ENT1099ME02 - Design and Development of a Self-Powered Sensing System for Machinery Fault Diagnosis Using Vibration Energy Harvesters

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Background of the problem

The advent of Industry 4.0 has made continuous condition monitoring essential for predictive maintenance in rotating machinery. However, the widespread deployment of wireless sensor networks (WSNs) is critically constrained by one fundamental component: the battery. Traditional battery-powered sensors, while effective, introduce significant logistical and economic burdens. In large-scale industrial environments such as oil refineries, wind farms, or automated factories regular battery replacement for hundreds or thousands of sensors is labour-intensive, costly, and often hazardous when sensors are located in inaccessible or high-risk areas. Furthermore, the environmental impact of disposable battery waste contradicts global sustainability goals.

Simultaneously, vibration energy harvesting has emerged as a promising alternative to power sensors from ambient machine motion, yet its current application remains limited to merely replacing the power source. A critical, underexploited opportunity lies in using the harvester itself as the sensing element. Present systems still require a separate, power-hungry accelerometer for fault diagnosis, thereby doubling the complexity and undermining the goal of true autonomy. This disconnects between power generation and sensing capability represents a significant technological gap.

There is an urgent need for an integrated paradigm: a self-powered sensing system where the vibration energy harvester's electrical output serves dual purposes both powering the electronics and providing the diagnostic signal for faults like bearing defects, imbalance, and misalignment. Addressing this need will eliminate battery dependency, reduce lifecycle costs, and enable truly autonomous, sustainable machinery health monitoring.

List of publications related to the field

https://www.sciencedirect.com/science/article/pii/S0263224121008009

https://www.sciencedirect.com/science/article/pii/S0196890422002394

https://onlinelibrary.wiley.com/doi/full/10.1155/ijrm/7970678

https://onlinelibrary.wiley.com/doi/full/10.1002/eng2.70202

https://www.sciencedirect.com/science/article/pii/S0924424723000031

https://www.sciencedirect.com/science/article/pii/S0924424717319106

Research Objectives and Expected Outcomes:

Aim and Objectives of Study

1. To design and develop a vibration energy harvester (piezoelectric or electromagnetic) tuned to the typical vibrational frequencies of industrial rotating machinery.

2. To characterize the electromechanical response of the harvester and develop a model that correlates its electrical output signal with specific machine health states.

3. To create a novel signal processing and machine learning framework for extracting fault-related features directly from the harvester's generated voltage/current signal.

4. To validate the performance of the fully integrated self-powered sensor prototype by comparing its diagnostic accuracy against a standard battery-powered accelerometer on a laboratory test rig.

Expected Outcomes

This research will deliver three key outcomes: (1) a functional prototype of a self-powered vibration sensor that operates without batteries, (2) a validated machine learning model for automatic fault diagnosis using the harvester's signal, and (3) design guidelines for industrial deployment.

These outcomes directly address critical needs in Bahrain's industrial sectors. The oil and gas industry (e.g., BAPCO) operates numerous pumps, compressors, and motors in remote or hazardous locations where battery replacement is both costly and dangerous. A self-powered, battery-free sensing system would enable continuous monitoring with minimal human intervention, reducing unplanned downtime and safety risks.

Similarly, Bahrain's aluminum and manufacturing sectors (e.g., ALBA) rely on large-scale rotating machinery. The proposed technology lowers the total cost of ownership for condition monitoring, making predictive maintenance economically viable for a broader range of assets. Furthermore, by eliminating disposable batteries, this project supports Bahrain's Environmental Vision 2030 and national sustainability goals by reducing electronic waste.

Ultimately, the outcomes will enhance industrial asset reliability, reduce maintenance logistics, and position Bahrain as an adopter of innovative, sustainable Industry 4.0 technologies tailored to the region's heavy industries.

Research Design & Methodology

1. System Design and Harvester Development:

• Select a suitable energy harvesting principle (piezoelectric cantilever or electromagnetic generator) and design a device resonant at common machine vibration frequencies (e.g. 20-150 Hz).

• Design the accompanying power management circuit to efficiently store harvested energy in a capacitor and power a micro-controller and wireless transmission module.

2. Prototyping and Characterization:

• Fabricate the VEH prototype and characterize its power generation capability and frequency response using a shaker table.

• Develop a physics-based model to understand how fault-induced vibration modulations affect the harvester's electrical output.

3. Algorithm Development and Integration:

• Interface the VEH with a data acquisition system on a rotor-dynamics test rig capable of simulating various fault conditions (healthy, unbalanced, bearing defects).

• Develop and train machine learning models (e.g., 1D Convolutional Neural Networks) and advanced signal processing techniques (e.g., envelope analysis) tailored to the VEH's signal for automatic fault classification.

4. Experimental Validation and Benchmarking:

• Install the self-powered sensor prototype and a commercial accelerometer on the same test rig.

• Conduct a series of tests under different operational speeds and fault scenarios to collect synchronized data.

• Quantitatively compare the fault detection sensitivity, classification accuracy, and power autonomy of the proposed system against the conventional system.

5. Data Analysis and Reporting:

• Analyze the results to determine the efficacy and limitations of the self-powered sensing system.

• Develop implementation guidelines for industrial adoption.

Significance and potential impact of research in Bahrain

This project has the potential to significantly advance the state-of-the-art in wireless sensor networks for industrial applications. By creating a sensor that is both powered and informed by its environment, it enables the long-term, cost-effective deployment of monitoring systems on critical assets like motors, pumps, and generators. This contributes directly to improved asset reliability, reduced unplanned downtime, and more sustainable industrial practices by reducing electronic waste and lower total cost of ownership for condition monitoring. The outcomes will be valuable for a wide range of sectors, including manufacturing, energy, and transportation, aligning with global goals for industrial efficiency and environmental stewardship.

Alignment with Bahrain's national research strategy

Contribution to Bahrain Society

This research reduces electronic waste from disposable batteries, supporting Bahrain's Environmental Vision 2030. It promotes workforce upskilling in machine learning and energy harvesting, creating high-value jobs for Bahraini engineers. Workplace safety improves by minimizing human intervention for battery replacement in hazardous industrial areas like oil refineries.

Alignment with Industry

The project directly serves Bahrain's oil and gas (BAPCO), aluminum (ALBA), and manufacturing sectors. These industries operate hundreds of rotating machines requiring continuous monitoring. Current battery-powered sensors impose high maintenance costs. Our self-powered system eliminates battery replacement, reduces total cost of ownership, and enables deployment in inaccessible locations. For an industry partner, benefits include reduced unplanned downtime, lower labor costs, extended asset life, and improved environmental compliance.

National Research Priorities / Strategy and EDB Policies

This research aligns with Bahrain Economic Vision 2030's pillars of sustainability and knowledge-based innovation. It supports the National Industrial Strategy for advanced manufacturing and the National Energy Strategy for efficiency in energy-intensive industries. It also aligns with EDB policies attracting high-value technology investments and fostering indigenous R&D in smart monitoring. By developing local intellectual property in self-powered IoT sensors, this project strengthens Bahrain as an emerging hub for innovative industrial solutions tailored to regional needs.