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Energy Harvesting from Ambient Sources for Self-Powered IoT-Enabled Power Electronic Systems in Industrial Automation

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Abstract

The rapid advancement of industrial automation and the Industrial Internet of Things (IIoT) has created an urgent need for reliable, self-sustaining power solutions that eliminate the dependency on conventional wired or battery-operated energy sources. Energy harvesting from ambient sources has emerged as a transformative approach to powering IoT-enabled power electronic systems in industrial environments. This book chapter explores cutting-edge techniques for energy harvesting from multiple ambient sources, including mechanical vibrations, thermal gradients, solar radiation, and radiofrequency energy, to develop self-powered industrial systems. A comprehensive analysis of hybrid transduction mechanisms, advanced materials for durability in harsh environments, and AI-driven power management strategies was presented to enhance energy conversion efficiency and system reliability. The integration of energy harvesting with IIoT networks for predictive maintenance and asset health monitoring was examined, demonstrating its potential to optimize industrial operations. Challenges related to long-term performance degradation, environmental sustainability, and scalability are discussed, along with emerging solutions for enhancing energy harvesting efficiency. The insights presented in this chapter provide a foundation for developing resilient and intelligent industrial automation systems that operate autonomously, reducing energy costs and promoting sustainability.

Keywords: Energy harvesting, Industrial IoT, Power electronic systems, Predictive maintenance, Hybrid transduction, AI-based power management.

Introduction

The advancement of IIoT technologies has significantly transformed industrial automation by enabling intelligent monitoring, real-time analytics, and predictive maintenance [1]. The widespread deployment of IIoT-enabled power electronic systems was often constrained by power limitations, particularly in large-scale industrial environments where wired power infrastructure was impractical, and battery maintenance poses logistical challenges [2-4]. Energy harvesting from ambient sources has emerged as a sustainable and reliable solution to overcome these limitations, providing self-powered alternatives that enhance the operational efficiency and longevity of industrial automation systems [5]. By capturing energy from environmental sources such as mechanical vibrations, thermal gradients, solar radiation, and electromagnetic waves, energy harvesting enables continuous and maintenance-free operation of industrial IoT devices, reducing dependency on traditional energy sources [6].

Hybrid transduction mechanisms that integrate multiple energy conversion techniques have gained prominence in industrial energy harvesting applications. The combination of piezoelectric, thermoelectric, photovoltaic, and electromagnetic transduction systems enables efficient energy capture from diverse industrial environments, ensuring stable power generation under varying operational conditions [7]. Hybrid energy harvesters can adapt to dynamic energy availability by switching between different energy sources or simultaneously utilizing multiple transduction mechanisms to optimize power output [8]. The integration of power conditioning circuits and energy storage solutions, such as supercapacitors and high-efficiency batteries, further enhances the reliability of self-powered industrial IoT networks, ensuring continuous energy supply for critical operations [9-11]. The development of smart power management algorithms also plays a key role in optimizing energy utilization, allowing IIoT devices to adjust power consumption dynamically based on available harvested energy.

The application of energy harvesting in predictive maintenance and asset health monitoring has revolutionized industrial maintenance strategies, shifting from reactive and scheduled maintenance to condition-based and predictive approaches [12]. Self-powered IIoT sensors embedded in machinery and equipment can continuously collect real-time data on temperature, vibration, pressure, and other critical parameters, enabling early fault detection and proactive maintenance interventions [13]. Predictive maintenance powered by energy harvesting reduces unplanned downtime, minimizes maintenance costs, and extends the operational lifespan of industrial assets. Additionally, AI-driven analytics combined with energy-efficient wireless communication protocols allow IIoT nodes to transmit data seamlessly while optimizing energy consumption [13]. The integration of energy harvesting with IIoT infrastructure ensures the sustainability of predictive maintenance solutions, eliminating the need for frequent battery replacements and enhancing the scalability of industrial monitoring systems [14].

Material durability and environmental resilience are critical considerations for energy harvesting technologies deployed in industrial automation. Harsh industrial conditions, including extreme temperatures, chemical exposure, humidity, and mechanical stress, can degrade the performance and efficiency of energy harvesting devices over time [14]. The development of advanced corrosion-resistant materials, nanostructured coatings, and self-healing composites enhances the longevity and robustness of energy harvesters [15]. Protective encapsulation techniques and self-cleaning surfaces further mitigate environmental degradation, ensuring reliable energy conversion even in challenging operating conditions. Research in material science continues to focus on improving the mechanical flexibility, thermal stability, and chemical resistance of energy harvesting materials to support long-term deployment in industrial settings [16].

The advancements in energy harvesting technologies, several challenges must be addressed to achieve large-scale industrial adoption. Variability in ambient energy sources, energy conversion efficiency limitations, and integration complexities pose significant hurdles in the widespread implementation of self-powered IIoT systems [17]. The development of hybrid and adaptive energy harvesting systems, intelligent energy storage solutions, and AI-powered energy management strategies was crucial for overcoming these challenges [18-22]. Future research should focus on enhancing energy harvesting efficiency, developing scalable and cost-effective architectures, and improving the interoperability of energy harvesters with existing industrial automation frameworks [23]. By addressing these challenges, energy harvesting can play a transformative role in enabling sustainable, autonomous, and intelligent industrial automation systems, driving advancements in IIoT-enabled smart manufacturing and industrial maintenance [24,25].