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High-power density miniscale power generation and energy harvesting systems

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ABSTRACT

This paper reports design, analysis, evaluations and characterization of miniscale self-sustained power generation systems. Our ultimate objective is to guarantee highly-efficient mechanical-to-electrical energy conversion, ensure premier wind- or hydro-energy harvesting capabilities, enable electric machinery and power electronics solutions, stabilize output voltage, etc. By performing the advanced *scalable* power generation system design, we enable miniscale energy sources and energy harvesting technologies. The proposed systems integrate: (1) turbine which rotates a radial- or axial-topology permanent-magnet synchronous generator at variable angular velocity depending on flow rate, speed and load, and, (2) power electronic module with controllable rectifier, *soft-switching* converter and energy storage stages. These *scalable* energy systems can be utilized as miniscale auxiliary and self-sustained power units in various applications, such as, aerospace, automotive, biotechnology, biomedical, and marine. The proposed systems uniquely suit various submersible and harsh environment applications. Due to operation in dynamic rapidly-changing envelopes (variable speed, load changes, etc.), sound solutions are researched, proposed and verified. We focus on enabling system organizations utilizing advanced developments for various components, such as generators, converters, and energy storage. Basic, applied and experimental findings are reported. The prototypes of integrated power generation systems were tested, characterized and evaluated. It is documented that high-power density, high efficiency, robustness and other enabling capabilities are achieved. The results and solutions are scalable from micro (~100 μW) to medium (~100 kW) and heavy-duty (sub-megawatt) auxiliary and power systems.

1. Introduction

Focused developments have been performed on enabling medium- and heavy-duty energy conversion, energy generation systems and auxiliary units from kilo- to mega-watt range. Sound solutions at the device (component) and system levels have being emerged which resulted in possibility to design high-performance systems in various applications [1,2]. The energy conversion in those systems has been examined [3–5], and, the major components have being developed. Depending on power range, specifications and requirements, conventional and permanent-magnet AC and DC generators are designed, tested, characterized and deployed [6–14]. In general, synchronous generators guarantee superior performance as compared with DC generators. Rear-earth permanent-magnet synchronous generators are the key components of high-performance sub-megawatt auxiliary power systems. For those generators, the matching controllable rectifiers [15–20] and *soft-switching* converters [12,21–24] have been used. However, in variety of applications, *scalable* super-high-density, affordable and robust miniscale energy harvesting, energy generation and auxiliary power units should be designed, developed and deployed. These miniscale systems, with output power from micro- to subkilo-watt may not effectively utilize the existing device- and system-level solutions (components, devices, topologies and organizations) used in medium- and heavy-duty energy conversion systems. In fact, radial- and axial-topology permanent-magnet synchronous generators, power electronics and energy storage solutions can be profoundly different. The aforementioned systems commonly required to operate in harsh environment and rapidly-changing operating envelope, yet guarantee *achievable* super-high-power density and energy storage, efficiency, robustness, etc. The solutions and technologies for the aforementioned systems under intensive developments, and, sound systems are reported in this paper. We focus the efforts on the most promising solutions, further advancing electric machines design and analysis (analysis and design of heavy-loaded radial and axial-topology synchronous generators operating within the entire *BH* curve, entire load and speed envelopes) as well as power electronics solutions.

In automotive, avionics, biomedical, marine, robotics and other applications, energy harvesting and power systems are key components because there is a need to generate electric energy through mechanical-to-electrical energy conversion. In fact, in various applications, from biomedical implantable devices to sensors, or from aerospace to underwater systems, self-sustained (autonomous,

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alternative and renewable) sources of energy are an ideal solution. It is important to design high-performance systems utilizing emerged technologies and advancements in electronics, energy conversion and electric machinery. The power density, efficiency, robustness and other key performance measures must be maximized. One may convert various forms of energy to electric energy. This concept has been used in geothermal, hydro, nuclear, solar, wind and other medium and large power generation systems. However, new solutions needed for various micro-, mini- and conventional systems.

The designed self-sustained energy systems are aimed to power various actuators, communication units and sensors embedded, implanted or installed in *autonomous* platforms. For example, surface and underwater vehicles (ships, submarines, submersible vehicles, etc.) have an impenetrable hull. There is a need to power actuators, sensors, *servos* and other devices located outside the hull. Energy systems for implantable medical devices are also considered. In various applications, it is feasible to install micro- and miniscale power generation systems which perform controlled energy conversion and storage. For example, a turbine harvests of the water flow energy and rotates a generator which induces the voltage. This voltage is controlled by a rectifier/converter, and, the generated energy can be stored.

We focus on basic research to further enable engineering and technology forefronts by applying most advanced recent findings and solutions. Highly efficient energy conversion is guaranteed by designed high-performance radial- and axial-topology permanent-magnet synchronous generators, rectifiers and *soft-switching* converters, etc. We examine high-power and high-energy densities generators, converters and supercapacitors. Subsystems are integrated within advanced energy system organizations. Different electronic modules are designed using distinct controlled and uncontrolled rectifiers, as well as various switching converter topologies.

The system design and development include various fundamental tasks such as: (i) control and optimization of energy conversion and generation; (ii) efficient energy storage; (iii) device- and system-level optimization and matching; (iv) synthesis and design of high-performance generators; (v) synthesis of rectifiers and converters; (vi) high-fidelity analysis; and, (v) verification, testing and characterization. Some of those tasks are long-standing multidisciplinary research activities. Though electric machinery, power electronics and control of power systems are well-established engineering areas, many advances can be accomplished. In this paper, we utilize contemporary findings, as well as further enable multidisciplinary engineering and science advancing energy systems. The designed proof-of-concept prototypes of subsystems and power generation systems are tested and characterized in various applications including harsh and submersible environments. Depending on the system specifications, different topological, behavioral and performance designs are accomplished synthesizing and integrating subsystems, e.g., turbine, generator and electronics. The results are analyzed in sufficient details.

2. Power generation system

The power generation system consists of a turbine, generator and power electronic module. Sound solutions are researched and applied. We utilize: (1) high efficiency turbines; (2) high-power density permanent-magnet radial and axial topologies synchronous generators; (3) high efficiency controlled rectifiers and *soft-switching* converters, integrated with high energy density storage double-layer capacitors (supercapacitors). The designed energy generation systems are aimed for harsh environment, submersible and biocompatible applications.

To ensure an optimal design, guarantee soundness and enable an expanded operational envelope, a turbine rotor houses permanent magnets forming an *integrated turbine-generator module*. The coated rear-earth *hard* magnets, encapsulated in polymers, are embedded in the turbine aperture. The generator windings and electronic module reside in a sealed package. The airgap between magnets and windings, filled with water or air, can vary to maximize the power density, efficiency and other core performance measures. The induced phase voltages are supplied to a multistage electronic module which rectifies the voltage, varies the voltage magnitude to the specified DC or AC voltage, stabilizes the output voltage, and stores the energy. We design, integrate and optimize all system components thereby guaranteeing soundness, optimality, efficiency, robustness, losses minimization, etc. The energy conversion and output voltage are effectively controlled by controlling a rectifier and switching converter.

Various permanent-magnet generators were synthesized, designed and tested. The analysis is performed for commercial and newly synthesized generators. The images of some examined high-performance radial- and axial-topology generators with the outer diameter from ~2 mm to ~10 cm are documented in Fig. 1a. These medium- and high-speed generators (~100 to 100,000 rad/s, ~1 mW to ~100 W) induce *ac* phase voltages from 1 to 100 V. The windings are placed in the stationary sealed waterproof case. In radial and axial-topology generators, the segmented permanent magnets are used to form ring- and disk-shaped magnets with various outer and inner diameters matching the *integrated turbine-generator* rotor housing. The Pelton turbine is utilized for submersible applications. The vanes sizing, geometry and curvature are defined performing an application-specific design to ensure maximum efficiency within the operating envelope. An *integrated turbine-generator module*, shown in Fig. 1b, contains permanent magnets on the turbine rotor thereby guarantying a unique utilization of the turbine structure. This solution ensures superior performance, robustness, enhanced operating envelope, harsh environment operation, etc.

Controlled two- and three-phase rectifiers with filtering capacitors and inductors are used to rectify the induced *ac* phase voltages to a DC voltage. Controlled two- and four-quadrant *buck*, *boost* and *buck-boost* converter topologies [12,21–24] were synthesized and utilized to ensure high efficiency within the expanding current and voltage envelopes. The operating principle is based on the changing the duty ratio (duty cycle). We utilize the *soft-switching* concept in order to increase efficiency, reduce losses, reduce electromagnetic loading, etc. As rectifier and converter topologies are defined, analog proportional-integral control laws are designed and implemented to stabilize the output voltage or to ensure the desired output voltage. It is found that the DC output voltage can be increased by a factor of ~10 within the operating envelope. The *flyback* converter is used to enable the stabilization abilities maintaining the output voltage of the controlled switching converters to the desired value. The converter utilizes a transformer to reduce or increase the voltage, isolate the input from the output, and enable the desired impedance. The low-amplitude voltage ripple (~±0.1 V), produced on the transformer output due to the transistors switching, charging/discharging and other effects, is eliminated by using a supercapacitor-inductor circuitry parallel with the resistive-inductive load with time-varying impedance $\mathbf{Z}_L$. It is found that one may effectively control the power factor which is of a great importance to guarantee high efficiency if the loads impedance $\mathbf{Z}_L(t)$ varies. The supercapacitor stage stores the energy. Supercapacitors have high energy and power densities (~100 J/g and 10 W/g). In addition, supercapacitors possess high charging capacity, enabling charging/discharging characteristics, unlimited number of cycles, high efficiency, temperature stability, robustness, etc. The power electronic module may integrate a power management system with a microcontroller to optimize the energy conversion, control and stabilize the output