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A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads

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ABSTRACT

As the demand for alternative sources of energy has increased, harvesting abundant environmental energy such as vibration energy including track vibrations in railway systems has attracted greater attention. In this study, we develop a portable high-efficiency electromagnetic energy harvesting system with supercapacitors that converts the energy of track vibrations into electricity. The generated electricity is stored in the supercapacitors and used in remote areas for safety facilities or in standby power supplies for rail-side equipment. The proposed system consists of a mechanical transmission and a regulating circuit. Acting as the energy input and transmission, Gears and a rack amplify the small vibrations of the track, and one-way bearings enhance efficiency by transforming bidirectional motion to unidirectional rotation. Supercapacitors are used in the vibration energy harvesting system for the first time. The supercapacitors permit the storage of energy from rapidly changing transient currents and a steady power supply for external loads. The proposed system is demonstrated through dynamic simulations, which show the rapid response of the system. An efficiency of 55.5% is demonstrated in bench tests, verifying that the proposed electromagnetic energy harvesting system is effective and practical in renewable energy applications for railroads.

1. Introduction

Rail transportation plays an influential role in the economy and everyday life in China. The railroad infrastructure has been improved dramatically over the last two decades, mainly because of large investments in construction by the Chinese government. The total length of the rail lines in China is greater than 100,000 km [1]. Rail transportation has been improved in many aspects, particularly the total length of railway lines, the electrification rate and the operating speed, which requires greater safety. To ensure the safety of the railway system, it is essential that rail-side electrical equipment such as signal lights, wireless communications, monitoring devices and positive train control are well maintained and operating correctly. Unfortunately, a considerable proportion of the railroad tracks lie in remote areas, where electric power is in short supply [2]. In these regions, equipment such as warning signal lights and wireless sensors for track monitoring often cannot be installed because of the lack of a reliable power supply or low-maintenance batteries. Therefore, it is important to develop a portable, highly efficient and low-cost power source for rail-side equipment in remote areas. Energy can be harvested from the vertical movements of railway tracks caused by transient loads from the train wheels when a train passes over the track. These movements are a potential renewable energy source that can completely or at least partly replace batteries as the source of power in trackside equipment.

Harvesting ambient energy from the environment by transforming mechanical energy into effective electrical power is a desirable solution for remote areas. In railroad applications such as safety facilities or standby power supplies, energy harvesting from the tracks would be particularly useful in remote areas. Existing vibration energy harvesting systems based on the rail tracks can be classified into two categories: piezoelectric and electromagnetic.

Practical and reliable piezoelectric designs have been developed [3–8]. However, because of their low power density and average power (milliwatts), piezoelectric energy harvesting systems are suitable mainly for microelectronics and micro-electromechanical systems (MEMS) [9]. For example, Hu et al. presented a nanogenerator constructed of piezoelectric materials for tire pressure monitors in which the maximum output power density approached 120 $\mu W/cm^3$ [10]. Guan et al. investigated a piezoelectric energy harvester using a rotating system in which a piezoelec-

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tric component was repeatedly compressed by rotors and produced an output power of 83.5–825 μW [11]. The main problem with piezoelectric systems is that the power output of piezoelectric materials is very low; thus, they are restricted to small applications and are not suitable for railway safety facilities.

An alternative to piezoelectric energy harvesting is electromagnetic harvesting [12–17]. These types of systems have been designed to tap inconspicuous motions in the environment such as road surface vibrations and building vibrations, transforming them into relative motion between permanent magnets and coils. For example, Zuo et al. developed a regenerative vehicle shock absorber with an electromagnetic energy harvesting device consisting of gears, racks and a rectifier to replace conventional shock absorbers. These shock absorbers convert the vibrations of vehicles into energy, delivering a peak power of 68 W [18]. Cassidy et al. developed a transducer for energy harvesting in large-scale structures, utilizing ball screws to convert mechanical energy into electricity. This transducer was coupled to a base-excited, tuned mass-damper system and achieved a power level of 100 W [19]. Lu et al. developed an energy harvester based on a single-degree-of-freedom transmission for use on bridges to scavenge vibrational energy [20]. Zhang et al. developed an energy harvesting system for use in speed bumps, using electromagnetic linear alternators to store the energy of friction and compression between vehicles and the road surface [21]. The device achieved a relatively high output voltage of 194 V, indicating the potential for higher outputs. Electromagnetic energy harvesters appear to have favorable characteristics for applications in ancillary railroad equipment.

Several energy harvesting systems have been used in railroad safety devices. Yuan et al. developed a drum transducer with piezoelectric materials to be placed underneath railroad tracks that produced a peak voltage of 70 V [22]. Pourghodrat et al. designed an energy harvesting system for railroads by converting the kinetic energy of the track into electricity to provide an alternative power source for remote areas [23]. Hansen conducted field tests of an electromagnetic energy harvester for railroads that performed both energy harvesting and track safety monitoring [24]. Nagode proposed two types of energy harvesting devices for railroad applications using linear generators and rotary generators to produce up to 54 W from motions of 0.75 in. at 1 Hz [25]. These systems for railroad energy harvesting can supply the necessary amount of power but are cumbersome; thus, there is a trade-off between output and usability.

To increase the efficiency of energy harvesting systems and to effectively use the electricity produced, several studies have focused on energy management [26–28]. Hendijianizadeh proposed the efficiency of linear and rotational electromagnetic energy harvesting systems, showing that a rotational system delivers more power than a linear system [29]. Phillips developed a control system for an electromagnetic railroad energy harvester to regulate power and adjust to the electric loads [30]. These results suggest that energy harvesting systems for railroad applications have been developed to a considerable level but are nevertheless inadequate in many respects such as portability, speed and durability.

Although the existing systems have been intended for railroad safety facilities, certain aspects of railroad energy harvesting have not been addressed. Two main challenges remain with this technology: (i) capturing and rectifying the highly variable vibrational energy efficiently and responsively and (ii) increasing the output power so that the system is suitable for trackside equipment that requires high power.

In this study, a novel, portable high-efficiency energy harvesting system with supercapacitors for railroad applications is investigated. A mechanism for converting bidirectional motion to unidirectional rotation enables this system to efficiently perform high power energy harvesting for railroad safety devices. Supercapacitors are included to rapidly capture and rectify the input energy, which is important for energy harvesting. In addition, this design considers portability and ease of installation, which are important for railroad emergency power supplies.

The remainder of this paper is organized as follows. In Section 2, the system architecture is described. The design of the system is described in Section 3, including the mechanical components and the electric circuit, and the operating principle of the system is illustrated. A mathematical model of the system is derived in Section 4. In Section 5, the setup for bench tests performed to validate the system is presented. The test results and a discussion are provided in Section 6. Finally, some conclusions are drawn in Section 7.

2. Architecture

The goal of this study is to develop an electromagnetic energy harvesting system for use in railroad systems that is highly efficient, portable, reliable and simple. A mechanical transmission consisting of gears and a rack was designed to convert the energy of rail vibrations into electricity. The general architecture of our portable high-efficiency electromagnetic energy harvesting system, shown in Fig. 1, consists mainly of the mechanical transmission and the electrical regulator.

When a train rolls over a section of track, vertical displacements are induced by the weight of the train. Because of the elasticity of the rails, they vibrate. A rack that is fixed to the rail moves at the same amplitude and frequency as the rail. The rack harvests the vertical vibrational energy of the rail. The movement of the rack is amplified by a high-ratio gear set, thereby converting small displacements and velocities into high-speed rotation of a shaft connected to a generator. Two one-way bearings mounted on the shafts engage alternately to convert the bi-directional input displacement to unidirectional rotation to increase efficiency. As shown in Fig. 1, the output shaft drives a DC generator in only one direction to generate power. The power is stored in the supercapacitors and can be drawn upon or stored for standby power in trackside applications such as crossing lights, switches and maintenance.

3. Design of the electromagnetic energy harvester

3.1. Mechanical design

Vibrations in the rail produce a small amount of motion. Therefore, a gear set is included to magnify these small but strong vibrations. The rack is connected to the rail by a fixture and transmits the vibration to a pinion gear. Torque is applied to the generator by the gear set, causing the generator to rotate at a high speed to generate power.

The input assembly includes a fixture placed under the track, a vertical rack that meshes with a small pinion gear, a gear set with a high ratio and a pair of output gears that mesh with a gear on the generator shaft. The gear set amplifies the velocity and the displacement of the rack. The gears are fixed to shafts that are mounted on bearings, and the bearings are mounted on a wooden board. Fig. 2 shows the design and a prototype of the electromagnetic energy harvester.

The most important part of the electromagnetic energy harvester is the reversing mechanism that converts the bidirectional vibration into unidirectional rotation. As shown as Fig. 3a and b, this bi-directional-to-unidirectional (B2U) conversion mechanism consists mainly of two one-way bearings. The one-way bearings engage the shaft only when rotating in one direction. The one-