Ad Hoc Networks 75–76 (2018) 98–105

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

On the lifetime analysis of energy harvesting sensor nodes in smart grid environments

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ARTICLE INFO

Article history:
Available online 22 March 2018

Keywords:
Energy harvesting
Smart grid
Wireless sensor networks

ABSTRACT

Smart grids represent the future of power generation, distribution and transmission systems. Integration of renewable energy sources with fluctuating power output into the grid requires constant monitoring of grid assets. Wireless Sensor Networks (WSNs) provide an efficient monitoring infrastructure for data collection from multiple locations for extended periods. The aim of this study is to investigate the lifetime of the energy harvesting WSN nodes inside a substation, where the sensor nodes exploit the abundant electromagnetic field in the substation environment. Performance results show that the impact of harvesters on node lifetime is crucial compared to available power management systems, when realistic substation channel conditions are considered.

1. Introduction

Traditional grids are replaced with smart grids that enable the incorporation of renewable energy sources without impairing reliability. This integration requires active monitoring of unpredictably fluctuating energy generation and consumption levels to provide efficient distribution of the generated energy and blackout-proof infrastructure. Such monitoring task can be achieved using a scalable network of inexpensive and reliable nodes. In this respect, utilization of Wireless Sensor Networks (WSNs) technology is the most common practice among enabling technologies. Current WSN based smart grid applications include remote monitoring of transmission lines, automatic fault detection, demand and delivery optimization, smart metering, and outage management [1–3].

WSNs consist of multiple nodes with sensor(s), processor(s), and radio hardware integrated in each node. In a smart grid environment, the power supplied to the nodes is usually provided by batteries since powering directly from the grid requires expensive and complicated converter circuits. After a battery is depleted, a replacement procedure has to be initiated. In a smart grid environment, this scenario is not desired due to costs and high electromagnetic/electric field intensities harmful on human body. Moreover, requiring frequent battery replacements may impair data integrity. Therefore, extending node lifetime plays a vital role on diminishing the negative outcomes of monitoring tasks.

Node lifetime can be extended by either increasing the total available energy or decreasing the average power consumption. The former can be accomplished using bigger batteries or energy harvesting devices while the latter is limited to available low power components and power management practices. The scope of this study is limited to energy harvesting devices and power management practices since the utilization of bigger batteries or low power components is limited to application constraints and market availability.

Energy harvesting devices aim to increase total available energy by converting ambient energy into electrical energy and assisting the integrated battery. Ambient energy can be present in various forms, such as electromagnetic, solar, and kinetic with each type requiring a unique harvester design. In a smart grid environment, harvesting from electromagnetic and electric field seems promising due to high current and voltage levels inside the facilities. However, electromagnetic harvesters are found more suitable for smart grid applications considering the physical size and output power it is capable to provide [4]. Consequently, this study focuses solely on electromagnetic harvesters.

Harvesting from electromagnetic waves can be performed using inductive coils or permanent magnets placed inside electromagnetic field. Using coil, the AC voltage induced at the terminals of the coil can be rectified and used to power the sensor node or assist the node battery. Similarly, force is applied on permanent magnets exposed to electromagnetic waves and the force can be used to vibrate a piezoelectric beam and generate voltage at its terminals by attaching the permanent magnet to the tip of a beam.

Moreover, power management methods aim to decrease the average power consumption. This study focuses on two

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https://doi.org/10.1016/j.adhoc.2018.03.002
1570-8705/

different power management methods namely schedule-driven power management and event-driven power management that introduce sleep cycles and redundant triggering hardware to reach this goal. The methods also enable adapting to different application scenarios by altering their parameters. In summary, the following contributions have been made:

- The impact of two promising energy harvesting devices based on electromagnetic field on sensor node lifetime within a smart grid facility has been analyzed.
- The effects of both schedule-driven and event-driven power management schemes on lifetime of sensor nodes deployed in smart grid environments have been investigated.
- The impact of radio propagation characteristics for different smart grid environments, such as 500 kV outdoor substation Line of Sight (LOS) and Non-Line of Sight (NLOS) environments, on sensor node lifetime have been investigated.

The remainder of this paper is organized as follows. An overview of the available studies for electromagnetic energy harvesting in smart grid environment is presented in Section II. Energy harvesting methods used in this study are introduced in Section III. Section IV provides insight on the power management methods utilized throughout the study. Section V presents the results of the simulations conducted and Section VI concludes the paper.

2. Related work

To date, there have been numerous studies analyzing the feasibility of harvesting device utilization in smart grid environments. In these studies, electromagnetic field harvester is the most common harvester type. However, the mechanisms and the methods used for capturing the ambient electromagnetic energy and converting it into electrical energy vary.

Moghe et al. design a self-sufficient hardware that exploits the magnetic field present in the environment to harvest energy and reports its readings of environmental parameters [5]. The designed harvester requires clamping besides the conductor and enables sensor node to report measured data once in 61 s when 100 A of current flows through the conductor.

Han et al. use a vibrating beam structure with permanent magnet attached to its tip to harvest energy from varying magnetic field of a power line [6]. The alternating torque due to the force AC magnetic field exerts on the magnet is applied on the cantilever beam with piezoelectric material. The electric potential generated along the terminals of the stressed material is used to power the sensor node. The maximum harvested power of 9.40 mW from 40 A of current flow is stated to be more than sufficient to power a low power sensor node.

The authors of [3] adopt the electromagnetic harvester design proposed in [7] to integrate it into sensor node that will energize itself. Their proposed design possesses a cubical structure that will be positioned next to a conductor preventing installation hindrances. Their results show that the harvester is capable to provide 744 mW of power when positioned next to a conductor with 170 A of current.

In [8], the authors propose a multilayered coil structure to harvest electromagnetic energy along with its accurate mathematical model. They show that their design is superior to previous coil designs in terms of harvested energy. They manage to harvest around 10 mW of power from a conductor with 13.5 A current. In addition, the analytical model they suggest provides results within an error margin of 10% compared to practical results.

Another study analyzes the feasibility of utilizing mobile vehicles with electromagnetic wave based wireless charging capabilities to charge the nodes [9]. The routes of the vehicles and the landmark locations to activate charging operations are optimized to meet the energy demand of the nodes with least residual energy while using minimum path traversing.

Roscoe et al. focus on Free-Standing Harvesters (FSHs) where the coil is not necessarily be clamped around a conductor [10]. They state that the magnetic flux levels within substations may be sufficient to energize wireless sensor nodes. According to the results, magnetic flux density level in an ordinary 400 kV indoor substation is sufficient to power a MICAz sensor node performing data transmission every 4 minutes.

Yuan et al. analyze the structure of coil to be used as a harvester when positioned under overhead transmission lines [11]. They propose a novel bow tie shaped coil structure with its proven superiority over traditional cylindrical shape. Optimizing the design further by using the most effective core material among many types, they manage to scavenge 146.7 mW of power when the harvester is positioned 5 m above the ground with a magnetic flux density of 11 μT_{rms}. In addition, an analytical model to calculate the output power is provided.

Another study similar to [6], aims to eliminate the requirement of coil surrounding the conductor by using permanent magnet to convert magnetic energy into mechanical energy [12]. However, the mechanical energy is converted into electrical energy using another permanent magnet-coil pairs instead of a piezoelectric cantilever used in [6]. This way, they manage to harvest 0.16 mW of power from a conductor with 50 A of current. Although the output power is reduced greatly, they suggest that not using piezoelectric material on a continuously vibrating beam increases the durability of the system.

Table 1 shows a summary of energy harvesting methods based on electromagnetic field. Although these studies provide valuable insights on the contribution harvesters make, they do not evaluate how the contribution is affected under different usage scenarios. In our previous work, the harvesters are tested in NLOS smart grid environment using event driven scheme [13]. In this study, we carry the experiment further by incorporating schedule driven scheme and LOS smart grid environments. This way, lifetime analysis with different duty cycle ratios and event arrival rates is enabled.

3. Energy harvesting methods

Energy harvesting aims to generate electrical energy using various types of hardware exploiting ubiquitous energy resources present in the environment. This study focuses on electromagnetic field harvesters utilized to assist integrated batteries of a sensor node inside smart grid environment. In this study, electromagnetic harvesters called Conductor Winding Harvester (CWH) and Free Standing Harvester (FSH) are used.

The first harvester type is clamped around a current carrying conductor exploiting the energy of electromagnetic field generated due to current flow. The device harvests the electromagnetic energy using an inductive coil with its cross sectional area overlapping the electromagnetic field's circular area. Such design is especially useful for monitoring conductor voltage, current or temperature levels.

The second harvester type focuses on cases where clamping around a conductor is not feasible or the locations at which the parameters are measured do not contain conductors within their close proximity. Being positioned away from a conductor, the assumption of overlapping the coil cross sectional area and electromagnetic field's circular area loses its validity. Although this usually causes lower output power, having a wider physical space available allows using bigger coils.