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Hybrid energy harvesting for condition monitoring sensors in power grids

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In this paper, we present a novel hybrid scheme of magnetic, thermoelectric, and vibration energy harvesting (EH) system, which is directed towards the low-power sensing applications within power grids. The topology aims to address the energization of wireless sensor networks that are deployed for the condition-based monitoring purposes of electric facilities. To this end, we have investigated the energy conversion properties of the three EH modalities by means of simulation studies and in-lab experiments. Thereafter, a hybrid energy management system has been established using an ultra-low power consumption circuitry to regulate and integrate individual outputs from the front-end harvesters. During a proof-of-concept, we have observed from a developed demonstrator that a DC output voltage held steady and the output was fed into a ZigBee sensor to keep it operational meanwhile without downtime, which indicates that the power consumption of a ZigBee node can be fully covered by the harnessed energy in the context of this article. Hence, the ambient energy scavenging methodologies discussed herein are well-suited to empower energy-autonomous sensors. The work is characterized by the first demonstration of thorough assessment of the three stray energy forms in the grid and the joint utilization thereof to enhance the system loading capacity. Rather than exploiting a single ambient energy source of some kind, this hybrid and versatile option is proven to accomadate more stable power throutput, and the system signifies feasibilities and potentials to improve the problematic power supplies of the sensors that are deployed within the grid.

1. Introduction

Potential defects or unforeseen failures within the transmission and substation assets on power grids may lead to costly power outages [1–3]. As such, more accurate tracking of the assets health is technically and economically justified, which can be achieved by monitoring the real-time information critical to conditions of the assets. To name a few, such status information may include parameters associated with the operational conditions (e.g. voltage, current), insulation degradation (e.g. leakage current, power loss factor), and the meteorological factors at the deployed site (e.g. temperature, humidity) [4–6]. As an alternative to run-to-failure or the maintainence strategies relying on "worst case scenario" assumptions, the practice of condition monotoring (CM) can effectively reveal incipient defects and conduce to alleviate the risks beforehand, which enables the operators to make more informed decisions proactively for improving reliablity and efficiency of the power delivery.

To benefit the enhanced CM utilization for more efficient asset management, low-power wireless sensor networks (WSNs) have aroused considerable research interest, particularly in the distributed monitoring tasks [7,8]. However, the power supplies are getting problematic under scenarios that rule out wiring or frequent energy replenishment. On the one hand, as for the batteryless sensor nodes which are situated in harsh environment, like the hard-to-reach locations inside substations or places in the vicinity of transmission lines, wired power from a fixed utility is locally unavailable. For instance, some sensors are mounted on the high voltage (HV) terminals (e.g. busbars, breakers), where dedicated power wires are prohibitive or in the remote locations (e.g. transmission lines, towers), where any ready-made power sources are difficult to be supplied. Further, if otherwise applicable elsewhere, the on-site cabling and maintenance towards numerous nodes will

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yield a high volume of work. On the other hand, in any applications of WSNs, the nodes must be non-intrusive and with minimum impacts on the host equipment. In this regard, the CM sensors should be miniaturized, which however constrains the capacity of onboard batteries as well as the lifetime of battery-operated nodes. Therefore, the desire to sustain long-lived operation (months to years) of the sensors necessitates periodical battery replacing or recharging while depleted, which significantly imposes its own burden on the operators. By this token, the costs of both cabling and battery maintenance may outbalance the benefits. Where this is the case, exploration of novel alternative power sources is highly desirable and an autonomous manner to energize the CM sensors by ambient energy harvesting (EH) has been consequently put forward.

EH means scavenging various forms of stray energy from environment [9–11]. There are many location dependent sources of harvestable energy in the context of a power grid. Presented hereinafter is a brief state-of-the-art review of solar, electromagnetic field, thermoelectric and vibration-based energy harvesting technologies and the energy consumption profiles of low-power sensors.

Given its ubiquitous abundance, solar power is one of the most preferably harvestable energy to top up the batteries. The generation of electricity using solar power is well-established by two enabling techniques, solar photovoltaic and solar thermal [12]. Solar thermal is mainly employed for large-scale concentrating solar power (CSP) plants, solar absorption systems, or combination with photovoltaic to consist hybrid solar applications [13–15]. Solar photovoltaic is more applicable for an embedded power supply of miniaturized sensors by using small-size photocells, and in this manner, as power source for sensors, solar energy harvesting outweights the other EH approaches because of its relatively higher outdoor power density, which can be up to 15 mW per cm^2 [16].

There has been much recent interest to harness solar energy for general-purpose wireless sensors. Typically, the developing applications involve power supplies for the sensors in traffic management, structural monitoring, environmental monitoring and aerospace facilities [17–19]. In particular, the representative solar-powered application in electric facilities can be refered to the stand-alone monitoring devices furnished with solar panels and deployed near overhead transmission lines, which monitor the vibration, galloping, and temperature of overhead conductors or the surrounding meteorological parameters [5,20]. Besides, research efforts are dedicated to increase cell efficiency, reduce costs and develop improved manufacturing methods. The materials and technologies being studied include various organic semiconductors, dye-sensitised cells, organic-inorganic heterostructures, nanomaterials (e.g. nano crystalline silicon, carbon nanotubes, quantum dots), a range of optical metamaterials, three-dimensional cell structures and multi-junction cells [21–23]. The ongoing research of solar-powered sensors also focuses on maximum power point tracking (MPPT) and adaptive policies for activation, communication, and power management of solar-powered WSNs [24,25].

Another pervasive energy is present within the electromagnetic field. Radio frequency (RF) energy harvesting and inductive/capacitive coupling are the two major schemes to scavenge the electromagnetic energy [26,27]. Obviously, the grid is awash in the power frequency magnetic field and the potential magnetic energy is the most abundant and achievable therein, which is excited by the live conductors carrying high currents in power plants or substations. Magnetic coupling has attracted much interest of investigation since the early stage. It was reported that the magnetic energy directly extracted from CTs surrounding HV conductors had been employed previously to power relays [28]. More recently, plenty of self-powered (CT based) sensors have been developed and placed on transmission lines, which float at the HV potential for wireless monitoring of the line sag, vibration and conductor temperature [5,29]. The CT based toroidal core has become the main structure for magnetic energy harvesters. Increasingly, research efforts are focusing on addressing the difficulties in magnetic energy harvesting from low currents and meanwhile the protection from abnormal large currents in the primary side [30–33].

Heat is much likely to be generated concurrently, whether desired or not, by the propagation and conversion of other energy forms (e.g., Joule heat from electricity or heat concentration from photothermal conversion). Recovery of waste heat is promising, which can be achieved by the Seebeck effect. A thermoelectric generator (TEG) can be employed to produce electricity at the interfaces where steep temperature gradients exist in close proximity. Typically, the throughput of power density can be 15 μW per cm^3 while the temperature gradient across the device reaches 10 °C [34]. TEG is advantageous for light weight, no noise, and no moving part, which lead to high reliability. Influencing factors of the delivered power are predominantly properties of the thermoelectric material (usually characterized by the figure of merit *ZT*). The following methods are usually employed to improving the *ZT* value, including super-lattice, plasma treatment, segmented element, nano-composite and nanostructure [35,36]. On the other hand, increasing researches are focusing on improving the device structure for more efficient heat exchange [37,38]. Due to the distinct advantages, thermoelectric devices have been utilized in aerospace applications, transportation tools, industrial utilities, medical services, electronic devices and temperature detecting facilities [39–41].

The kinetic energy present in vibrations is another potential source, which can be readily found in transportations, buildings, industrial machineries and so forth. The typical power density produced by a vibration energy harvester can reach 300 μW per cm^3, which is considered to be more usable where vibration is intensive [42]. Piezoelectric energy harvesting attracts much recent interest among the three established mechanism (i.e. static, electromagnetic, and piezoelectric patterns) [43–45]. Concerning the piezoelectric material, piezoelectric ceramic material has been widely used and polyvinylidene fluoride (PVDF) is studied for better flexibility [46,47]. The type of harvester structures and interface circuits are also being studied [48,49]. Basically, the cantilever, cymbal, stack, and shell are four primary types of piezoelectric structures. The rectangle cantilever beam is the most common type and researchers have investigated triangle and trapezoid type, in which higher power density was obtained [50]. Synchronized switch harvesting on inductor (SSHI) has been proposed by Lefeuvre [51]. It has been widely used due to improved transmission efficiency by 400% compared with standard interface circuits. Vibration energy harvesting mainly serves for implantable, wearable devices and wireless sensors [52–54]. For instance, the representative work can be refered to a suspended-load backpack developed by Rome, which converts mechanical energy from the vertical movement of carried loads to electricity during normal walking [55].

The aforementioned three forms of potential energy coexist and the reserves are definately plentiful in power grids, as they are directly affiliated to three effects of the current, i.e., calorific effect, electrodynamic effect and electromagnetic induction. The EH technologies are promising to address the trade-off between the energy budget and performance in any energy-limited sensor nodes, particularly in low-power sensing applications. Low-power devices integrate sensing, computing, and wireless communication abilities, and wherein most off-the-shelf transducers are