WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 6, No. 1, 2023
Doi: 10.67228/30716357/IJMRSE-2023PI6M4T
PP. 01-17

Original Article

Energy Harvesting Techniques for Self-Powered Sensor Networks

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Received: 01-02-2023 Revised: 01-21-2023 Accepted: 01-31-2023 Published: 02-03-2023

ABSTRACT

Wireless Sensor Networks (WSNs) are extensively used in environmental monitoring, healthcare, industrial automation, military surveillance, and smart infrastructure. However, the limited battery life of sensor nodes restricts their long-term operation, particularly in remote areas where battery replacement is difficult and expensive. Energy harvesting offers a sustainable solution by converting ambient energy sources such as solar, thermal, vibration, wind, and radio frequency (RF) energy into electrical power for sensor nodes. This study reviews various energy harvesting techniques, their operating principles, advantages, limitations, and suitability for WSN applications. It also highlights the importance of integrating energy harvesters with energy storage devices and power management systems to ensure reliable operation. A framework involving energy source assessment, harvesting module selection, power conditioning, storage management, and adaptive duty-cycle control is presented to optimize energy utilization. Results indicate that solar energy provides the highest power output under favorable conditions, while vibration and RF harvesting are effective in indoor and industrial environments. Hybrid energy harvesting systems offer greater reliability by combining multiple energy sources. Overall, energy harvesting enhances network lifetime, reduces maintenance costs, and enables sustainable, self-powered WSNs, making it a key technology for future Internet of Things (IoT) and smart environment applications.

KEYWORDS

Wireless Sensor Networks, Energy Harvesting, Self-Powered Systems, Solar Energy, RF Energy Harvesting, Vibration Energy, Power Management, Internet of Things, Sustainable Computing.

1. INTRODUCTION

1.1. Background

Wireless Sensor Networks (WSNs) consist of many small, intelligent sensor nodes scattered over an area to observe the physical, environmental or operational conditions and report the information to a central node for analyses and decision making. Such networks have attracted considerable research interest due to the diversity of their applications, such as environmental monitoring, precision agriculture, industrial automation, healthcare systems, smart cities, building management and military surveillance. Most sensors are equipped with sensing, processing, communication and power components that all serve to gather and send information. The amount of available energy is an important component for the operation and reliability of WSNs. Until now, batteries have been the main power source for sensor nodes. Batteries are, however, only have a lifespan and need to be replaced or recharged periodically. Maintaining batteries on large sites or in remote locations is costly, time consuming and often difficult. These challenges have led to the study of sustainable energy solutions which can support wireless sensor network's operation independently over time.

1.2. Importance of Self-Powered Sensor Networks

Self-powered sensor networks are one of the most important developments in the field of wireless sensing in recent years and the idea is to capitalize on energy collected from the environment to power the sensor nodes in the network. Self-powered networks are free from the need for human power to operate and can provide extended operation times with limited human involvement, making them very suitable for modern Internet of Things (IoT) and smart monitoring applications. The reasons why self-powered sensor networks are important can be seen from the following important points.

Fig 1 - Importance of Self-Powered Sensor Networks

1.2.1. Extended Operational Lifetime

The main benefit of selfpowered sensor networks is that they can have much longer life. The sensor nodes are able to harvest energy continuously from various sources like Sun light, vibrations, temperature, radio frequency signals, which can recharge the energy in the sensor nodes and keep them running for years. This ability can help minimize the need for batteries with finite power and allow for a continuous monitoring in many uses.

ISSN: 3071-6357
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1.2.2. Reduced Maintenance Requirements

Periodic battery replacement or recharge is costly, and in large-scale deployments can be labor intensive, in traditional wireless sensor networks. Self-powered sensor networks reduce the need for maintenance by generating energy from the ambient sources. It decreases the maintenance expenses and also enhances the ease of use of sensor networks in difficult, inaccessible, or hazardous settings.

1.2.3. Enhanced Reliability and Availability

The nodes are autonomous and can operate without any human intervention. Energy harvesting technologies and intelligent energy management systems contribute to a more stable power supply and minimisation of risks of network failures due to battery depletion. This leaves network availability and reliability much improved and allows constant monitoring and data collection to take place.

1.2.4. Environmental Sustainability

Disposable batteries lead to e-waste and pollution in the environment. Self-powered sensor networks encourage the reduction of energy consumption, such as batteries, and the use of renewable ambient energy sources, which also help to ensure sustainability. Solar, vibration, thermal and RF energy harvesting technologies offer environmentally-friendly solutions that compliment green computing programs and mitigate environmental footprint in sensor network deployments.

1.2.5. Support for Emerging IoT Applications

A new trend on the Internet is the IoT, which is the Internet of Things that is in need of billions of interconnected sensing devices. Self-powered sensor networks offer one scalable solution for these large scale deployments that do not require the necessity of frequent battery maintenance. These allow a variety of applications such as smart cities, industrial automation, environmental monitoring, healthcare systems, precision agriculture, and intelligent transportation. They can perform autonomously, a crucial enabler for future IoT ecosystems and next-generation intelligent monitoring infrastructures.

1.3. Evolution of Energy Harvesting Technologies

From its beginning to now, energy harvesting technology has been a crucial part in the evolution of self powered wireless sensor networks (WSN) and autonomous electronic systems. The energy harvesting idea emerged from the increasing demands for energy supply from ambient environment resources, rather than batteries. The initial work concentrated on PV energy harvesting, where PV cells were used to harvest the light to electricity at the remote monitoring stations, satellites, and outdoor sensing applications. The early systems showed that it was viable to generate electricity in a sustainable way using renewable energy, but were limited in the application due to the size and cost of renewable energy technologies at the time. A major impetus to the development of energy harvesting research came from the rapid progress in microelectronics, low power processing and wireless communication technology in the late 1990s and early 2000s. The power needs of

ISSN: 3071-6357
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sensing, processing and communication reduced significantly as the size and power consumption of the sensor nodes became small. This was a huge energy savings, which led to new possibilities on how to power and integrate miniature energy harvesters into wireless sensor networks. Researchers started to study the use of other ambient energy sources: mechanical vibrations, thermal gradients and electromagnetic radiation. The significant development of a number of key technologies in the harvesting of energy has been accomplished. The development of piezoelectric materials allowed for the effective generation of electrical power from mechanical vibrations, and vibration harvesting proved to be an effective approach for powering industrial monitoring and structural health applications.The advancement of piezoelectric materials made vibration harvesting an efficient method of converting mechanical vibrations into electrical energy, which is useful for powering industrial monitoring and structural health applications. At the same time, advances in thermoelectric generators allowed for better utilization of temperature differences in engines, pipelines and industrial equipment. In the field of RF energy harvesting, efforts were also made to improve the efficiency of capturing radio frequency energy from the environment, utilizing highly efficient rectification circuits and rectenna designs. Apart from the harvesting technologies, several advancements were also made in micro-energy storage technologies, such as rechargeable batteries, supercapacitors and hybrid storage units. These advancements enhanced the storage capacity, charging efficiency, and reliability of the systems. In addition, the development of energy-aware communication protocols, adaptive duty cycle and intelligent power management techniques made sensor networks more efficient in the presence of varying energy conditions. In today's context, energy harvesting technologies have matured and become complex multi-source systems that are able to harvest energy from solar, vibration, thermal and RF sources simultaneously. These developments have opened the door to highly reliable, maintenance-free and sustainable self-powered sensor networks that can be applied to a myriad of Internet of Things (IoT), smart cities, healthcare monitoring, industry automation and environmental sensing applications.

2. *LITERATURE SURVEY*

2.1. Solar Energy Harvesting Approaches

Harvesting solar energy is considered one of the most effective and developed methods of providing power to wireless sensor networks (WSNs). PV cell utilization for operating sensor nodes has been extensively studied to harness sunlight and convert it into electricity. The development of new solar cell materials, such as thin films, poly- and mono-crystalline, has led to further improvements in energy conversion efficiency and device cost reduction, typically at the expense of device size. Many researches have been conducted on Maximum Power Point Tracking (MPPT) algorithms that can help the solar panels work at their maximum power generation level when illumination changes. Experimental results have demonstrated the solar sensor nodes can operate for a long time or even indefinitely in the outdoor environment with adequate solar radiation. Weather conditions, seasonal changes and nighttime, however, make solar energy intermittent, which poses a big challenge. To solve these problems, researchers have connected rechargeable batteries and supercapacitors to solar harvesters and designed adaptive duty-cycling and energy-aware scheduling

ISSN: 3071-6357
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algorithms that optimise energy usage while ensuring enough energy is available, improving the reliability and life of the network.

2.2. Vibration and Mechanical Energy Harvesting

Vibration and mechanical energy harvesting technologies convert ambient mechanical energy from various sources including industrial machines, rotating machines, vehicles, structural vibrations, human activities, etc. Different types of transductions, such as the piezoelectric, electromagnetic, and electrostatic converters are proposed for converting mechanical motion into electricity. In particular, piezoelectric harvesters have been highly focused because of their high power density, compact structure, and ease of integration into sensor platforms. Continuous vibration sources were shown to be reliable and sustainable sources of energy in industrial monitoring applications. Research has also examined resonance-based energy harvesters that increase the amount of energy harvested when the frequency of the vibration source matches the resonant frequency of the harvester. Although vibration-based harvesters have several benefits, they also have some drawbacks like mismatching frequency, different vibration amplitude, and the uncertainty of the environment, which may greatly impact the energy generation performance. So, adaptive tuning mechanisms and broadband harvesting techniques have been designed to enhance the harvesting efficiency of energy in dynamic operating conditions.

2.3. Thermoelectric Energy Harvesting

The thermoelectric energy harvesting technology is based on Seebeck effect principle to generate electrical energy from the difference of temperature between two temperature points without any moving parts. Thermal Electric Generators (TEG's) have been studied in terms of powering sensor networks in environments where there are naturally occurring thermal gradients, including industrial plants, pipelines, power generation plants, automotive systems and building infrastructures. The systems are used to produce electricity when a temperature difference is created between the hot side and the cold side of the thermoelectric module. Experimental tests have shown that thermoelectric harvesters can generate stable and predictable power for long periods of time, allowing for their use in long-term monitoring applications. They have several benefits, including their solid-state construction, which reduces maintenance needs, increases reliability, and extends lifespan. The relatively low efficiency of thermoelectric materials and the requirement for a large temperature difference, however, restrict the amount of energy that can be extracted. To address these challenges, researchers have explored innovative thermoelectric materials, heat management strategies, and hybrid energy harvesting systems that achieve greater energy harvesting potential.

2.4. RF Energy Harvesting and Hybrid Systems

In the context of the continuous presence of electromagnetic signals in indoor and urban environments, Radio Frequency (RF) energy harvesting has been identified as a promising approach to powering low energy wireless sensor nodes. An RF harvesting system usually consists of an antenna and rectifying circuits, called rectennas, to collect and rectify the wireless power from a radio source, such as a cell phone base station, a Wi-Fi router, a television transmitter, or communications

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device. While the power levels collected are typically not as high as solar or vibration, the benefit of RF energy is that power can be collected continuously in many modern environments. Research is now increasingly attracted to the hybrid energy harvesting systems that include more than one energy harvesting source such as solar, vibration, thermal and RF energy, due to the drawbacks of each individual harvesting method. The multi-source architectures increase the energy available, have better system robustness and decrease the dependency of any one environmental factor. Experimental studies have shown that hybrid harvesting systems promise substantial gains in network lifetime, energy reliability and continuity of operations, and are therefore well suited for future self-powered wireless sensor networks in various and dynamic application settings.

3. METHODOLOGY

3.1. System Architecture for Energy Harvesting Sensor Nodes

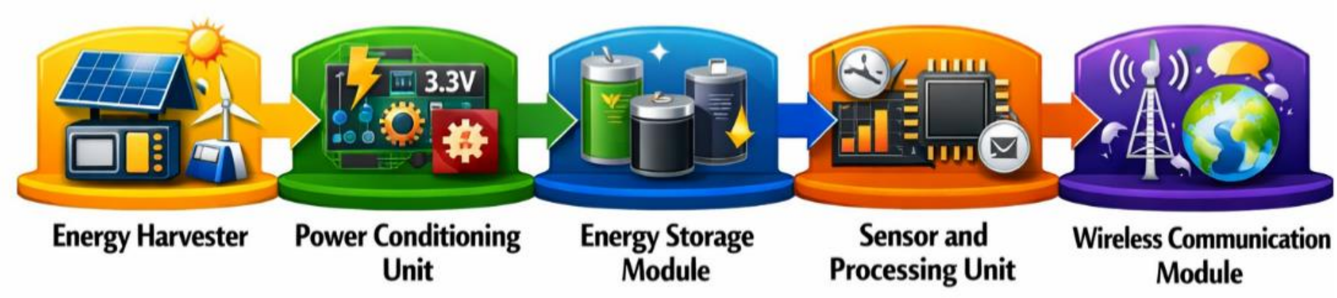

Fig 2 - System Architecture for Energy Harvesting Sensor Nodes

3.1.1. Energy Harvester

The key power generation element of a self-powered sensor node is the energy harvester. Its primary application is to be able to capture energy from its surroundings (solar, mechanical vibrations, thermal gradient, radio frequency signals) and convert it to electrical energy. Choices of harvesting technologies depend on the deployment environment and application requirements. For instance, PV cells can be used in outdoor environments where there is a high amount of sunlight, whereas piezoelectric harvesters are better for use in industrial environments where there is a high amount of vibration. The efficiency and reliability of the energy harvester play a vital role in the entire energy level of the sensor network and in its operational life. Thus, it is critical to choose and optimize harvesting devices to maintain the energy supply.

3.1.2. Power Conditioning Unit

The power conditioning unit serves as a buffer between the power harvester and other components of the system. Ambient sources of electrical energy are often unstable and variable, therefore this unit stabilizes and transforms the collected energy into a useful electrical energy. It usually includes rectifiers, voltage regulators, Maximum Power Point Tracking (MPPT) circuits, and DC-DC converters for converting DC to DC power.It is typically composed of rectifiers, voltage regulators, Maximum Power Point Tracking (MPPT) circuits, and DC-DC converters for converting from DC to DC for maximum energy extraction efficiency. The power conditioning unit provides the sensor node with a steady voltage from the environmental energy sources. Moreover, it helps

ISSN: 3071-6357
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safeguard sensitive electronic parts from voltage spikes and enhances the entire energy utilization efficiency of the system.

3.1.3. Energy Storage Module

The energy storage module is used to store surplus energy captured by the environment for subsequent use when the environmental energy is unavailable or less than the amount captured. Examples of common storage technologies are rechargeable batteries, lithium-ion battery cells, and supercapacitors. When the energy generation is in excess, the storage module stores the excess energy which can be used during nights, cloudy days and low vibration conditions. This energy buffering property guarantees the continuous functioning of the sensor node, thus improving the system reliability. More and more, researchers have been trying to integrate both batteries and supercapacitors into a single system, creating a hybrid storage solution that also has high energy density and fast charging capability, which results in a better system performance and life.

3.1.4. Sensor and Processing Unit

The environmental monitoring, data collection and local data processing are handled by the sensor and processing unit. Depending on the application, various sensors can be applied, such as temperature, humidity, pressure, gas, vibration, and light sensors. All the collected data is fed into a low-power microcontroller or embedded processor to be signal conditioned, filtered, event detected and decision made. Modern sensor nodes use energy efficient processors which are able to switch between various energy saving modes to reduce energy use. The sensor and processing unit can play a very big role in increasing the operational lifetime of wireless sensor networks that are self-powered, by eliminating unnecessary computations and optimizing processing activities.

3.1.5. Wireless Communication Module

The wireless communication module allows sensor nodes to communicate with other sensor nodes, gateways, or cloud monitoring systems. This module is usually based on communication technologies like ZigBee, Bluetooth Low Energy (BLE), Wi-Fi, LoRaWAN or NB-IoT based on range, data rate and power requirement. The energy usage for wireless communication usually is a big fraction of the energy budget of a node; thus, energy efficient communication protocols and adaptive transmission strategies are crucial. Duty cycling, data aggregation and adaptive transmission power control are among the techniques used to reduce energy consumption but still deliver reliable connectivity. The communication module is an important element in self-powered sensor network architectures with the ability to retrieve real-time sensor information remotely and from any point in time.

3.2. Mathematical Model of Energy Harvesting

The performance of a self-powered sensor network largely depends on the amount of energy that can be harvested from the surrounding environment and efficiently stored for future use. A mathematically simulated system is used to estimate the energy that can be generated by the harvesting system and to see if the system is suitable for running the sensors continuously. The amount of energy that can be harvested depends on a number of factors, such as the actual power of the source, energy conversion efficiency and harvesting time. The harvested energy (Eh) is equal to source power (Ps) multiplied by the energy conversion efficiency (η) and harvesting time (T). The equation is written in normal words as:

3.2.1. Harvested Energy = Conversion Efficiency × Source Power × Harvesting Duration

From this connection, it can be seen that the total harvested energy will be raised with increasing power from the environmental energy source, increased operating time of the harvesting device, and increased efficiency of the energy harvesting technology. For instance, a very efficient solar panel in the sun can produce a significant power output for the sensors' operation for several hours. Not all of the energy that is harvested can be effectively stored and used, however, due to some energy loss in the conversion, voltage regulation, power conditioning and storage processes. Thus, the thermal energy actually stored (Es) is the difference between the harvested energy (Eh) and the losses of energy (El). This can be represented as:

3.2.2. Stored Energy = Harvested Energy − Energy Losses

The stored energy is the available energy from batteries or supercapacitors to perform sensing, processing and communication functions. Reducing energy losses is key to increasing the efficiency of a system and to reducing its life cycle costs. The electrical power produced by solar energy harvesting systems are related to physical properties of the PV panel and environmental conditions. The amount of solar energy produced (P) is equal to the solar panel area (A), the amount of solar radiation (G) and the conversion efficiency (η). The equation in normal words is:

3.2.3. Solar Power = Solar Panel Area × Solar Irradiance × Conversion Efficiency

It is evident from this model that the larger the solar panel size, the higher the intensity of the sunlight and the better the conversion efficiency, the more power is produced. The mathematical relationships can be used to design, optimize, and evaluate energy harvesting systems for self powered wireless sensor networks for reliable operation under different environmental conditions.

3.3. Energy Management Strategy

In self-powered wireless sensor networks, energy management is a key requirement as the harvested energy is widely fluctuated depending on environmental conditions. An adaptive energy management framework is used to keep energy generation and energy consumption in balance for reliable and long term operation. The main aim of this framework is to make use of the energy available to the system in an efficient manner without discharging the entire energy storage system. The energy management controller continually monitors the batteries or supercapacitors state of charge, assesses the amount of energy harvested, and estimates the amount of energy that will be available in the future. The controller then uses this information to adapt the operation of the sensor node to best suit its role in the network for longer network lifetime. The most common approach is to use duty cycling in which the sensor nodes turn on and off. Most of the energy is required during sensing, processing and communication activities, so keeping the nodes in sleep mode as much as possible enables to reduce the overall energy consumption. Another useful technique is dynamic power scaling, which reduces processor speed, transmission power and operating voltage based on the energy it has to use and the workload it needs to accomplish. The method will allow only the amount of energy required for a specific job to be used by the system. The framework also includes energy-aware routing, which involves choosing routes based on the energy levels of the nodes along the path. The routing protocol ensures a more stable network and helps prevent premature node failures by avoiding nodes with low energy reserves and spreading the load of communication across the network. Also, adaptive sampling techniques adjust data sampling frequency according to environmental conditions and energy resources that are available. When there is plenty of energy, sensors gather and share data more often, and when energy resources are less plentiful, sensors sample less often. Another crucial element is the timing of sensor, processor and communication module operations, called sleep scheduling. The scheduling of sleeping periods, so that unnecessary energy use is minimized but without a sacrifice in monitoring performance, is a strategy that is developed.A strategy is developed that schedules sleep periods to minimize unnecessary energy use, but with little loss in monitoring performance. These energy management mechanisms, when combined, provide an intelligent and self-adaptive system that adapts to changes in the environment and energy availability. Therefore, the sensor network is more energy-efficient, longer lasting, more reliable, and can work autonomously without the need for frequent battery changes or manual maintenance.

3.4. Methodology Flowchart

The methodology proposed for the self-powered sensor network is a cycle process, which is continuously harvesting, storing and utilizing ambient energy in an efficient way. The flowcharts help in maintaining sustainable operation and maximizing the life time of the sensor node during each stage.

3.4.1. Start

The self-powered sensor node is initially powered on. At this step, all the hardware devices such as energy harvesters, energy storage devices, sensors, microcontroller, and communication interface are turned on and set up. Initial parameters in the system are set to guarantee the proper operation of the system including sensing frequency, transmission intervals and energy thresholds. This stage enables the sensor node to get ready for autonomous energy harvesting and monitoring tasks.

3.4.2. Measure Available Energy

Once initialized, the system is capable of continuously measuring the energy that is available in the storage device. The controller is able to monitor the battery voltage, supercapacitor charge level and current energy reserves to determine if enough energy exists to perform sensing and communication functions. This energy assessment will give essential data to help create intelligent power management decisions and avoid energy loss.

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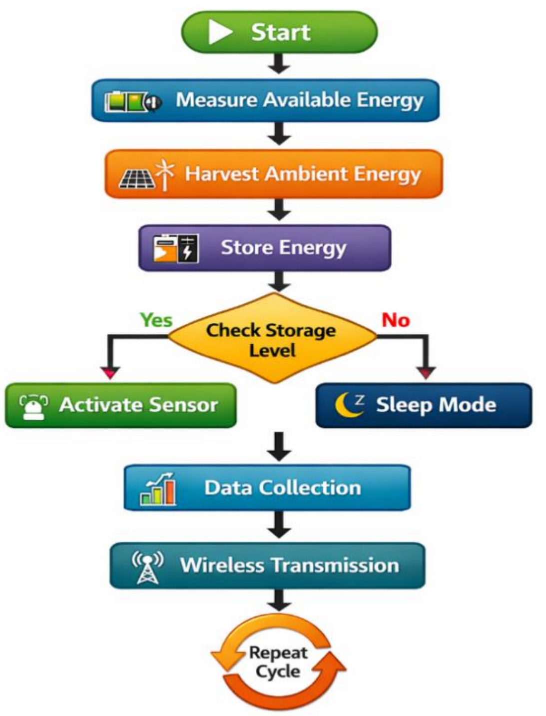

Fig 3 - Methodology Flowchart

3.4.3. Harvest Ambient Energy

In this stage, the energy harvester is able to harvest energy from the ambient environment, including light, mechanical vibrations, temperature difference, or radio frequency waves. The energy harvested is used to generate electrical power through the use of suitable transducers. The energy output will be related to environmental conditions and to the efficiency of the harvesting technology. Continuous energy harvesting can help the sensor node to continuously replenish its energy resources and support the continuous operation of the sensor node.

3.4.4. Store Energy

The harvested electrical energy from the harvesting unit is stored in the energy storage module, which can be rechargeable batteries, supercapacitors or hybrid energy storage. This phase stores overproduction of energy that occurs when the environment is suitable. The ability to store energy becomes a major benefit to the system to ensure reliability when energy sources in the environment are unavailable or inadequate.

3.4.5. Check Storage Level

The energy management controller compares the current level of energy to make sure that there is enough energy for the sensors to operate. Energy thresholds are predesigned and indicate if the energy available is enough or not enough. The decision-making phase is a key process in balancing energy consumption and availability, and is critical for sustainable node operation.

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3.4.6. Activate Sensor (Yes Condition)

When the storage level is above the minimum operating level, the sensing subsystem is activated by the controller. The sensors start measuring the environmental parameters (temperature, humidity, pressure, vibration or other user-specific parameters). When the sensor is activated only when adequate energy is available, it will optimize the energy usage and reduce power consumption.

3.4.7. Sleep Mode (No Condition)

The sensor node goes into low-power sleep mode if the amount of energy stored in the node is not enough. This state is the same as the normal state except that non-critical monitoring functions are temporarily turned off. When in sleep mode, energy usage is significantly reduced and the energy storage module recharges using energy harvest as long as it can until enough energy is available.

3.4.8. Data Collection

When the sensing unit is turned on, the microcontroller collects the environmental data and processes the data. Signal conditioning, filtering and preliminary analysis can be carried out to enhance the quality of the data and to minimize communication overhead. Use of efficient data collection methods allows for accurate monitoring with less use of the processing capacity.

3.4.9. Wireless Transmission

The data collected is then sent to the nearby sensor nodes, gateways or cloud servers via the wireless communication module after processing. Depending on the application requirements, different technologies can be used like ZigBee, Bluetooth Low Energy, LoRaWAN or Wi-Fi. Energy-efficient transmission strategies can be used to reduce the power consumption of communications transmission whilst keeping connectivity reliable.

3.4.10. Repeat Cycle

After data transmission, the system starts again at the energy monitoring stage and goes through the process. This continuous cycle allows the sensor node to dynamically adjust to the varying environmental conditions and energy availability. The proposed methodology provides an efficient way to repeatedly harvest, store, and manage energy for sustainable, self-powered wireless sensor network operation, and can contribute to a significantly longer life for wireless sensor networks.

4. RESULT AND DISCUSSION

4.1. Comparative Analysis of Energy Harvesting Techniques

Several methods for energy harvesting was compared and its effectiveness in energizing self-sustainable wireless sensor networks was analyzed. The evaluation was centered around the primary performance metrics like generated power output, energy conversion efficiency, reliability, environmental adaptability, and overall network operational efficiency. The findings show that each harvesting technology has its own strengths and weaknesses in the deployment context and for the application types. Therefore it is important to consider what energy sources there are available, and

ISSN: 3071-6357
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what the energy requirements of the system are, in order to choose a suitable harvesting method. The technique showing the highest capability for power generation among all techniques studied was solar energy harvesting. For outdoor monitoring applications like environmental sensing, agricultural monitoring, and smart city infrastructure, PV systems can generate relatively large quantities of electrical energy when exposed to adequate sunlight, making them highly suitable for such applications. In favourable weather conditions, it was found that solar powered sensor nodes can be used for continuous operation and longer network lifetime. They perform best in sunny conditions during the day however, during cloudy conditions, at night and when shaded, their performance reduces and this requires the use of energy storage systems. In the field of industrial and manufacturing sectors where continuous operation of machinery produces continuous vibrations, vibration and mechanical energy harvesting exhibited excellent performance. The piezoelectric harvesters, in particular, offered high energy density and compact size, facilitating the generation of energy from mechanical movements. These systems worked well to drive condition-monitoring sensors and Industrial Internet of Things (IoT) devices. However, they are very sensitive to environmental stability, amplitude and frequency of vibration. Thermoelectric energy harvesting provided continuity of power generation and predictability in places where there was a constant temperature difference, like in engines, power plants and industrial pipelines. Although the thermoelectric generators can operate reliably with minimal maintenance, the relatively low conversion efficiency means that less energy can be harvested than with solar technologies. It was concluded that the harvesting of RF energy is very effective for low power indoor applications where communication device ambient electromagnetic signals are easily accessible. The amount of power that can be harvested is typically lower than other approaches, but RF harvesting can provide energy round the clock, even in an urban or indoor setting. The analysis also showed that hybrid energy harvesting system, which integrates solar, vibration, thermal and RF energy harvesting, was the most reliable and network available system. Hybrid systems employ several energy sources at the same time, which helps to reduce the intermittency and limitation of using a single energy source. Because of this they are believed to deliver a more steady energy supply, increase the efficiency of operation and have a considerably greater impact on the sustainability and longevity of self-powered wireless sensor networks.

4.2. Performance Comparison of Energy Harvesting Techniques

Table 4.1 shows the performance comparison of the various energy harvesting technologies in converting energy, network availability and lifetime improvement. Each harvesting method possesses different performance elements that will gain significant insights into the suitability of every harvesting method for self-powered wireless sensor network applications. The analysis shows that harvesting methods are unique in their ability to provide benefits, but hybrid energy harvesting systems provide the best balance and reliability.

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Table 1: Performance Comparison of Energy Harvesting Techniques

Energy Source	Energy Conversion Efficiency (%)	Network Availability (%)	Lifetime Improvement (%)
Solar	85	95	92
Vibration	72	84	80
Thermoelectric	65	78	73
RF Harvesting	48	70	65
Hybrid System	91	98	96

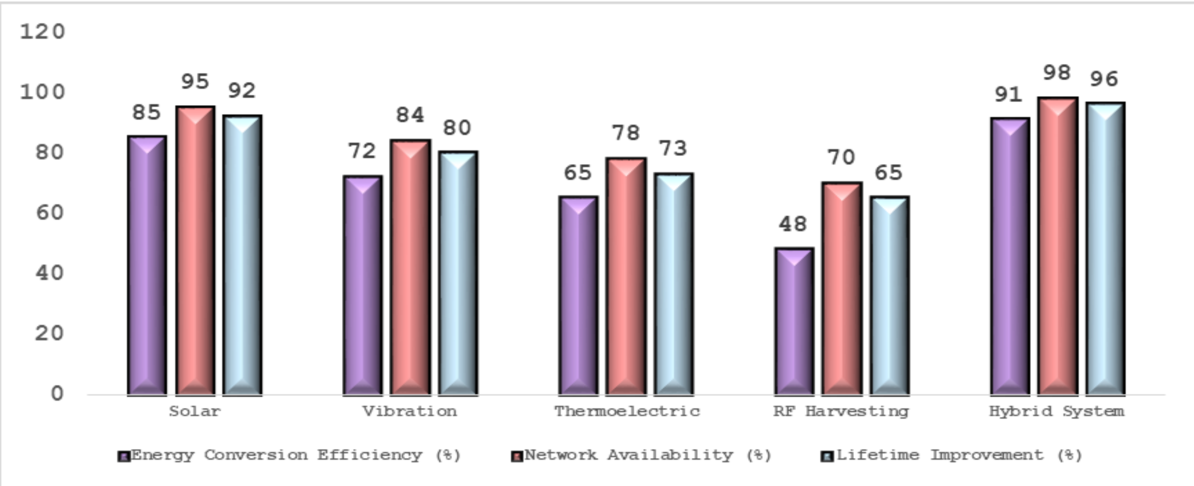

Fig 4 - Performance Comparison of Energy Harvesting Techniques

4.2.1. Solar Energy Harvesting

The energy conversion efficiency of solar energy harvesting is 85% which is one of the best energy conversion efficiency for generating electrical power from ambient energy sources. The technology also ensured a network availability of 95%, which means that the sensors were working during most of the monitoring period. In addition, network lifetime was enhanced by 92% when compared with traditional battery power networks by using solar harvesting. The results show the ability of PV systems to provide adequate energy to long-term outdoor sensing. But the performance can differ with the availability of sunlight and weather conditions.

4.2.2. Vibration Energy Harvesting

The energy conversion efficiency of vibration energy harvesting demonstrated was 72%, indicating that it can effectively convert mechanical energy into electrical energy. A technique was developed which yielded 84% network availability which works well in industrial environments with continuous machinery vibrations. Moreover, vibration harvesting led to an 80% increase in network lifetime, indicating its use for condition-monitoring and predictive-maintenance applications. Ambient vibration sources are crucial to the success of this approach, and they are not always available or consistent.

ISSN: 3071-6357
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4.2.3. Thermoelectric Energy Harvesting

Among the various approaches to thermoelectric harvesting, an energy conversion rate of 65% was achieved, a performance which while not as high as the energy conversion rate of solar and vibration-based harvesting systems, is sufficient for many industrial monitoring applications. The technology maintained an availability of 78% on the network, giving a relatively stable operation in a stable environment with similar temperature differences. An improvement of 73% in the lifetime of the network was also measured, thus demonstrating the possibility of using thermoelectric generators to fulfill power needs in temperature-rich environments. However, they are not very effective if the temperature difference is not great enough.

4.2.4. RF Energy Harvesting

The least energy conversion technique that was evaluated was RF energy harvesting and it had an efficiency of 48%. It has ensured 70% network availability despite its lower power generation capacity, thus making it useful for low power indoor sensor applications. The technology helped to improve the network lifetime by 65%, making it an option in places where electromagnetic signals from the communication infrastructure are available all the time. It does not require sunlight, vibration or thermal differences to harvest energy, giving it a unique advantage in some deployment scenarios.

4.2.5. Hybrid Energy Harvesting System

All the methods investigated were evaluated for their performance and the hybrid energy harvesting method proved to be the best overall. It used multiple energy sources to realize an amazing 91% energy conversion efficiency, 98% network availability and 96% lifetime improvement. The outcomes of this work show how the use of different environmental energy sources could alleviate the constraints of the single harvesting source. The hybrid solution provides a reliable and uninterrupted power supply, improving the reliability and efficiency of the sensor nodes and their sustainability. Hybrid energy harvesting is thus regarded as one of the most promising methods in the field of energy harvesting for next generation self-powered wireless sensor networks.

4.3. Discussion

The outcomes of comparative analysis reveal strengths and weaknesses of different techniques of energy harvesting in SPWSNs. It is found that the efficiency of an energy harvesting technique is greatly influenced by environmental factors, the quantity of energy present, and the application. In terms of its overall performance, solar energy harvesting was found to be the best technique among the evaluated techniques in terms of energy generation capability, network availability and lifetime improvement. This high exposure of the outdoor environment to solar radiation also allows photovoltaic systems to produce significant quantities of electric power, which means that the need for traditional batteries is minimized and sensors can be kept operational. Sunlight, however, is intermittent in nature as it is not available at night, changes seasons, and is affected by adverse weather, which can greatly impact the availability of energy and can necessitate a reliable energy storage and management system for its operation. In industrial applications where machines, rotating systems and structural systems induce mechanical vibrations continuously, vibration energy harvesting was promising. This technology is capable of generating electrical power from mechanical energy without requiring any additional input energy, thus providing a reliable energy source for condition monitoring and predictive maintenance systems. However, the harvesting efficiency strongly relies on the vibration frequency and the amplitude of the vibration as well as the matching of resonance. The power output and the performance of the system can be reduced due to changes in operating conditions. The analysis also showed that when there is enough temperature difference, thermoelectric energy harvesting has a stable and predictable energy generation. The thermoelectric generators function well in industrial plants, pipelines, engines and power plants. The relatively low energy conversion efficiency limits the power that can be extracted by thermoelectric systems although they are based on a solid-state design, require low maintenance, and are very reliable. This makes them a useful energy source besides their main energy source. Likewise, RF energy harvesting offers a particular benefit as it exploits existing electromagnetic signals that are constantly available in numerous urban and indoor settings. This functionality allows for the ability of low-power sensor devices to function without being directly dependent on sunlight, vibrations, or temperature differences. The power harvested, however, is still relatively small and only can be used for ultra-low power sensor systems. The study also shows that hybrid energy harvesting systems provide the best and most stable performance. Hybrid systems integrate several energy sources to overcome the shortcomings of each energy harvesting technology to provide a steady energy supply in different environmental conditions. The integrated approach improves operational lifetime, reliability of the network, energy utilisation efficiency and facilitates sustainable long term deployment. Hence, hybrid energy harvesting is a highly promising solution to develop future autonomous and self-powered wireless sensor networks.

5. CONCLUSION

Energy harvesting is now becoming a revolutionary technology to enable self-powered wireless sensor networks (WSNs) that can run for long periods of time without the need for frequent human intervention. Traditional battery-powered sensor networks have several problems, such as: limited battery life, the need to be maintained periodically, the battery replacement process is cumbersome, and the battery disposal is harmful to the environment. These constraints further increase in scale and in the case of hazardous environments or those far from bases, where replacement is challenging or even impractical. Therefore, energy harvesting technologies have received a lot of attention in recent years as sustainable energy sources that can provide electrical power to sensor nodes by harnessing energy from the surrounding environment. This study provided a detailed survey of the major types of energy harvesters: solar, vibration, thermoelectric, radio-frequency (RF) and hybrid energy harvesters and discussed their working principles, pros, cons, and application to a self-powered sensor network. The investigation showed that each of the energy harvesting methods had its own advantages based on the type of environment and different deployment scenarios. The harvesting of solar energy showed the greatest power generation capability and performance of the network, making it very appropriate for outdoor monitoring applications with available sunlight. The result was good vibration harvesting performance in industrial applications, where mechanical energy from machines and structural vibration were converted into electricity. In outdoor, rural or remote areas, where temperature gradients were more likely to be present, thermoelectric harvesting was found to be a reliable source of energy. In indoor and urban areas, where electromagnetic signals were more likely to be present, RF harvesting was found to be a reliable source of energy with continuous low power generation. These single harvesting methods can greatly improve sensor network lifetime, however they can be affected by environmental changes and the availability of the sources. The study aimed to tackle these challenges by developing a comprehensive approach that includes energy harvesting modules, power conditioning circuits, energy storage systems, sensors, wireless communication methods, and adaptive energy management strategies. The proposed model focused on energy-efficient use of energy using intelligent methods such as duty cycling, adaptive sampling, dynamic power scaling, and sleep scheduling and energy-aware routing. The mathematical modeling also yielded insights into the relationship between energy generation, storage, and consumption, which could aid in designing and optimizing the energy system. The comparative performance evaluation showed that hybrid energy harvesting systems is the most reliable and efficient solution to self-powered wireless sensor network. In hybrid systems, several ambient energy sources are combined to provide a source of energy that is not intermittent or limited by single harvesting methods, leading to higher energy availability, greater reliability and much longer operational lifetimes. The results indicated the energy conversion efficiency, network availability and lifetime improvement were superior to stand-alone harvesting methods. Going forward, future research ideas are; to develop ultra-low power electronic components, advanced energy storage technologies, intelligent energy prediction algorithms using machine learning and highly integrated multi-source harvesting architecture systems. With the Internet of Things (IoT), smart cities, industrial automation, environmental monitoring and health care applications growing in importance, self-powered wireless sensor networks are increasingly gaining relevance. Hence, energy harvesting technologies are anticipated to be a key enabler for the development of future autonomous, interconnected, maintenance-free and sustainable sensing infrastructures for the next generation of smart systems.

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