A Solar powered Radio Frequency Based Wireless Sensor Network for Pneumatic and Gas Pipeline Monitoring

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Abstract- One of the most important infrastructures in contemporary life is pipeline networks. Pipeline networks must be monitored and inspected regularly to ensure their safe and effective operation. Existing monitoring and maintenance approaches are costly and inefficient because pipelines are installed on a large scale and in an inaccessible and hazardous environment. To overcome these challenges, a self-powered radio frequency-based pipeline monitoring system is developed. The developed system comprised mainly three units: An energy harvesting unit, a wireless data transmission unit, and a date receiver unit. The wireless transmission unit is comprised of a pressure sensor that senses the flow pressure inside the pipeline and sends data to the receiver unit with the help of a microcontroller unit. The receiver unit displays the pipeline flow pressure data on a small LCD screen to users for further processing. A 2200 mAh rechargeable lithium-ion battery is used to provide power to the developed wireless sensor node. The rechargeable battery is initially charged with direct AC using a 220 V AC adaptor and T6845-C power management module. Experimental results show that the battery can be recharged from 3.08 V to 4.21 V in a time duration of 300 minutes. Later on, a 10 W solar panel is used to recharge the same battery during sunny and cloudy weather at different light intensity levels. On a sunny day it took 1200 minutes to enhance the battery level from 3.07 V to 4.17 V while on a cloudy day, the battery level enhanced from 3.1 V to 4.01 V in a time duration of 1500 minutes. The charged battery is then used to power all the onboard components of the wireless transmission and receiver unit. During the discharging of the battery with data transmission and receiver units, it took 1200 minutes to decline the battery level from 4.17 V to 2.97 V.

Index Terms- Energy Harvester, NRF Module, Self-Powered, Pipeline monitoring, harvester

I. Introduction

Pipelines for the transportation of oil, water, and gas are essential components of the national energy sector and have a considerable economic effect. In developing nations, pipelines are considered the safest way to transport oil, gas, and other fluids between stations. As a result, pipeline transmission systems are installed in many countries, ranging in length from a few meters to several kilometers [1]. These pipelines pass through various locations where continuous inspection and surveillance by the naked eye is not feasible. In these locations, even a minor pipeline collapse may lead to serious damage to people's health, property, environment, and most importantly the economy. As reported in [2], a leak of about 267000 gallons of oil happened in the Tundra of Alaska, North America, for five days until field employees detected the crude oil via dispersed oil smell while traveling through the region on March 2, 2006. This leak was caused by a two-thirds-of-a-centimeter hole in the pipe section caused by corrosion. On the 13th of June 1996, the Midwest oil industry observed a significant decrease in crude oil pressure in the pipeline network [3]. Following an examination, it was discovered that a minor leak had occurred in the pipeline, resulting in a loss of about 360 m^3 (95102 gallons) of crude oil. Furthermore, a gas accident in Columbia resulted in a $285,000 gas loss [4], [5]. In the United States, a gas distribution firm reported a 69 billion cubic foot loss of natural gas owing to a pipe network leakage [5]. The magnitude of the issue and the urgent need for safe pipeline operation are reflected in the incidents and accidents associated with the transmission pipeline network.

To ensure the safe operation of pipeline networks, several systems for condition monitoring of oil and gas pipeline networks have been developed. such as acoustic signal-based system [6], Fiber optic cable-based system [7], smart pigging method [8], sensor hose system [9], soup bubble screaming method [10], pressure point analysis system [11], and video monitoring system [12]. However, the use of wireless sensor nodes (WSNs) technology for pipeline condition monitoring is becoming increasingly popular, since WSNs can constantly monitor the pipeline network and transmit the necessary data in real-time to the control station for analysis.

Figure 1 depicts a wireless sensor technology-based pipeline monitoring system. In such a system a large number of wireless sensor nodes (WSNs) are installed across the pipeline network which gather pipeline physical parameter data and send it to the gateway sensor node through wireless data transmission modules. The information is subsequently sent to the control room where it is displayed to the user. Correspondingly, the user can also send control action commands to WSN installed over the pipeline. Among the many parts of a wireless pipeline monitoring system, the WSN is the most important one. It is comprised of a sensor unit, signal conditioning and processing unit, wireless data transmission unit, microcontroller unit, memory unit, and power management unit. The sensor unit senses the physical parameters (pressure, temperature, humidity, vibration, flow rate, etc.) of the pipeline and converts them into electrical signals (digitals or analog) which are then processed by the signal processing unit. The processed data is then transferred to the transceiver unit. The microcontroller unit controls all the onboard activities and also controls the modes of operation (sleep, transmission, and alert). Furthermore, the battery unit in WSN powers all onboard components.

The major concern here is providing power to the WSNs. WSNs for pipeline monitoring are often powered by batteries. However, Due to the short lifecycle of a battery, WSNs often need regular maintenance, such as battery replacement or recharging. Since a large number of WSNs are installed over the pipeline network which may be spread throughout several thousands of kilometers, therefore, the battery's recharging or replacement over the enormously long pipeline networks is not feasible. A long-lasting, alternate power source is required for the continued functioning of WSNs. Energy harvesting from the ambient source surrounding the pipeline is the best possible solution. There is a lot of ambient energy present in the surroundings of the pipeline, such as wind[13]–[16], thermal, vibration[17], Acoustic [18]–[22] energy, and solar energy. Although, some of these energy sources have limitations, such as, wind energy highly depends on locality and climate. On the other hand flow energy harvester disturbs the flow in the pipeline so it is also not used as a prominent source for energy harvesting. The presence of RF energy also depends on locality, moreover, their output power density is also very low. So, the best possible source of energy is the solar energy. In this study, a solar energy harvester will be utilized to power the WSN as well as recharge the power bank for backup. As solar energy is not available at night time so power bank will used as an alternative source.

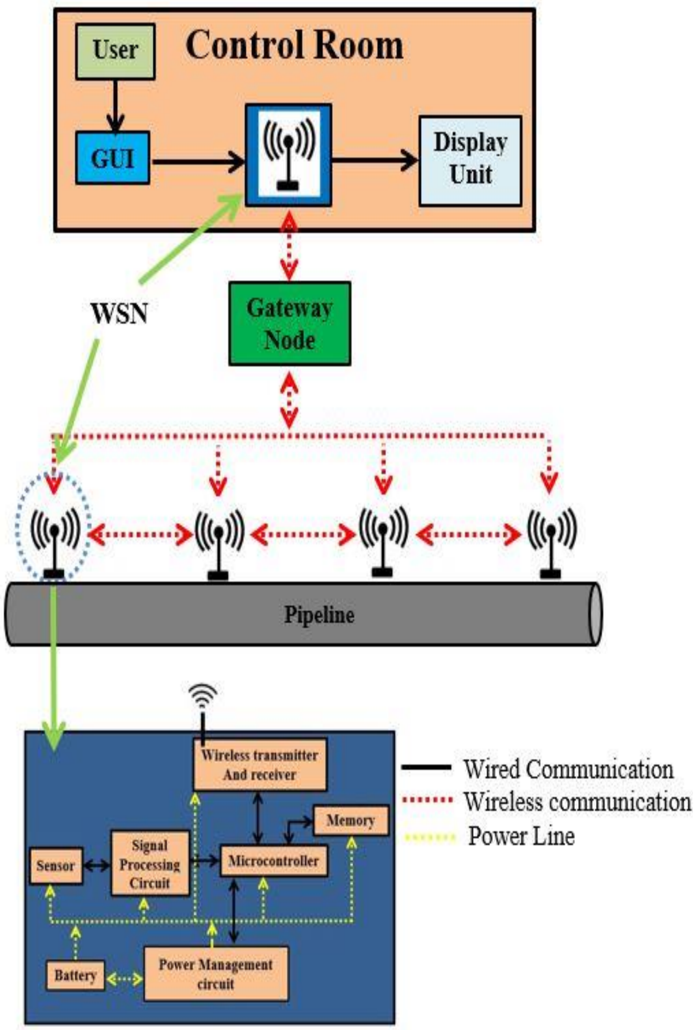

Figure. 1: IoT based Pipeline monitoring system

II. LITERATURE REVIEW

Several researchers have worked to develop a self-power monitoring system and energy harvesting devices for long pipeline networks[23]–[30]. A sensor network platform developed by Jin and Eydgahi [2] for pipeline monitoring uses acoustics sensing devices such as Lead Zirconate Titanate (PZT) sensors. This solution is based on the transmission and detection of lamb waves and uses a simple triangulation method for event localization. PipeNet, a wireless sensor network proposed by Stoianov et al. [31], integrates sensors that can generate acoustic vibration and collect hydraulic and acoustic/vibration data at high sampling rates. This system detects leakage and locates it via cross-correlation of acoustic/vibration signals. GASNET [32] is a self-powered wireless network of keyhole-installed and keyhole-replaceable sensors capable of measuring and communicating pressure, flow, and vibration in natural gas distribution system pipelines. WSNs have been applied to use for underground pipeline monitoring [33]. Here flow pressure and soil properties sensors are used for detection and localization leakage in an underground pipeline. The measurements taken by the underground sensors out of pipelines are transmitted by utilizing magnetic induction (MI) upon on wireless underground sensor networks. A wireless sensor network-based pipeline monitoring system is developed in [34]. The system consists of an accelerometer that senses the pipeline acceleration and sends the data to the base station via ZigBee protocol for further processing. The system can report the knocking and drilling operation at the pipeline network to the base station. An efficient wireless sensor network for pipeline monitoring systems was presented in [35]. This system is based on the REMONG solution for pipeline monitoring systems. An experimental setup was developed which consists of a 14.1-meter-long pipe having an internal diameter of 2 inches. A water tank is used as a fluid source which provides water to the pipeline network through an electric motor. Four valves are used for creating artificial leaks in the pipeline network. Digital temperature and pressure sensors are used for measuring the temperature and pressure of the pipeline network. A ZigBee protocol-based module is used for wireless communication, which has a communication range of 3200 m outdoors and 90 m indoors. Pipeline pressure and temperature sensors date transmitted successfully to the base station, and on analysing the data, leaks were found in short intervals of time. Ali M.Sadeghioon et al [36] developed a wireless sensor network for leak detection in pipelines. A full experimental and real-time setup was developed. The experimental setup consists of a U-shaped section made up of PVC pipe having 40 mm diameter A water pump is used for the circulation of water in the pipeline with a pressure of 3 bars. A 10 mm hole is made at the center of the pipe. Five FSR pressure sensors are attached to the pipeline at a distance of 2 m which measure the pressure of fluid in the pipeline and send the data to the DAC card (Labjack u3) where it is analyzed and the leaks alarm is activated. The system is also installed in real-time conditions in which two temperature sensors and one FSR pressure sensor are installed. One temperature sensor is used for measuring pipeline wall temperature while another temperature sensor is placed 30 cm away from the pipeline to measure the pipeline's surrounding temperature. Each sensor node sends its data to the mother node, from where it is sent to the main server through the Internet. The main advantage of this system is that the power consumption of the wireless sensor node is very low up to 2 µW. A wireless sensor network for pipeline damage detection was presented by Hadil Mustafa [37], [38]. The system consists of three units: a sensing unit, an aggregation unit, and a server. The sensing unit consists of a sensing node which is an accelerometer and microcontroller. The accelerometer measures the acceleration of the pipeline and sends data to the aggregator unit for logging, processing, and transmission purposes. The aggregation unit consists of a data aggregation unit and a high computational microcontroller unit. The aggregation unit logs the data to the removable source or transmits it to the main server via Wi-Fi for further processing. Zhi Sun et al. [39] developed a magnetic induction-based wireless sensor network for a pipeline monitoring system called MISE Pipe. The system consists of two types of sensors; one is installed inside the pipeline while the other is outside along the pipeline. Inside the pipeline pressure and acoustic sensors are installed at two different checkpoints. Outside the pipeline soil monitoring sensors are installed along the pipeline. This overall system works in three phases, In the first phase the pressure sensor measures the flow pressure and sends the data to the remote administrator center via Wi-Fi. In the second phase after analyzing the data, the administrator notified the pressure sensor about the suspicious location. The pressure sensor then sends the data request to the soil property sensor which comes out from sleep mode and measures the soil properties. The soil property sensor then sends data to the pressure sensor processing hub through magnetic induction communication. In the third phase after receiving the soil property data, the processing hub confirms the leak location and informs the administrator server. Masanobu Shinozuka et al. [37] developed a MEMS-based wireless sensor network called PIPETECT for the pipeline monitoring system. This system consists of a sensing node named Gopher, a data aggregation unit, and a wireless data transmitting unit called Roocas. The Gopher consists of three MEMS-based accelerometers, which sense the vibration of the pipe in X, Y, and Z directions. A full experimental setup was developed which consisted of 40 PVC pipe having 1 inch diameter. Seven control valves and eight Gophers are installed in the whole setup. The Gophers sensor collects vibration data of the water pipeline network in real time and sends the data to Roocas for data aggregation. After aggregation, Roocas sends the data to the host computer through a Wi-Fi medium for further processing.

With advancements in solar harvesting technology and small-size power solar cell development, solar energy harvesters are nowadays used to power the wireless sensor node used for monitoring and control of different applications. Different research-based and commercial products of solar power wireless sensor nodes have been developed. Vijay Raghunathan [40] developed a solar energy harvesting prototype named helimote. The devised system is used to power the wireless sensor node used for monitoring different applications. The main challenges that occur while harvesting solar energy via small solar cells are discussed in detail. A 3.75 x 2.5 inches size solar panel having the power of 190 mW is used to power a Ni-MH battery with having capacity of 1800 mAh. In [41], the design modeling and simulation of a micro solar power plant for powering wireless sensor nodes has been discussed. A 2.3 x 2.3 inches solar panel was used to power a small rechargeable battery having a power capacity of 2500 mAh. The power capacity and energy production per day of the solar panel used in the prototype are 276 mW and 139 mWh/day. Farhan Simjee [42] developed an IoT-based monitoring system called Everlast powered by a solar energy harvester-based supercapacitor. A 450 mW small solar panel having a size of 2.24 x 3.75 inches is used to power a supercapacitor having a capacity of 100 F. The experimental results of the developed prototype show that the system can power the WSN for a long time. Masateru Minmani [43] et al. reported the design and implementation of a battery-less WSN that used a supercapacitor powered by a small solar panel. A 2x2 inches solar panel having a power capacity of 150 mW was used to power a 1 F capacitor. The developed prototype was successfully tested inside the lab as well as in a real environment. Experimental results show that the designed energy harvester is capable of powering wireless sensor nodes.

In the existing landscape of pipeline monitoring systems, a predominant reliance on wired or Ethernet-based solutions poses significant limitations, especially in areas where Ethernet infrastructure is unavailable. This becomes even more challenging in remote regions where these monitoring systems are often powered by batteries, necessitating frequent recharging or replacement. The study introduces an innovative pipeline monitoring system that integrates a radio frequency-based data transmission system and operates continuously using a solar energy harvesting unit. This system features a wireless sensor node with a pressure sensor and microcontroller, transmitting pipeline flow pressure data to a receiving node via NRF Modules. By eliminating the need for wired infrastructure and ensuring sustained power through solar energy, the proposed system offers a versatile and eco-friendly solution for autonomous pipeline monitoring in diverse geographical settings.

III. ARCHITECTURE AND OPERATIONAL MECHANISM OF THE HARVESTER

Figure 2 depicts the architecture of the wireless communication-based pipeline monitoring system that is powered by a solar energy harvesting unit. An energy harvesting unit, a wireless data transmission unit, and a date receiver unit are the three primary components that make up the proposed system. To convert the solar energy into electrical energy, a solar panel with a power output of 10 W is utilized. It is necessary to make use of a step-down power supply converter to convert the 12 V DC output of the solar panel to 5 V. The solar energy harvester not only supplies power to all of the components that are already present on the wireless transmission unit, but it also recharges the battery so that it may be used as a backup. A pressure sensor is used in the wireless transmission unit. This sensor is responsible for monitoring the pressure within the pipeline and transmitting the information to the microcontroller unit. The microcontroller unit analyzes the pressure sensor data and transmits it to other nodes with the assistance of the wireless transverse unit (NRF-Module). The receiver unit of this system is made up of a wireless transceiver unit that receives the pipeline pressure data from the transmitter unit and then displays the data on an LCD screen for further processing.

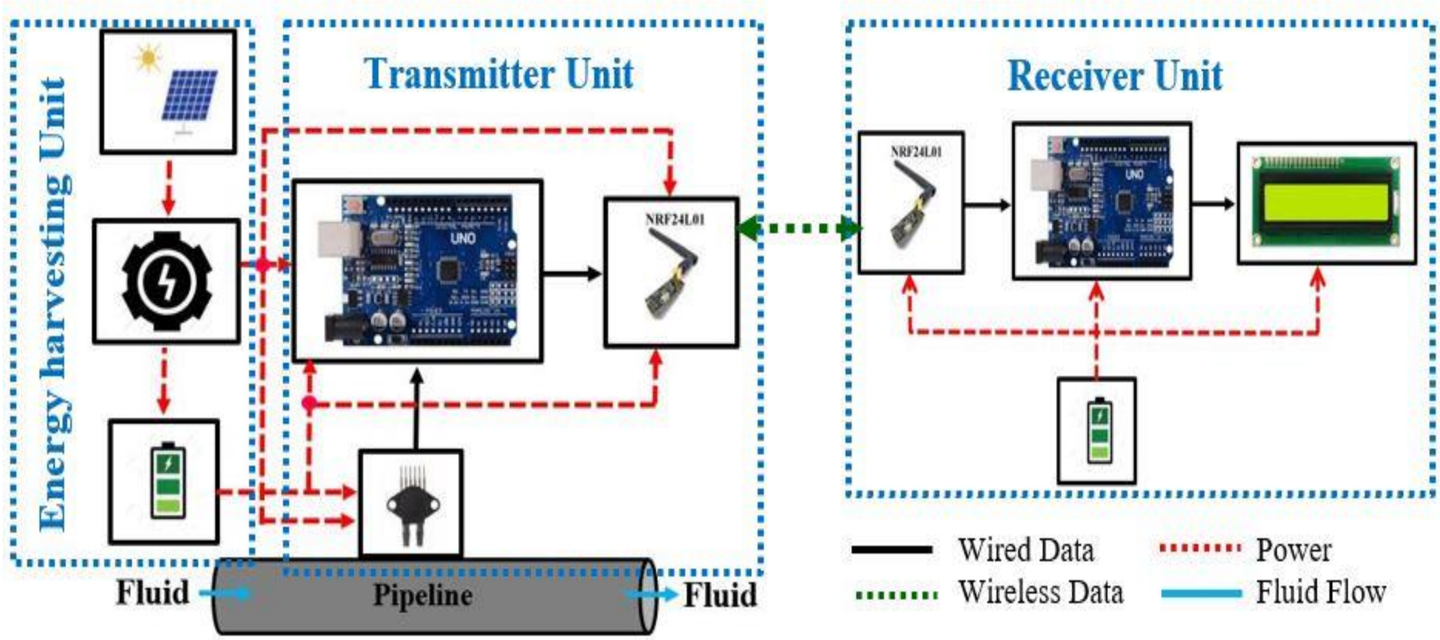

Figure. 2: Architecture of proposed self-powered pipeline monitoring system

IV. DEVELOPMENT OF PROTOTYPE

The wireless transmitter and receiver units, integral components of the meticulously crafted pipeline monitoring system, are showcased in Figures 3 and 4. The prototype's casing is meticulously fabricated using a 3 mm thick acrylic sheet, demonstrating a robust and precisely engineered design. Various machining processes were employed to cut the sheet into distinct sections for constructing the casing walls. The assembly process involved a combination of screws and adhesive materials to achieve the desired structural integrity and proposed shape. Intricate slots were strategically incorporated into the casing walls to accommodate the pressure sensor, Arduino cable, and a compact LCD screen. A pressure sensor MPX5010DP, is utilized to correctly measure the flow pressure amplitude of the pulsing flow that occurs within the pipeline. The Arduino Uno (ATmega) is the primary processing unit that is responsible for managing the data from the pressure sensor. The implementation of a wireless transceiver unit (NRF24L01) is used to send pipeline pressure data to the receiver unit in the control room. Figure 4 shows the receiver unit of the proposed system. it comprised of Arduino UNO R3, an NRF24L01 module, and an LCD screen . The NRF24L01 received the data and displayed it on a small 16x2 LCD screen for further processing. This comprehensive wireless transmitter unit, which is distinguished by its advanced sensor integration and cutting-edge wireless communication technology, is an essential component in the pipeline monitoring system that has been developed. It contributes to the system's increased efficiency and reliability in capturing and transmitting vital pipeline pressure information. Table 1 shows the description and value of different components of the developed prototype.

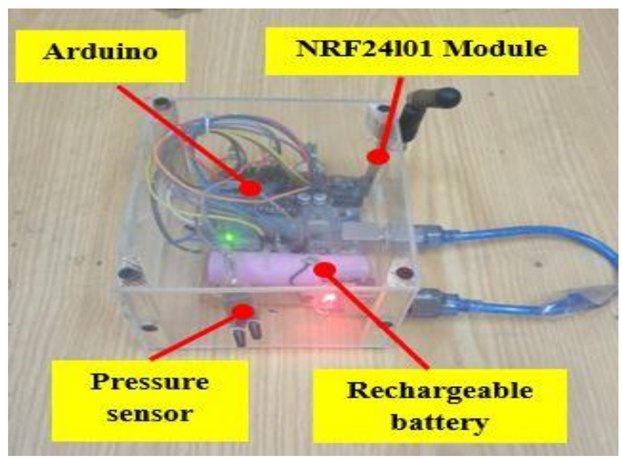

Figure. 3: Wireless transmitter unit

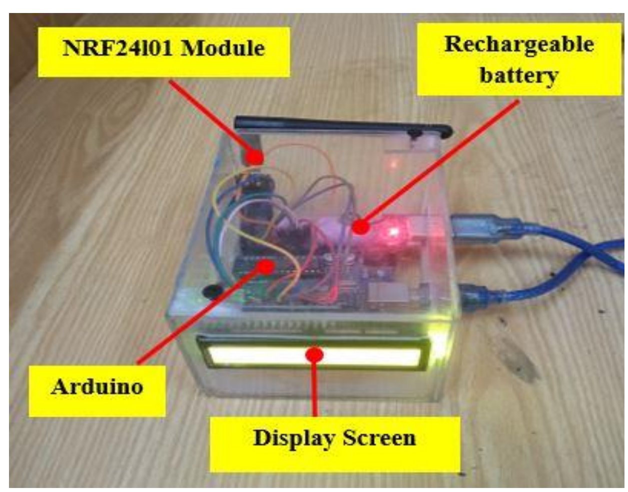

Figure. 4: Wireless receiver unit

Table 1: Different components of the prototype

Unit	Specification	Value
Transceiver	Transceiver Model	NRF24L01
	Frequency	2.4 GHz
	Input voltage	1.9 to 3.6 V
	Current (transmitter)	11.3 mA
	Current (Receiver)	13.5 mA
	Transmission range	800 m
	Operating Temperature	-40 to 85 ^oC
	Dimension	(2.9 x 1.5 x 1.2) cm
Microcontroller	Microcontroller type	Atmega328P
	Operating voltage	3.3 – 5 V
	Dimension	(68 x 54 x 10) mm
Sensor	Sensor Model	MPX5010DP
	Pressure range	0 to 10 kPa
	Operating voltage	4.5 V
	Sensitivity	450mV/mm
	Media measured	Air/Gas
	Temperature range	-40 to +125^{0}C
Solar Panel	Peak Power	1o W
	Open Circuit Voltage	21.6 V
	Short Circuit Current	0.59 A
	Max. Power Voltage	18 V
	Max. Power Current	0.51 A
	Dimension	(415 x 268 x 22) mm
Battery	Battery type	Lithium-ion
	Battery capacity	2200 mAh
	Nominal Voltage	3.7 V
	Dimension (D x H)	(18.3 x 64.9) mm
	Weight	41 grams

V. Experimentation of the prototype

The block diagram and actual experimental setup developed for the experimentation of a self-powered wireless communication-based pipeline monitoring system are presented in Figures 5 and 6 respectively. To produce airflow, an air blower (B9027, BOSITENG, China) is used in the experimental setup. To isolate the vibration of the blower from the device, a rubber pipe is placed between the blower and the propylene pipe. The flow rate of the air is varied with the help of the flow rate regulator knob present in the blower. A pressure sensor (MPX5010DP) is placed in the pipeline for the measurement of the pressure amplitude of the pulsating flow. The Arduino acquires the signal from the pressure sensor and sends it to the control room with the help of the NRF24L01 module. To provide power to the wireless sensor module, a solar energy harvester is used. The voltage signal of the energy harvester is measured and analyzed using a digital multimeter (GDM-8034, Electronic Venta) and oscilloscope (GOB-6112, Electronic Venta). Furthermore, to convert the high DC output of the solar energy harvester into low DC output, a low voltage DC-DC converter built with solar panels is used.

The power bank used for powering the wireless transmitter unit is initially charged with direct AC power available at home. Normally available Samsung mobile phone charger is used to convert the 220 V AC voltage to 5 V DC voltage. Moreover, a Power Bank Module T6845-C is used to interface the mobile charger with the power bank. A 4.8 V rechargeable battery is first discharged to 3.08 V and then connected to a Solar panel with the help of a power management module. With the storage of energy in the battery, its voltage level increases over time and is observed with the help of a multimeter.

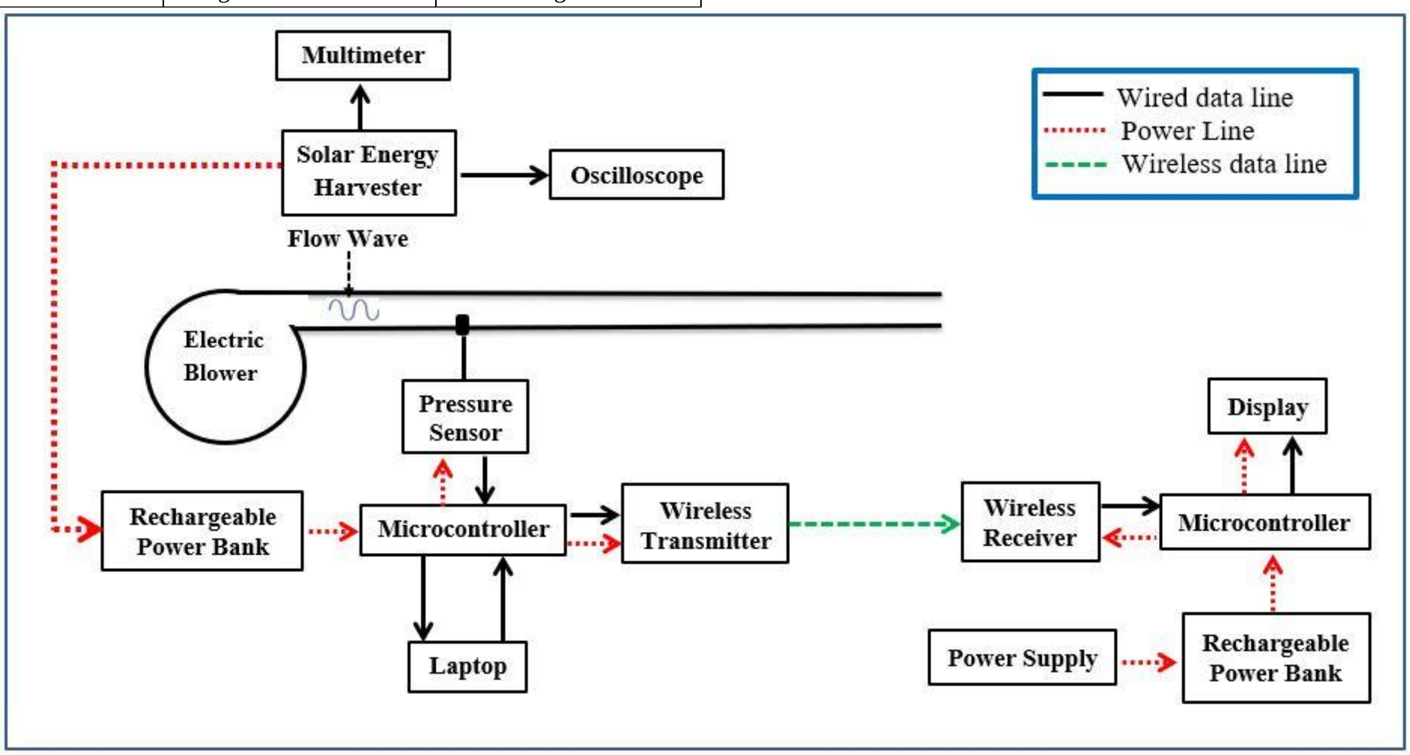

Figure. 5: Schematic of experimental setup

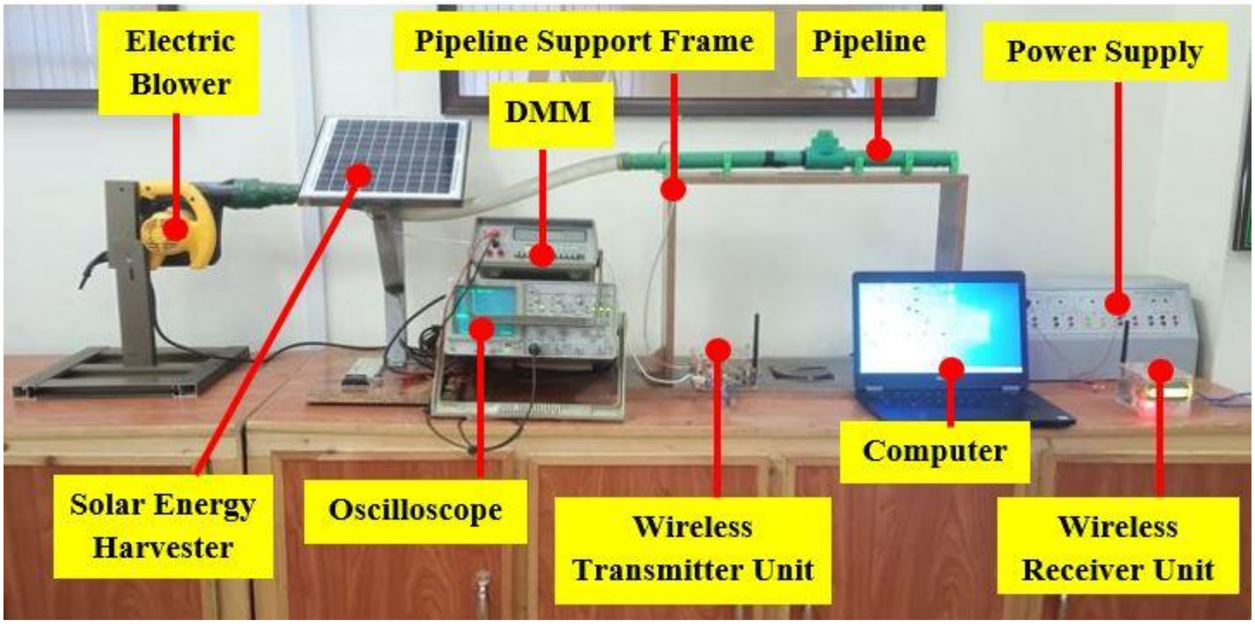

Figure. 6: Developed Experimental setup

Figure 7 shows that the voltage level in the battery reached 3.57 V in the first 30 minutes of the charging, however, its level enhanced to a level of 4 V in 180 minutes. After a time duration of 300 min, its level reached 4.2 V

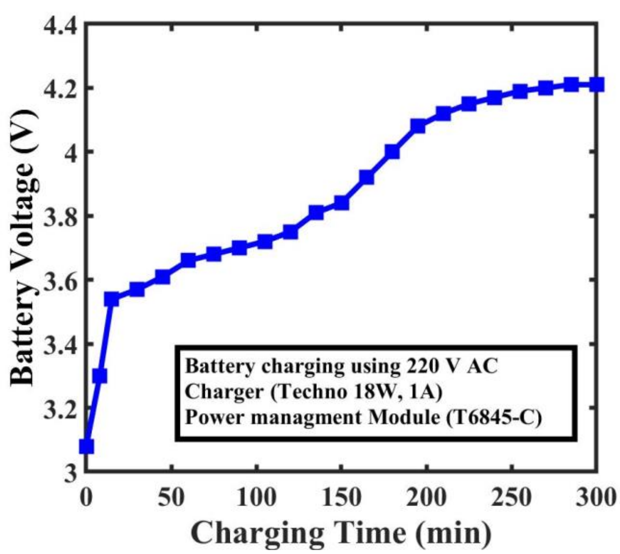

Figure. 7: Battery charging using 220 V AC

Figure 8 illustrates the battery charging process using a solar panel, where the initial battery voltage is depleted to 3.17 V before connecting it to the solar panel via an A5268 Step Down Power Supply Converter Board Module and USB cable. As energy accumulates in the battery, its voltage increases over time, monitored with a multimeter. In sunny weather conditions with a light intensity ranging from 4000 to 7500 Lux, the battery's voltage reaches 4.17 V after 1200 min of charging. Conversely, in cloudy weather, the charging duration extends to 1500 min, during which the battery voltage increases from 3.01 V to 4.01 V. This observation underscores the impact of varying weather conditions on the charging efficiency, emphasizing the system's adaptability to different environmental factors and highlighting the potential implications for sustained energy harvesting in diverse weather scenarios.

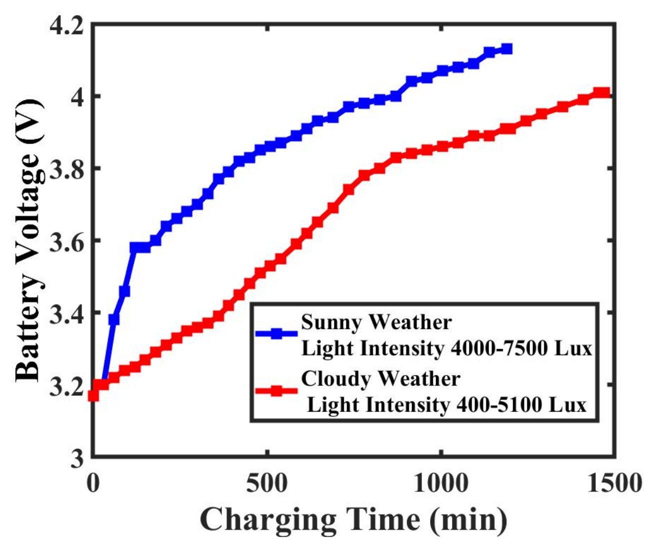

Figure. 8: Battery charging using a solar panel on sunny and cloudy days

Following the charging phase, the charged battery was connected to both the transmitter and receiver modules, and a discharge analysis was conducted. In the case of the transmitter module, as depicted in Figure 9, the initially recorded voltage level of the battery was 4.2 V. Over time, the battery voltage progressively declined, and measurements were taken using a multimeter. The RX Module stopped transmission after 1005 min when the battery voltage reached 2.97 V. Subsequently, the discharged battery underwent a recharging process through the solar energy harvester and was reconnected as a power source for the receiver module.

As depicted in Figure 9, After a prolonged period of 1200 min, the receiver module ceased operations when the battery voltage level reached 2.97 V. These discharge analyses highlight the temporal dynamics of the battery performance in both transmitter and receiver modules, providing valuable insights into the system's endurance and efficiency over extended usage periods.

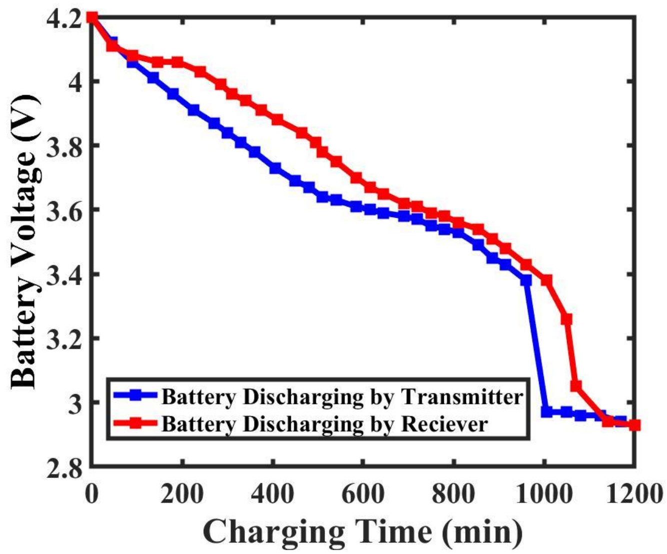

Figure. 9: Battery discharging with transmitter and receiver unit

VI. CONCLUSION

In conclusion, this research addresses a critical need for efficient and cost-effective monitoring solutions for pipeline networks, which are vital infrastructures in contemporary life. The developed self-powered radio frequency-based pipeline monitoring system demonstrates a pioneering approach to overcoming the challenges associated with the large-scale and hazardous nature of pipeline installations. The system, comprising an energy harvesting unit, wireless data transmission unit, and date receiver unit, offers a sustainable and autonomous solution for real-time monitoring. The successful implementation of a 2200 mAh rechargeable lithium-ion battery, charged both through direct AC and a 10 W solar panel, showcases the versatility of the energy harvesting approach. From testing results, it is shown that the battery can be recharged from 3.08 V to 4.21 V in a time duration of 300 minutes via a direct AC source. However, with a 10 W solar panel, it can be recharged from 3.07 to 4.17 V on sunny days with different light intensity levels (4000-7500 Lux). However, on cloudy days it took 1500 min to charge the battery from 3.1 to 4.01 with light intensity levels ranging from 400 to 1500 Lux. During the discharging of the battery with data transmission and receiving unit, it took 1200 min to decline the battery level from 4.17 V to 2.97 V. The utilization of solar energy not only enhances the sustainability of the system but also presents a viable solution in areas with limited access to traditional power sources. Overall, the developed pipeline monitoring system offers a promising solution to the inefficiencies of existing monitoring and maintenance approaches, contributing to the enhancement of pipeline safety and effectiveness in diverse environmental conditions

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