists of the mover component of PM, an air box, and three distinct interface types. The model has three temperature monitoring locations as shown in Figure 3.

To streamline the model and enhance computational efficiency, it was assumed that the stator could be cooled by direct cooling. Consequently, the stator was reduced to a wall with a constant temperature boundary condition. Incorporating the power loss from the PMs as a thermal source in the temperature field calculation, it was determined that the collective heating power of the two permanent magnets amounted to 12.3 Watt. Figure 4 illustrates the temperature distribution of the PM during a duration of 120 minutes, with the stator temperature maintained at a constant value of 340 K. By applying the stator at various constant temperatures as variables, Figures 5,6,7 demonstrates the temperature rise at the three monitoring points. After 120 minutes of generator operation, the temperatures at the three monitoring points nearly converge, as shown in the graph the temperature variations at three distinct monitoring points over time, corresponding to stator constant temperatures of 300 K, 320 K, and 345 K respectively. The temperature will stabilize marginally above the stator temperature at all locations. The higer resulting temperature is 378 K.

The higher temperature threshold for N42SH must not be exceeded, which is set at 423 K. The PM's temperature can be maintained at a maximum of 378 K, aligning with the typical operational limits for this particular brand of permanent magnet. By analyzing the temperature field of the PM using CFD, it is possible to conclude that the designed heat dissipation conditions of the generator satisfy the PM's requirements for stable operation.

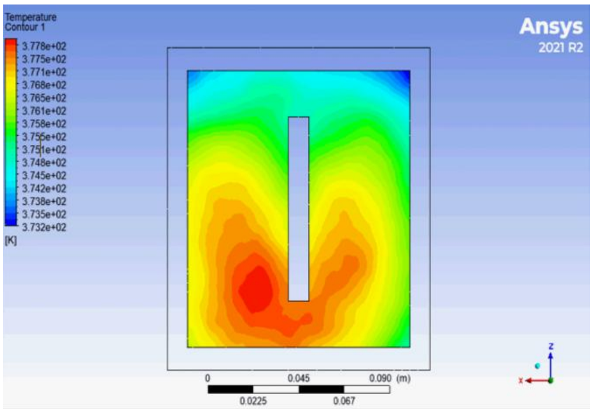

Figure 4: Temperature distributions of the PM

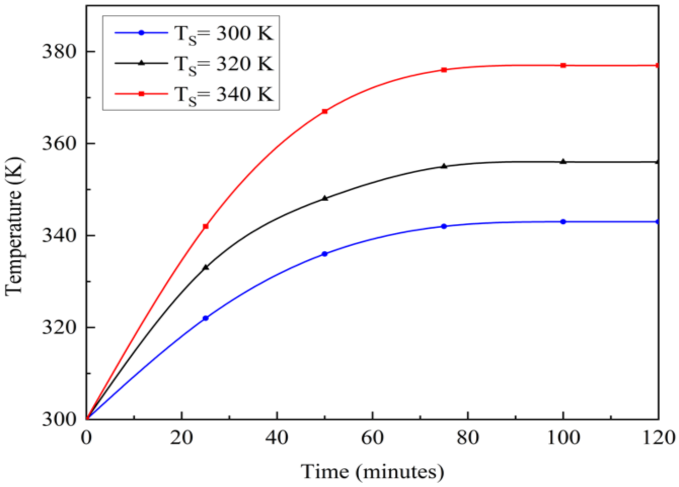

Figure 5: Temperature rise monitoring of point one

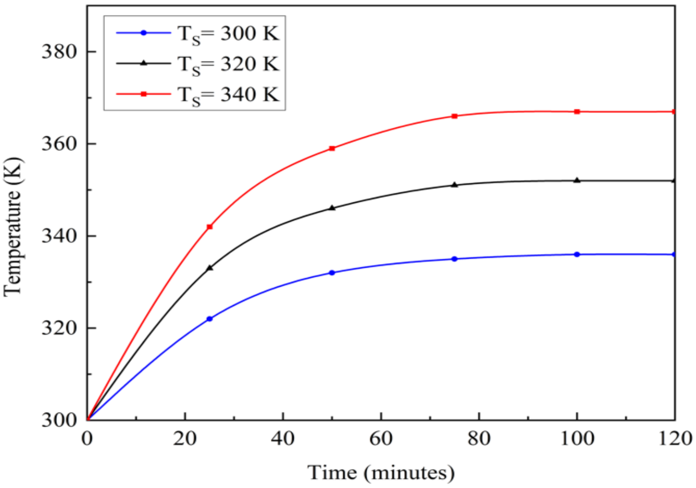

Figure 6: Temperature rise monitoring of point one

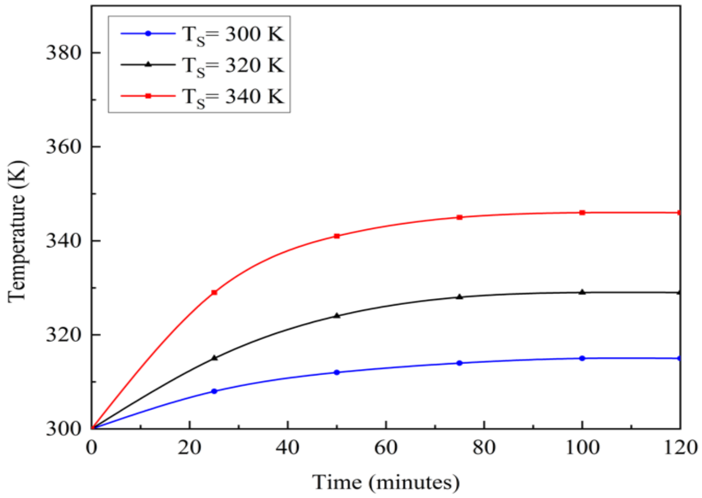

Figure 7: Temperature rise monitoring of point one

5. Conclusion

This paper describes the development of a novel flat double sided permanent magnet linear generator for free-piston engines. The structure of the generator is explained and the heat effect from the combustion is added. A complete temperature field model is developed and evaluated. The greatest temperature of the moving magnet will remain stable at 378K, which is within the normal operating temperature range of N42SH. For research purposes, the stator part of the generator temperature field model has been simplified into an ideal temperature surface. There's no risk of demagnetization will occur when the operation condition of the PM is stable at the temperature of 378 K and to ensure proper working condition cooling system must be designed and this will be established and analyzed later.

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