ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–20

Available online at www.sciencedirect.com

ScienceDirect

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

The design of long-life, high-efficiency PEM fuel cell power supplies for low power sensor networks

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ARTICLE INFO

Article history:
Received 27 May 2017
Accepted 29 May 2017
Available online xxx

Keywords:
PEM
Power supply
Degradation
Sensor networks
Hydrogen storage

ABSTRACT

Field sensor networks have important applications in environmental monitoring, wildlife preservation, in disaster monitoring and in border security. The reduced cost of electronics, sensors and actuators make it possible to deploy hundreds if not thousands of these sensor modules. However, power technology has not kept pace. Current power supply technologies such as batteries limit many applications due to their low specific energy. Photovoltaics typically requires large bulky panels and is dependent on varying solar insolation and therefore requires backup power sources. Polymer Electrolyte Membrane (PEM) fuel cells are a promising alternative, because they are clean, quiet and operate at high efficiencies. However, challenges remain in achieving long lives due to factors such as degradation and hydrogen storage. In this work, we devise a framework for designing fuel cells power supplies for field sensor networks. This design framework utilize lithium hydride hydrogen storage technology that offers high energy density of up to 5000 Wh/kg. Using this design framework, we identify operating conditions to maximize the life of the power supply, meet the required power output and minimize fuel consumption. We devise a series of controllers to achieve this capability and demonstrate it using a bench-top experiment that operated for 5000 h. The laboratory experiments point towards a pathway to demonstrate these fuel cell power supplies in the field. Our studies show that the proposed PEM fuel cell hybrid system fueled using lithium hydride offers at least a 3 fold reduction in mass compared to state-of-the-art batteries and 3-5 fold reduction in mass compared to current fuel cell technologies.

Introduction

Ubiquitous sensor networks operating in unstructured field environments have many important applications including exploration and mapping of inaccessible environments, environmental monitoring including measuring air, water and soil quality, disaster prediction of forest fires, avalanches, earthquakes and volcanoes and in wildlife monitoring to protect endangered species (Fig. 1) [1]. These sensor networks could be used to improve agricultural production, by closely monitoring soil humidity, crop health and making predictions for harvest. In the security sphere, sensor networks maybe used for monitoring borders for illegal entry or smuggling of dangerous goods. Several hundreds or thousands of modules

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http://dx.doi.org/10.1016/j.ijhydene.2017.05.206

Please cite this article in press as: Thangavelautham J, et al., The design of long-life, high-efficiency PEM fuel cell power supplies for low power sensor networks, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.05.206

Fig. 1 – Sensor networks have important applications in environment monitoring including monitoring of water, air and soil health.

might be deployed over large areas and wirelessly report to a base-station. To be practical, the systems need to be low-cost, reliable and operate unattended, ideally for years. Significant advances have been made in wireless communication, miniaturization of electronics, autonomous control systems, sensors and actuators. However, advancement in power supplies have not kept pace.

Conventional batteries do not meet the needs of many types of wireless sensor network due to their low specific energy. For long life missions, they need to be recharged or replaced. While significant work is being done to address their energy limitations [2,3], rechargeable batteries alone cannot meet the high energy requirements of long duration field sensors. Photovoltaics is another important power source but these devices are bulky, require periodic maintenance such as cleaning of panels and requires a steady source of solar insolation throughout the year. These factors limit their applications to certain climate zones or applications that can afford hibernation due to periods of inclement weather or winter. Typically, due to daily variabilities in solar insolation, photovoltaic systems need to be coupled with a battery. Energy harvesting using piezoelectric generators has been proposed for field sensors, but have yet to be practically applied. These generators require a steady source of vibrations and are suitable only for specific very low-power applications. A better solution is needed.

Here, fuel cells are proposed as power source for wireless field sensor networks. Fuel cell are electrochemical energy conversion devices that convert chemical energy directly into electricity [4,5]. Three types of fuel cells are attractive for sensor networks, they include PEM fuel cells, direct-methanol fuel cells and microbial fuel cells. These fuel cells operate at low temperatures and are quiet. Out of the three, PEM fuel cells are highly efficient operating at 60-65%, react with hydrogen and oxygen to produce electricity. However, the storage and release of hydrogen is typically a challenge. In this work, we address this major challenge and propose a feasible solution. Direct methanol fuel cells use methanol and oxygen from air to produce electricity. They tend to have lower efficiencies than PEM, longer startup times and produce carbon dioxide and water. Direct methanol fuel cells are attractive, because methanol is easy to store and has higher energy densities than conventional hydrogen storage. The main challenge with conventional direct methanol fuel cells is an inherent limitation with the fuel cell design, compared to PEM. The buildup of CO_2 accelerates degradation of the fuel cell and causes high rates of cross-over resulting in lower operating efficiencies and unreliability.

However, PEM fuel cells are not widely used in field applications because they also face significant challenges. Firstly, PEM fuel cells are faced with the problem of degradation of their components that result in shortened lives and unreliability compared to batteries. A second major challenge is the storage of hydrogen [6]. Conventional methods of hydrogen storage are bulky and inefficient, providing only a marginal advantage over current batteries. A third major challenge is that these fuel cells produce lower power compared to batteries. A fourth challenge is that PEM fuel cells have high costs. Significant progress is being made in all these areas. Our research addresses the first three challenges.

In this paper, we present PEM fuel cells as a promising solution to powering sensor networks for long duration. The PEM fuel cell power supply is implemented as a fuel cell hybrid system, held under controlled conditions to maximize life, maximize cell operating efficiency and minimize component degradation. This method enables the fuel cell power supply to achieve conversion efficiencies of 60–65% and operating lives of 3–5 years. The fuel cell is supplied with hydrogen fuel from a water activated lithium hydride hydrogen generator that freely extracts water vapor from the air. This method offers a theoretical specific energy of 5000 Wh/kg, nearly 40 times that of conventional lithium ion batteries. Our case studies presented in this paper show that through effective design and control that the proposed fuel cell power supply can be superior to conventional batteries for field sensor network applications.

The remainder of this article is organized as follows. Section Background presents background and related work. Section Long life, low power fuel cell power supply design presents power management, air management and fuel management design and control of the PEM fuel cell power supplies to achieve long life. Section Experimental system presents an experimental system used to test the concept. Section Case studies presents several case studies and discussion comparing the concept to conventional fuel cells technologies and batteries and Section Conclusions presents our conclusions.

Background

Fuel Cells have been proposed as power supplies for field sensor networks. An important factor in their selection is that they are clean, highly efficient, offer high specific energy and are quiet [4,5]. These factors make them well suited for