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High temperature operation of multi-watt, axial-flux, permanent-magnet microgenerators

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ABSTRACT

This paper presents the characterization and modeling of a permanent-magnet (PM) microgenerator operating at high temperatures. Due to the thermal dependence of the relevant properties of the conductor and magnetic materials, degradation of the output electrical power with increased temperature is expected. Each material of the PM microgenerator is magnetically or electrically characterized up to 375 °C. For a rotor designed for high temperature operation using SmCo magnets, 2.7 W of DC power has been obtained at 100 °C and 210,000 rpm, which is a 35% drop as compared to the output power at room temperature. This result is in good agreement with theory. Calculations showed that this PM generator is capable of 2.4 W of DC output power at an operating temperature of 300 °C if the rotational speed is increased up to the 300,000 rpm, as achieved with previous room temperature devices. This work demonstrates that MEMS-based permanent-magnet microgenerators are good candidates as a component of a heat-engine-driven electrical power generation system.

1. Introduction

The power requirements of modern electronic devices are rapidly outpacing the power density and energy of the best batteries. This has led to the development of small-scale, watt-level, electrical power sources intended for power electronics. Accordingly, heat-engine-driven MEMS-based systems are very attractive, and consist of a cm-scale gas-fueled turbine engine [1], and an electrical generator [2–4] as the chemical-to-mechanical, and mechanical-to-electrical converters, respectively.

Recently, there has been much work in the development of microscale mechanical-to-electrical generators as essential components of these heat-engine-driven electrical power sources for portable electronics. However, in such compact systems, the generators must function in the relatively high temperature environment adjacent to the heat engine. Although a number of small-form-factor microgenerator systems ultimately intended for integration with heat engines have been presented [2–4], less attention has been paid to their high temperature performance. Indeed, microgenerators typically use low temperature magnetic materials [2,3] to obtain better performance rather than high temperature compatible magnetics. Performance requirements are further exacerbated by the compact nature of these microsystems and the difficulties involved in maintaining large internal thermal gradients.

This paper reports the high temperature operation of axial-flux, permanent-magnet (PM) microgenerators. These devices are capable of delivering watt-level DC power to an external load at an operating temperature of 300 °C. First, the microgenerator design is presented, and considerations on the temperature range of operation of these microgenerators integrated with heat engines are detailed. The magnetic materials used in the PM microgenerators are characterized up to 375 °C, and the temperature dependence of the electroplated copper windings is also investigated. A phenomenological model is introduced to express the power degradation based on the measured material properties as a function of temperature. Finally, measurements of electrical power for several microgenerators at high temperatures are reported and discussed.

2. Generator design

As shown in Fig. 1, previously reported high-speed rotors [5] and optimized stators [4,6] are used for these high temperature experiments. The generators are three-phase, eight-pole, axial-flux, synchronous machines, each consisting of copper stator windings [7,8], and a multi-pole permanent-magnet rotor [9]. An external air-driven turbine spins the PM rotor, which creates a time-varying

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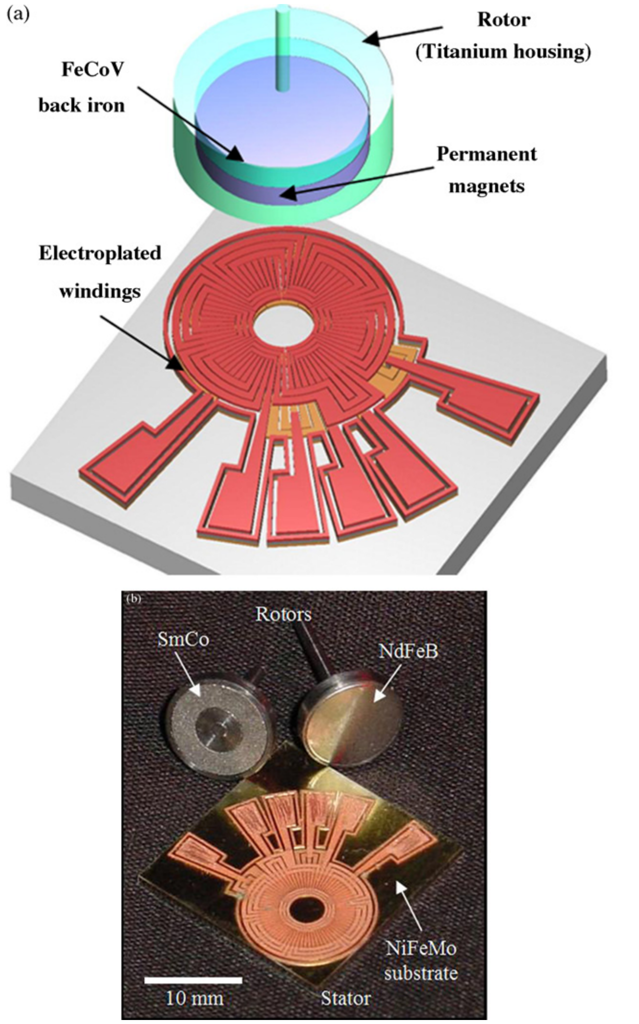

Fig. 1. Optimized winding geometry stator and rotors: (a) Three-dimensional (3-D) rendering, and (b) 3-D view of the stator and two rotors with different permanent-magnet materials.

magnetic flux. As a result, AC voltages are induced in the coils. When a load resistance is connected to the windings, electrical power is generated.

The stator is fabricated using conventional microfabrication approaches, and consists of two layers of electroplated copper coils with an SU-8 epoxy interlayer dielectric on top of a ferromagnetic NiFeMo (moly-permalloy) substrate. The stator is designed as an eight-pole, three-turn/pole device and exhibits a resistance per phase of approximately 170 mΩ. Simulations have previously been performed and have shown that this configuration yields the highest output power [4]. Per phase, open-circuit voltages are varying in the 0.5–2V_{RMS} range at room temperature. The rotor includes a ferromagnetic material (FeCoV – Hiperco 50) to serve as a back iron, and a permanent-magnet material. Rotors operate at speeds of up to 400,000 rpm.

3. Temperature considerations of small-scale gas engines

Such electromagnetic generators are intended for integration with heat-engine-driven, high-speed turbine systems. Fréchette and coworkers are developing a MEMS-based, Rankine cycle steam turbine [10,11]. Their current efforts are focused on the development of the high-speed rotating system, but considerations on the electrical generator have also been introduced. It must withstand high rotational speeds (rotor tip velocity of 100’s of m/s), and sustain high temperatures. The rotor should reside at an average of the minimum and maximum cycle temperatures, which corresponds to temperatures varying between 200 and 400 °C.

Stevens et al. discussed several design issues of a fuel-based micropower generator [12]. To overcome the temperature-related issues in the magnetic generator, the permanent magnets must be integrated at the lowest temperature side of the turbine (i.e., compressor side), and extra cooling should be provided through passing air across the magnets. The PM generator is located in an environment with temperatures varying between 200 and 300 °C. To surmount the detrimental effects caused by high temperatures, and because the output power delivered by the machine varies as the square of the rotor speed, high rotational speeds are required in order to fabricate microgenerators with high power density capabilities.

As a result of the temperature-related considerations reported by Fréchette and Stevens with regards to the integration of PM microgenerators with heat engines, the fabricated devices must be able to operate at temperatures around 200–300 °C. Detrimental temperature-dependent material effects consist of increased winding resistance and decreased magnetic properties, including decreases to both permanent-magnet remanence, and ferromagnetic saturation magnetization. Consequently, the PM microgenerators and their temperature-dependent materials have been characterized in this temperature range.

4. High temperature characterization

4.1. Magnetic characterization

The thermal dependences of the small-scale magnetics have been investigated using a Vibrating Sample Magnetometer (VSM) with an integrated furnace. The temperature ramp is set at 25 °C per 1.5 min. For each measurement, the system is stabilized for a few minutes before recording any data. Both PM materials and ferromagnetic materials in the geometries and size scales of interest have been tested. SmCo and NdFeB PM materials are 0.5 mm thick. FeCoV and NiFeMo back iron materials are of a thickness of 1 mm.

Both, SmCo and NdFeB are characterized as possible permanent-magnet materials. Although SmCo has a lower room temperature remanence (B_r = 11.5 kG) compared to NdFeB (B_r = 13.9 kG), it possesses a much higher Curie temperature ($T_c \sim 800$ °C) and maximum operating temperature ($T_{max} \sim 300$ °C) as compared to NdFeB ($T_c \sim 300$ °C, $T_{max} \sim 100$ °C). At high temperatures, SmCo will likely be preferred. However, high rotational speeds or directed airflow may provide sufficient cooling to use the better performing but more temperature-sensitive NdFeB magnets at moderate temperatures.

The temperature-dependent remanence of microscale rotor magnets have been experimentally determined as depicted in Fig. 2. These results for the different materials are presented as normalized to their respective room temperature values. Neglecting any potential cooling effects due to high rotational speeds of the PM rotors, these microscale NdFeB magnets cannot be used above approximately 150 °C due to a nearly complete remanence loss at high temperatures. From the experimental data, an approximate curve fit for the temperature dependence for microscale permanent magnets is defined by

$$B_r(T) = B_{r(25\,^\circ C)} \times (1 + \alpha_{PM} \times (T - 25)) \quad (1)$$

where $B_r(T)$ is the measured remanence of the permanent-magnet material at a temperature T in °C and α_{PM} is a linear coefficient