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REAL ENVIRONMENT APPLICATIONS OF A NON-RESONANT WIDE-BAND TRI-AXIAL ELECTROMAGNETIC ENERGY HARVESTER

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Abstract
This study details the testing and experimentation conducted in a real-world environment on a novel wide-band vibration-based electromagnetic energy harvester (VEMEH). The developed device distinguishes itself from conventional harvesters by utilizing a freely moving cylindrical magnet within a bobbin, rather than operating within a narrow frequency range. This design enables the harvester to react to ambient vibrations over a broad frequency spectrum, rendering it appropriate for various applications, including human body monitoring, household appliances, industrial machinery, and transportation systems. A notable obstacle in the implementation of energy harvesting systems is their capacity to deliver consistent, on-demand power in direct current form. Ambient energy sources generally yield low and inconsistent input energy, posing challenges for the design of energy harvesting systems that can effectively rectify and store output power. Moreover, vibration electromagnetic energy harvesters typically generate output voltages that are quite low, varying from a few millivolts to several hundred millivolts. To tackle this challenge, a three-stage Cockcroft-Walton (CW) voltage multiplier is utilized to enhance the output voltage, facilitating a more stable and dependable power supply to the load. A wireless sensor node was created for a system that monitors appliances. The wireless sensor network includes an ADXL345 acceleration sensor for measuring appliance vibration, a DHT11 temperature and humidity sensor for monitoring environmental conditions, and an Arduino ESP32 module for data processing and transmission. The transmission of sensor data to a mobile application facilitates the real-time observation of appliance status and the surrounding environmental conditions. The prototype of the vibration energy harvester was successfully integrated with the wireless sensor network and a rechargeable battery, enabling real-time monitoring of a car engine compartment. This autonomous condition monitoring system allows the energy harvester to perpetually recharge the battery, supplying power to the wireless sensor node. The device underwent testing across multiple applications, particularly in wearable contexts where the harvester was positioned in a trouser pocket and monitored during running activities. In a similar manner, the harvester was connected to a washing machine, kitchen blender, and domestic water pump. The vibration from the washing machine generated an open-circuit AC output voltage of 92.6 mV at

an acceleration of 0.31 g and a frequency of 35 Hz. The kitchen blender produced an open-circuit AC output voltage of 112.5 mV at an acceleration of 0.65 g and a frequency of 60 Hz. In contrast, the domestic water pump generated an open-circuit AC output voltage of 92.1 mV at an acceleration of 0.9 g and a frequency of 100 Hz. The harvester was positioned on a vehicle's dashboard and evaluated on both smooth and uneven road surfaces.

I. INTRODUCTION

Compact wireless electronics and sensors, such as wearable and implanted sensors, health monitoring devices, and environmental monitoring sensors, have advanced recently. These sensors must be completely implanted in the device or body without any external connection, which is difficult. Therefore, sensors or sensing nodes need a steady power source. Rechargeable batteries may reduce power supply equipment size. However, longevity is limited, requiring periodic replacement. Combining an energy harvester with a sensing node to convert environmental energy into electricity is a solution. Dynamic mechanics and equipment use mechanical vibration as energy. However, vibration-based energy harvesting (VEH) in low-frequency, large-amplitude, stochastic (time-varying) vibrations like human-induced movement presents many challenges. [1], [2]. Most VEHs use a resonant system with a proof mass oscillating in a frame and a suspension spring. Electromagnetic, electrostatic, and piezoelectric energy harvesting transform relative swinging into electrical power.

Vibration-based electromagnetic energy harvesters (VEMEHs) create electrical energy (induced voltage) at the coil terminals when the coil encounters a magnetic flux density fluctuation. Its many device topologies, fabrication procedures, low output impedance, and wide range of operating frequencies and accelerations make it suited for domestic, industrial, and health monitoring applications. In addition, VEMEHs provide low output voltages and high current.

Piezoelectric materials generate electrical charges when stressed or straining in vibration-based piezoelectric energy harvesters (VPEEHs). These devices produce high output voltage and simple rectification, but they require high frequency and quick acceleration to strain the material. Dependence on piezoelectric materials, limited device designs, and low output current limit VPEEHs. VESHEs use a variable capacitor design to generate energy from two plates' relative motion. Although these devices have high output voltage and many manufacturing options, they are limited by activation voltage, frequency, and acceleration. Among the three energy scavenging options, vibration-based electromagnetic energy harvesting has features that make it a better energy transduction alternative. A typical EMEH has a magnet attached to the free end of a cantilever beam and a coil attached to the device's casing, or vice versa. [9], [10].Faraday's law of electromagnetic induction states that environmental vibrations cause the coil and magnet to move relative to each other, creating an electromotive force (EMF) that flows current in the load circuit. This design uses a linear resonator with a narrow frequency spectrum, reducing broadband vibration harvesting [11], [12].Resonance-based EMEHs work only within a narrow excitation frequency range. Synchronizing low frequency and size reduction is difficult [13].Various broadband energy harvesting methods have been developed to address this critical issue, including resonance-tuning [14],

[15], multi-modal or multi-beam configurations [16], [17], frequency up-conversion [18], [19], [20], [21], dynamic response non-linearization [22], [23], [24], and wideband non-resonant spring-less EMEHs [25]. Non-resonant energy harvesters are ideal for human-powered devices and may solve these difficulties.

Resonant devices must run at their resonance frequency for best operation, although non-resonant devices normally do not. However, a vibration-based wide-band energy harvester can operate across a spectrum of frequencies when its output power exceeds a cut-off value. This shows that a wide-band, non-resonant energy harvester can generate power from a variety of incident vibrations, such as human motion and machine and household appliance vibrations.

II. LITERATURE REVIEW

Recent interest has focused on nonlinear VEMEH with a freely moving magnet about an exterior housing with or without magnetic repulsion and coils around the housing's outer surface [26], [27]. Bowers and Arnold and Rao et al. [28] scavenged energy for low-frequency applications via free oscillation. In their non-resonant vibration-based electromagnetic energy harvester, a ball magnet moves freely inside a copper coil-wrapped spherical chamber. The 100 cm^3 prototype assessed by later reported 300 μW average power during walking when linked to the ankle. Despite its tremendous power, the harvester is too big for human body uses.

Lee and Chung [29] introduced a copper coil, NdFeB permanent magnet, and planar spring VEMEH. The harvester is 21 cm^3 and weighs 30gm. The harvester generates 65.33 μW of electricity at 8 Hz resonant frequency at 0.2 g acceleration. Frequency-up conversion [30], [31] boosts power at lower frequencies.

Galchev et al. [32] employed VEMEH frequency-up conversion. The average power at 2 Hz and 0.1 g acceleration is 2.3μW.

A magnetic spring and planar coil were used to build a low-frequency VEMEH by Jo et al. [33]. At 8 Hz resonance frequency, an 11.25 cm^3 prototype produced 430 μW of maximum power.

Nonlinear vibration electromagnetic energy harvester by Dallago et al. [34] achieved 2.7 Hz bandwidth at 1 g base acceleration (1 g = 9.8 m/s^2).

Mann and Owens [35] examined VEMEH's non-linear magnetic levitation, where base acceleration (0.21 g to 0.85 g) increased bandwidth from 1.2 Hz to 2.1 Hz. Ulusan et al. [36] showed another VEMEH where base excitation from 0.4 g to 1.6 g increased bandwidth from 1 Hz to 2.1 Hz. Halim and Park's frequency up-converted VEMEH [37], [38] was tested horizontally to reduce gravity's impact on harvester performance and output. M. Bendame et al. [39] showed springless non-linear VEMEH's analytical model and experimental validation. Vertically mounted VEMEH had a 16 mV peak voltage at 17 Hz and 0.2g. Testing the horizontal equivalent of the springless VEMEH, altering the base excitation acceleration from 0.2g to 0.4g yielded 100 mV to 180 mV RMS voltage.

A wide band VEMEH with a fixed permanent magnet and 35 cantilevers of various lengths and resonant frequencies was reported by Sari et al. [40]. The device, with a volume of 1.4 cm^3, produced 10 mV RMS voltage at 4200 Hz to 5000 Hz, with a maximum output power of 0.4μW and a power density of 0.285 $\mu W/cm^3$. A wide-band frequency up-converted non-resonant VEMEH for low frequency applications was developed by M. A. Halim et al. [41]. The prototype operated at 14-22 Hz and measured 6.75 cm^3. At 1.53 g, the device's open circuit RMS voltage was 33.7 mV, and at 1.83 and 2.04

g, 40.1 and 45.3. Bin Yang et al. [42] created 2.7 cm^3 wide-band VEMEH. The harvester operated in 40–80 Hz frequency range. In the stated frequency range, the device produced 9 mV RMS voltage and 0.4 µW maximum power output with 1.9 g acceleration.

Bedkar et al. [43] developed a pen-type springless VEMEH with end caps as stoppers. In testing, the harvester produced 1 mW at 3.5 Hz and 0.56 g acceleration and 3 mW at 5 Hz and 1.14 g acceleration. Mohamed M.A et al. [44] designed another springless VEMEH for non-linearity and bandwidth extension. At 0.4 g acceleration and 2 Hz to 10 Hz frequency, a 19.8 cm^3 device generates 0.85 V peak RMS voltage.

Joyce et al. [45] created a springless wind turbine blade monitoring VEMEH. At 44-rpm wind speed, the harvester produced 3.3 mW. A cube-shaped spring-less VEMEH by Han et al. [46] transferred ambient vibrations from all three axes into power. A polyimide (PI) substrate and copper planar coil were folded into a cube to space a NdFeB permanent magnet, which could move freely in all three axes without spring support. The gadget, measuring $1cm^3$ and with a 3 Hz bandwidth, generated power from 20 to 100 Hz. With 0.5 g acceleration and 26.87 Hz frequency, the maximum induced voltage was 3.82 mV and the maximum power output was 0.75 µW. This harvester generated $0.75µW/cm^3$ power density.

A non-resonant VEMEH by Erol Kurt et al. [47] used fluctuating magnetic induction at the coil's center with two stable magnets and a spacer. Impact vibrations generated voltage in the spacer's air-gap. At 1 mm displacement amplitude and 60 Hz frequency, the gadget produced 2.41 mV RMS voltage. At this frequency and acceleration, the output power was 17 µW with 0.358 $µW/cm^3$ power density. Harvester frequency bandwidth ranged from 2 Hz to 1.5 kHz.

Another non-resonant VEMEH using a magnetic spring to collect human motion energy was devised by J. Zhang and Y. Su [48]. A non-magnetic housing, circular magnet, two cylindrical magnets, and six circular coils made up the harvester. Because fixed and mobile magnets have the same magnetization on one side, the moving magnet is repelled. Force created a magnetic spring between magnets. During tests at different body movements and frequencies, the VEMEH achieved 2.2 V output voltage and 0.024 W/mm^3 power density at 6 Hz.

A low-frequency VEMEH prototype using ferrite magnets to capture vertical vibration energy was designed by Royo et al. [49]. Upper face of revolving magnet had 350-turn coil. Four small ferrite magnets and two NdFeB magnets made the fixed and movable magnets. The harvester generated energy from low-frequency vibrations between 1 to 3 Hz. The gadget measured approximately 600 cm^3. At 1.7 Hz and 0.5 g acceleration the harvester produced 4.38 mW of peak power.

Wang. L. et al. [50] made a low-frequency VEMEH with compact flexure guiding structure to reduce magnet-housing friction. Flexure structure reduced coil-magnet gap, increasing induced emf. At 19.5 Hz and 0.1 g vibration, the 123 cm^3 VEMEH produced 6.08 V and 4.02 mW output voltage and power. The normalized power density was 3.28 mW/cm^3g^2. P.Xiaugi et al. [51] designed VEMEH for wearable applications for low-frequency human body vibrations. A tumbler with a permanent magnet on top easily generated power from human motion. Developed gadget volume was 30 cm^3.At 4 Hz frequency and 12 km/hr running speed, the output power, power density, and power per acceleration were 0.86 mW, 28.67 $µW/cm^3$, and 10.75 µW/g respectively.

R. Murugesan et al. [52] constructed a wide-band VEMEH with magnetic solenoid pendulum arrays. Each array had permanent magnet and solenoid coil pendulums. A vibrating host supported all hinged pendulums. Energy was generated via external vibration of pendulums and arrays. Compared to magnet-solenoid pendulum arrays, the harvester array achieved sustained energy across a wide frequency range. The output power was 200 µW and frequency bandwidth was noted to be 45.57% higher than a single harvester. The power density was 128 $\mu W/cm^3$.

Most of the reported VEMEHs are having some limitations either on the basis of size, power output and operating frequency range. Similarly almost all the reported VEMEHs are limited to laboratory experimentations only without their testing in real environment. This study presents the testing and experimentation conducted in a real-world environment on a novel wide-band vibration-based electromagnetic energy harvester. The developed device differentiates itself from usual harvesters by utilizing a freely moving cylindrical magnet within a bobbin, rather than operating within a narrow frequency range. This design enables the harvester to react to ambient vibrations over a broad frequency spectrum, rendering it appropriate for various applications.

III. ARCHITECTURE OF VEMEH

Figure. 1 illustrates the exploded view as well as the actual designed VEMEH on the basis of which the real environment experimentations are performed. The fundamental structure of the constructed wide-band VEMEH consists of a Teflon bobbin with a diameter and height of 3.5 cm each. The two ends of the spacer are sealed with a double-sided copper planar coil. A grade N38 permanent NdFeB magnet, exhibiting a residual magnetic flux density of 1.3T according to the supplier's standards, with dimensions of 2 cm x 2 cm, can freely move within the bobbin when subjected to external vibrations. The movement of the magnet is enhanced by the application of silicone micro-beads onto the lower planar coil. A wound coil encircles the exterior of the bobbin. Vibrations from the surrounding environment force the cylindrical magnet to move around inside the bobbin, thereby inducing an electromotive force across the coil terminals in accordance with Faraday's law of electromagnetic induction.

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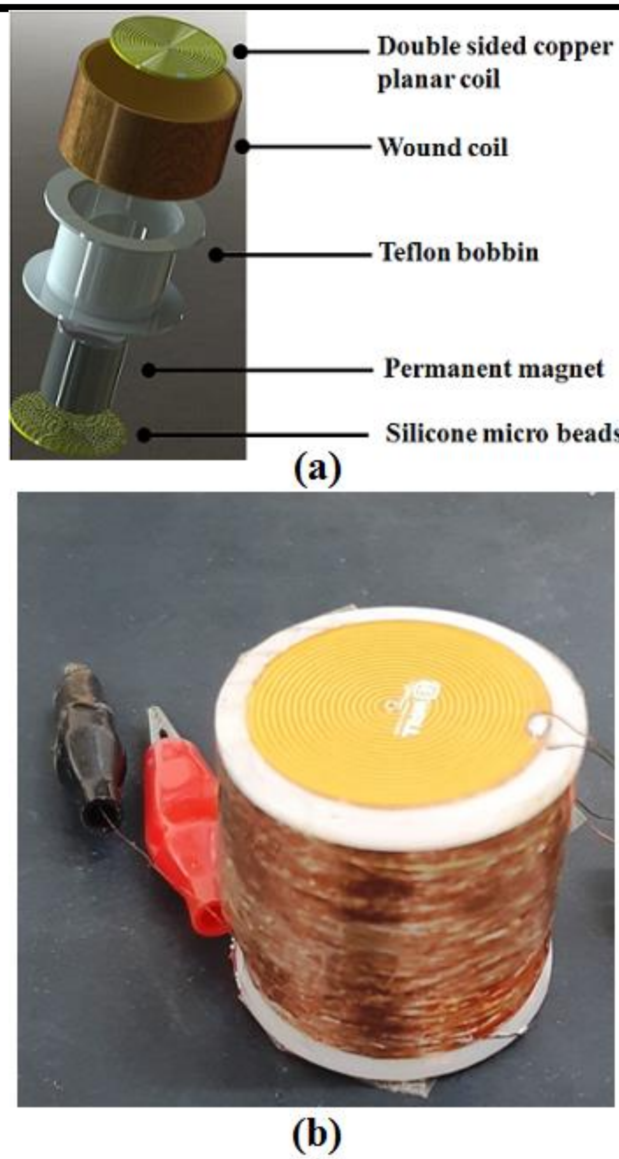

Figure 1. (a) Exploded view of VEMEH (b) Developed VEMEH

IV. VEMEH'S FABRICATION

Fabricating the VEMEH commences with the creation of a bobbin made from PTFE (Teflon) material, measuring 3.5 cm in diameter and 3.5 cm in height. The Lathe Machine fabricates the bobbin to fit the cylindrical magnet, upper planar coil, lower planar coil, and the wound coil, as seen in Figure. 2(a). A 2.5 cm bore accommodates the unrestricted movement of a 2 cm wide and 2 cm thick NdFeB permanent magnet (shown in Figure. 2(b)) along all three axes when subjected to external vibrations. A channel measuring 3.5 mm in depth and 3.1 cm in width, with a wall thickness of 2 mm, is designed for winding a copper wire of 150 µm gauge, comprising 1000 turns (Figure. 2(c)). An NdFeB cylindrical magnet is situated within this bobbin, which is sealed at both ends by a double-sided copper spiral planar coil. The copper spiral planar coil (shown in Figure. 2(d)) is created utilizing the PCB Express tool and subsequently exported as a Gerber file for production employing conventional PCB fabrication methods. The double-sided planar coil, constructed on a FR-4 substrate for its superior mechanical properties and electrical insulation in both dry and humid environments, consists of 17 turns with a 100 µm spacing between the lines, each line measuring 200 µm in width, and features two pads of 1.5 mm for terminal connections. The end connections of the double-sided copper planar coil are established with the side pads via soldering. Conversely, the two central pads are interconnected by a Via (an electronically conductive hole), thereby linking both sides in series to augment the generated output. The Via facilitates an aperture for air circulation, so diminishing the effects of air damping within the bobbin and permitting unobstructed movement of the magnet. The movement of the magnet is further facilitated by introducing many silicone micro-beads between the bottom planar coil and the magnet. Figure. 2(e) displays the magnified view of silicone micro-beads. The mean diameter of silicone micro-beads, as determined by a digital micro-meter, is approximately 300 µm; however, micro-beads measuring 200 µm have been precisely chosen for the harvester. Figure. 2(f) illustrates a magnet positioned above silicone micro-beads and a planar coil.

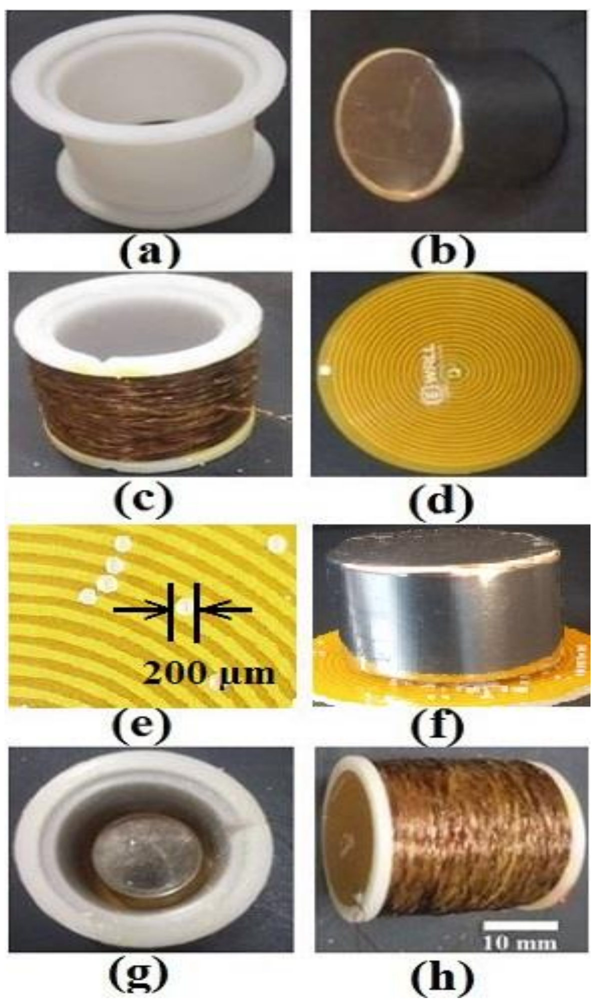

Figure 2. VEMEH's development : (a) Teflon bobbin, (b) NdFeB magnet, (c)Wound coil, (d) Double sided copper planar coil, (e) Silicone micro beads, (f) Magnet on top of micro beads and planar coil, (g) Bobbin, magnet, planar coil and wound coil combination, (h) Developed VEMEH.

The incorporation of silicone micro-beads enhances the magnet's mobility, rendering the device effective for minimal acceleration vibrations in the horizontal plane. Figure. 2(g) illustrates the assembly conclusion prior to the final connections and the closure of the upper planar coil. Figure. 2(h) illustrates the completed prototype, which comprises the bobbin, lower planar coil, upper planar coil, cylindrical NdFeB magnet, and wrapped coil.

V. RECTIFICATION AND VOLTAGE MULTIPLIER PROCESS

The capacity to supply power on demand and in direct current (DC) form is one of the most significant obstacles that must be overcome before the EH can be successfully deployed. Similarly, the energy that is brought into the EH from the surrounding environment is typically very low and erratic. Because of this, one of the most major challenges in the design of EH is the process of rectifying and storing the output power in order to provide a consistent, sufficient, and uninterrupted supply of power to the load. In addition, the output voltage of EMEHs is often quite low, ranging from a few millivolts to a few hundred millivolts. This is the case in most cases. In order to power handheld electronics and wireless sensor nodes (WSNs), voltage multipliers transform the low-voltage AC output of energy harvesters into a higher-voltage DC output. In order to charge a battery or run an electronic gadget, DC voltage conversion is necessary. An integrated voltage multiplier circuit is necessary to transform the energy harvester's low AC voltage output into a relatively high DC voltage. A Cockroft-Walton (CW) voltage multiplier with three stages is utilized in order to achieve this objective, which is to increase the output voltage. The low AC output of the electromagnetic energy harvester can be transformed into higher DC voltage to power the WSN in the appliances monitoring system. To do this, a three-stage Cockcroft Walton type AC to DC voltage rectification circuit is designed. Thanks to its multi-stage design, this rectifying circuit can do double duty: transforming the harvester's AC output into DC voltage and boosting its output even further. A small-voltage substrate mounted Schottky diode (SS34 1N588 SMA DO214AC), is chosen to provide minimal voltage drop across the circuit. Also used to connect these diodes are 330 µF, 25 V surface mount capacitors. Using precise soldering techniques, the prototype was created on a Vero circuit board. Figure. 3(a), Figure. 3(b) and Figure. 3(c) respectively depict the circuit schematic, back view and front view of the actual multiplier circuit.

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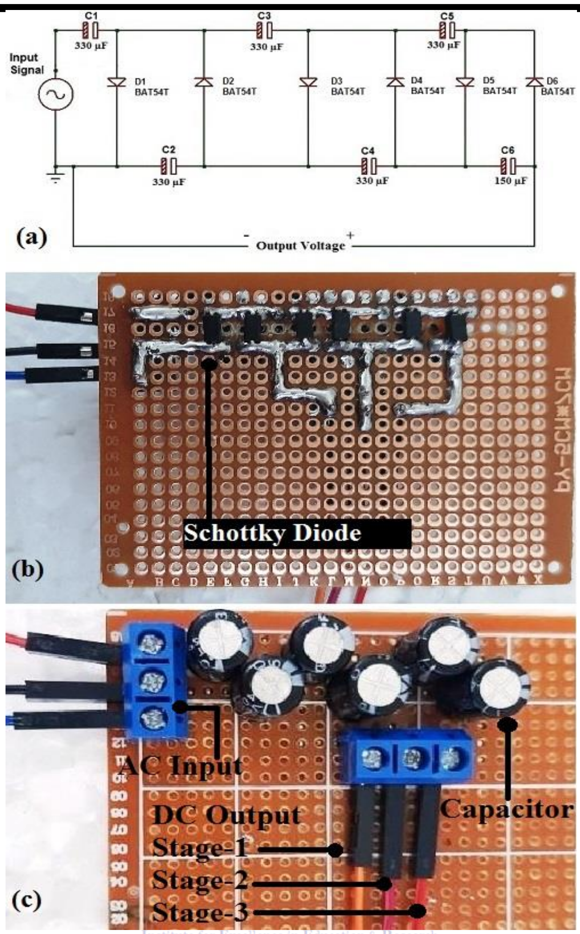

Figure 3. 3-Stage CW DC rectifier and multiplier circuit: (a) Schematic of simulating circuit, (b) Back view of actual circuit, (c) Front view of actual circuit.

VI. DEVELOPMENT OF WSN FOR ENVOIRNMENTAL MONITORING

A wireless sensor node (WSN) is developed which is utilized for the appliance monitoring system as shown in Figure. 4. A sensor called an acceleration sensor (ADXL345) shown in Figure. 4 (a) is used to measure the amplitude of the appliances' acceleration. An appliance's temperature and the humidity in the surrounding area are both measured by a temperature and humidity sensor, also known as a DHT11 sensor shown in Figure. 4 (b).

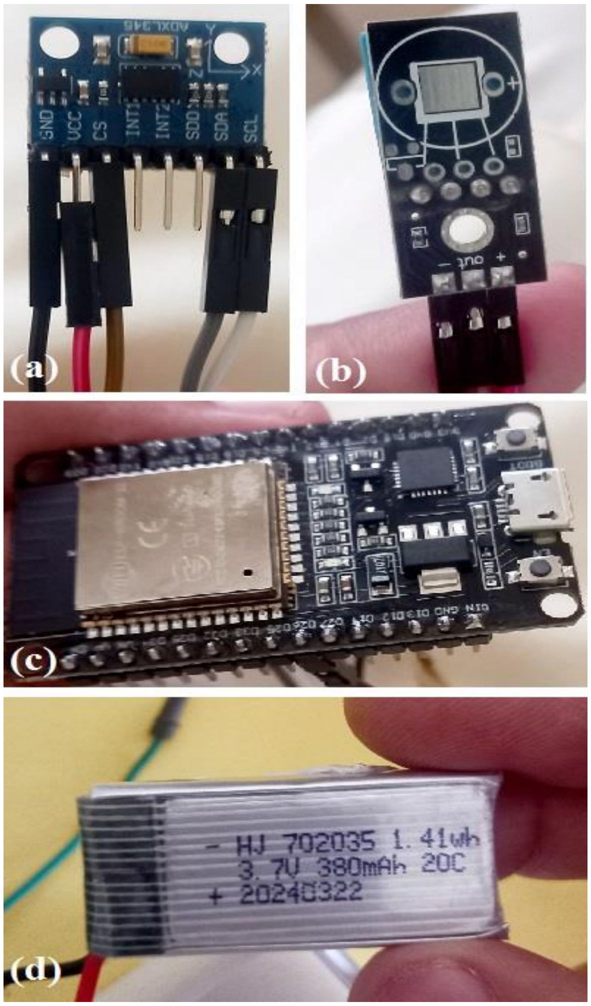

Figure 4. Assembling of WSN for wireless sensor monitoring of appliances: (a) A sensor for acceleration, (b) a sensor for temperature and humidity, (c) an ESP32 microcontroller, (d) a battery that can be recharged.

The acceleration, temperature, and humidity sensor data are processed by the Arduino ESP32 module through the Arduino platform shown in Figure. 4 (c). A 3800 mAh, 3.7 V rechargeable battery (shown in Figure. 4 (d)) is charged through the developed VEMEH and used to power all the sensors and ESP32 module. The developed WSN in a single package is shown in Figure. 5.

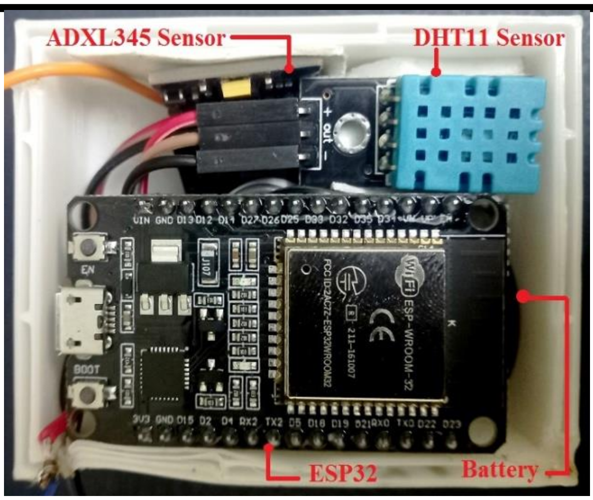

Figure 5. Assembled prototype of fabricated WSN.

The information from the sensors is transmitted to a mobile application specifically developed for this purpose, for monitoring in real time. This mobile application on screen shows the temperature, humidity and acceleration in the entire three axes of the domestic appliances or other applications as can be seen in Figure. 7. The date can also been monitored on computer desktop as shown in Figure. 6 and could be shared with multiple monitoring devices simultaneously.

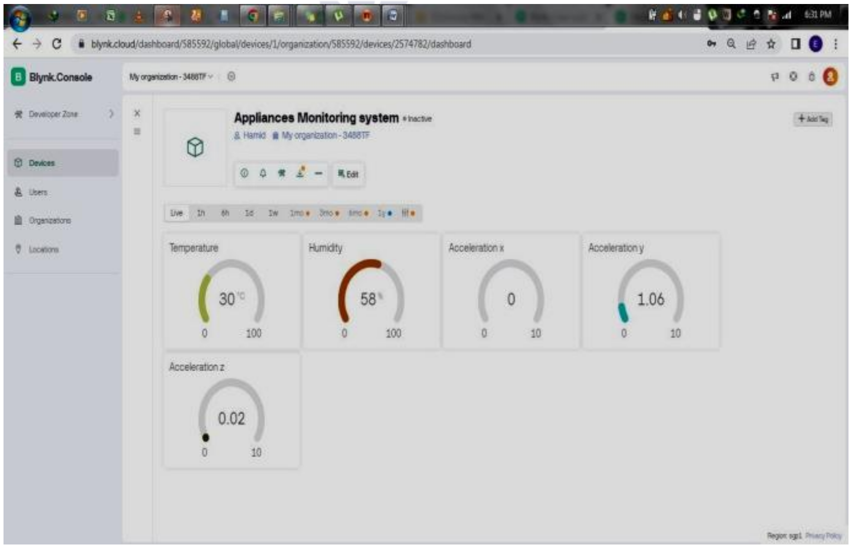

Figure. 6. Appliances monitoring system on computer desktop.

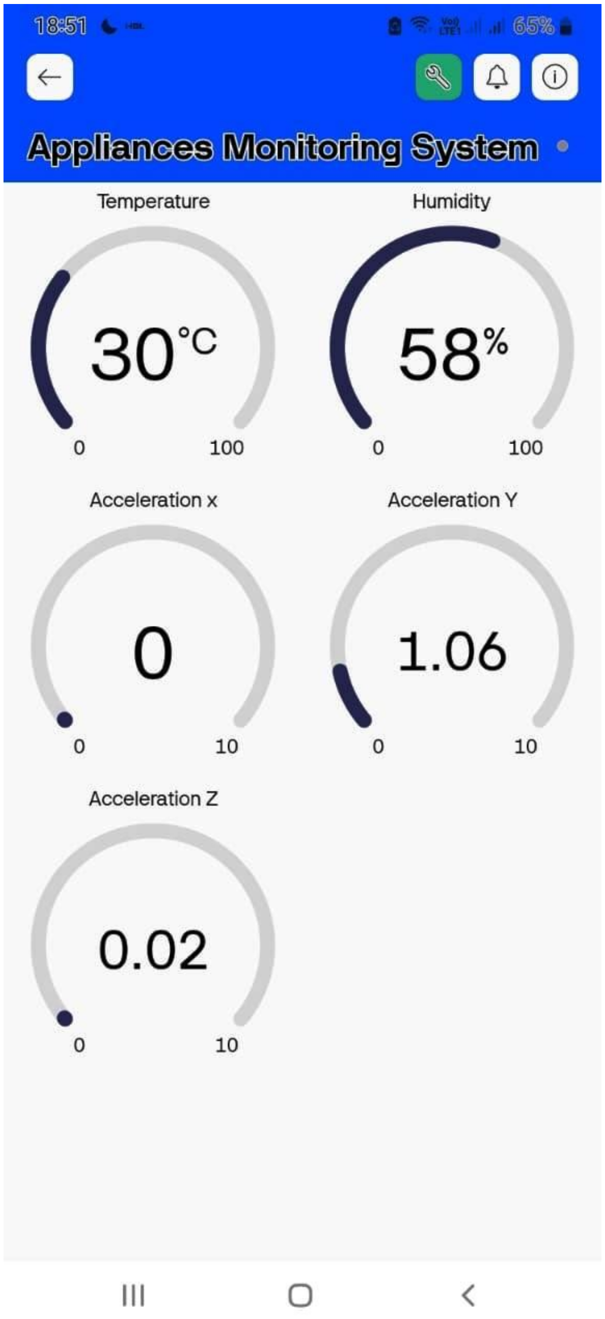

Figure 7. A smart-phone app for monitoring appliances has been developed.

The prototype of the vibration energy harvester that was constructed, along with the rectification circuitry and rechargeable battery, is combined with the fabricated wireless sensor node for the purpose of real-time monitoring of different domestic appliances, industrial applications, transportation and wearable applications. The energy harvester that was designed for this self-powered condition monitoring system of the appliances is responsible for continuously charging the battery, and the battery is responsible for supplying power to all of the onboard components of the wireless sensor node. The newly built transmitter module, on the other hand, will stop transmission if the charge of the battery falls below 2.7 V. In this particular scenario, a programmable microcontroller will be responsible for putting the module into sleep mode. Following this delay, the wireless sensor node (WSN) will continue sending information because the energy harvester that was created is capable of recharging the battery from 2.2 V to 3.3 V in less than 90 minutes. It is possible to compensate for the charging period of the monitoring system, which is ninety minutes, by taking a break or relaxing. It is possible to control the sleep mode of the monitoring system in a short period of time (like, a sleep mode of one minute after every fifteen minutes of transmission operation).

VII. EXPERIMENTAL SETUP FOR REAL ENVIRONMENT TESTING

The experimental setup for real environment testing is of two types.

- Type-1: For those applications where no mobility is required, a dual display digital multimeter (GDM-8034) along with an oscilloscope (GOS-6112) is used to record the RMS as well as peak value of the output voltage from the developed energy harvester. This experimental setup is applicable to those entire real environment testings where the appliance whose' conditions need to be monitored is either unmovable or no mobility is needed at all. These include but not limited to different household appliances like refrigerator, washing machine, water pump, kitchen blender etc.
- Type-2: This simple setup is comprised of a handheld digital multimeter which gives both AC and DC reading and could be used for measurement of the AC output from the energy harvester as well as the DC output from the rectifier and multiplier circuit. This simple setup is useful for those applications where the desired vibration is resulted from actual movement of the appliance or body whose' conditions need to be monitored. Again these applications include but not limited to human body movement, wearable and transportation application where carrying the experimental setup of type-1 is practically impossible. Both the experimental setups are shown in Figure. 8.

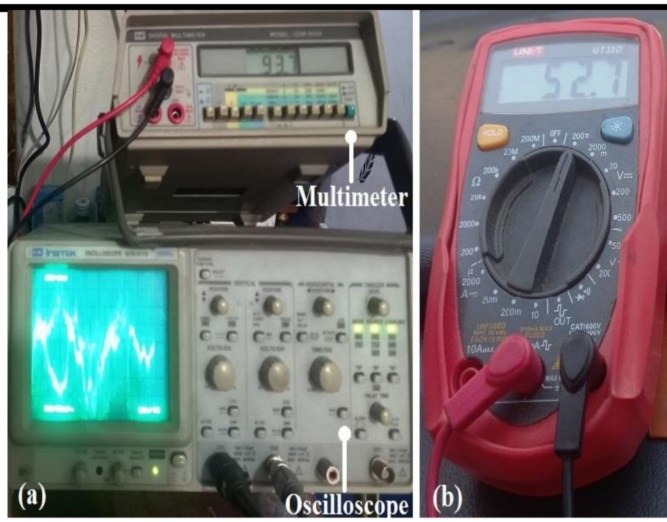

Figure 8: Experimental setup for real environment testing of appliances, (a) Type-1, (b) Type-2

VIII. APPLICATIONS OF THE DEVELOPED VEMEH AND WSN IN ENVIRONMENTAL MONITORING

The prototype of the vibration energy harvester, along with its rectification circuitry and rechargeable components, is coupled with a wireless sensor node for real-time monitoring of a car engine compartment, as illustrated in Figure. 9. Figure. 9 (a) shows the mobile-app and portable digital multimeter placed near the car windscreen and isolated from the actual vibrating environment for safety purpose of both the gadgets. Figure. 9 (b) shows the VEMEH along with the fabricated WSN placed on the most vibrating part of the car engine. This helps the energy harvester to harness maximum possible energy from the vibrating body and let the acceleration sensor in the WSN to measure and record the actual amplitude of vibrations. The whole arrangement including the energy harvesting device, rectifier circuit, wireless sensor node, digital multimeter and readily on mobile phone are shown in Figure. 9 (c). This self-sustaining condition monitoring system for appliances features an energy harvester that perpetually charges the battery, which in turn powers all integral accessories of the wireless sensor node. The on-screen data from mobile-app shows the temperature and humidity of the engine compartment as 33 °C and 62 % respectively. The acceleration of the compartment where the developed tri-axial VEMEH is placed in the X, Y and Z axis as monitored on screen is 0.25 g, 0.96 g and 0 g respectively, where $g=9.8\ m/s^2$ is the acceleration due to gravity and is taken as a reference unit for calculations. On this monitored vibration level of the car engine compartment, the open circuit DC output voltage as measured on digital multimeter is recorded to be 122.6 mV.

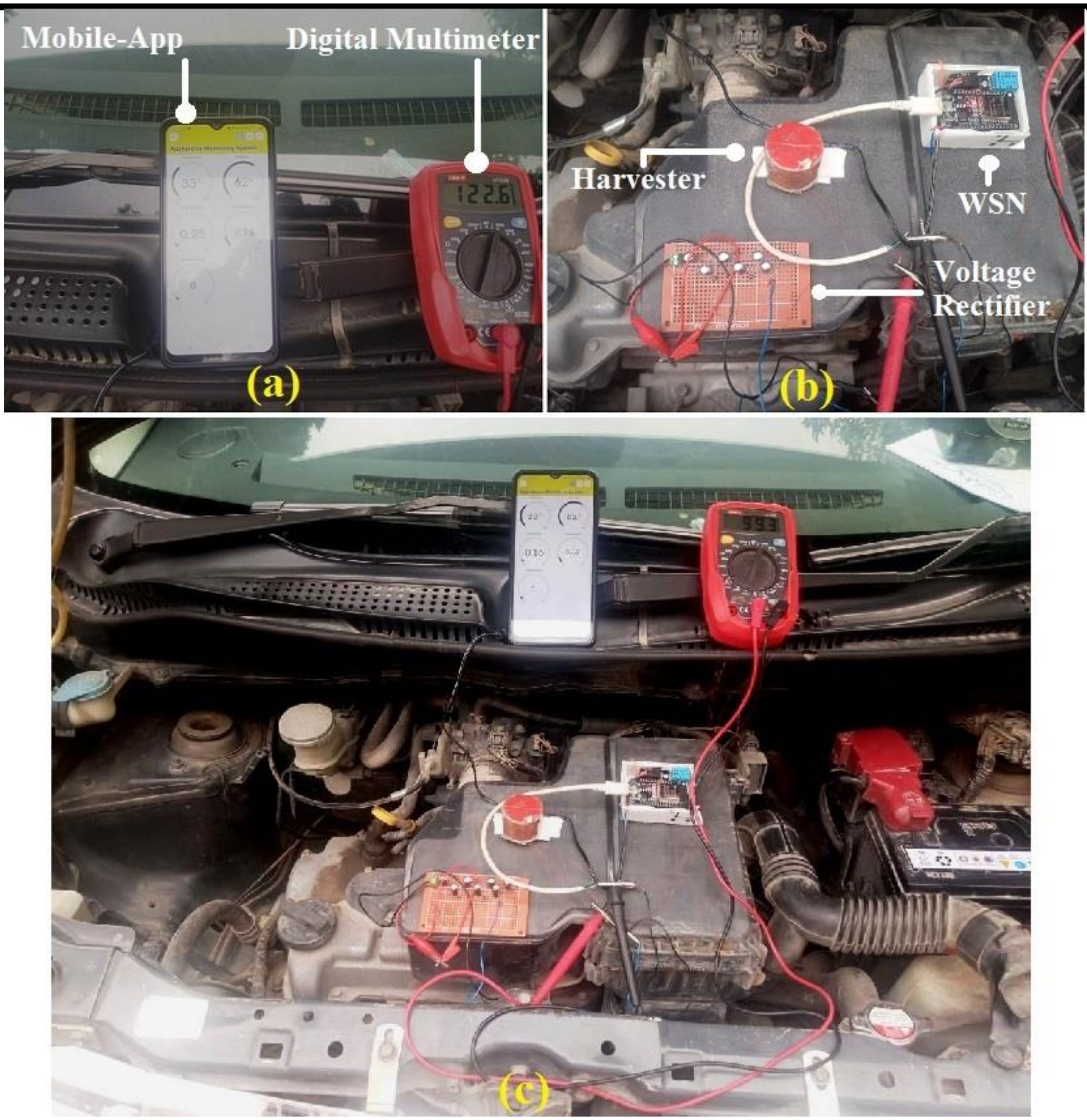

Figure 9: Prototype testing in an actual setting for car engine, (a) Mobile-app and digital multimeter, (b) VEMEH and WSN placed on engine compartment, (c) Whole arrangement

In addition, the harvester that was constructed is installed on the dashboard of the vehicle and evaluated for output voltage on both smooth and rough routes (Figure. 10). During this test, the rectified DC output voltage is measured to be 52.7 mV while the car was running on smooth road at a speed of 80 km/hr and the acceleration during this motion was recorded to be 0.71 g. On the other hand, at a speed of 45 km/hr on bumpy road, the recorded acceleration was noted to be 1.15 g resulting in a DC rectified open circuit output voltage of 89.4 mV.

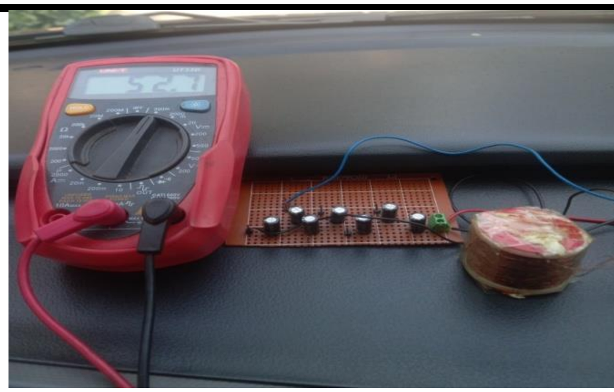

Figure10: Evaluation of the VEMEH on a vehicle's dashboard

Additionally, the developed device is experimentally tested for wearable applications, in which the created harvester is carried in the pocket of the trousers (as shown in Figure. 11), and output values are measured while the individual is running.

Figure11: Evaluation of the VEMEH while a person is running

Similar to the previous example, the created harvester is installed on a variety of home appliances, such as washing machines, kitchen blenders and domestic water pumps with a horsepower rating of half. The open circuit DC output voltage of a home washing machine (Figure. 12) while it was running on half capacity was tested to be 92.6 millivolts. The acceleration of vibration measured by acceleration sensor and through WSN shown on the mobile-app was noted to be 0.65 g.

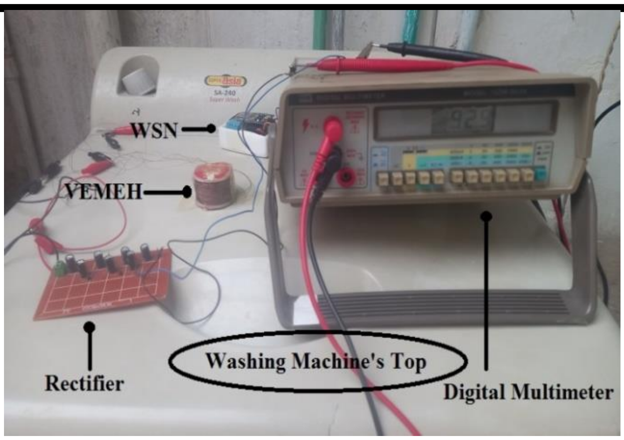

Figure 12: Prototype testing in an actual setting of a domestic washing machine

On the other hand, the open circuit ac output voltage of a kitchen blender (Figure. 13) was recorded to be 74.2 millivolts as read on digital multimeter. The acceleration of vibration was recorded to be 0.51 g.

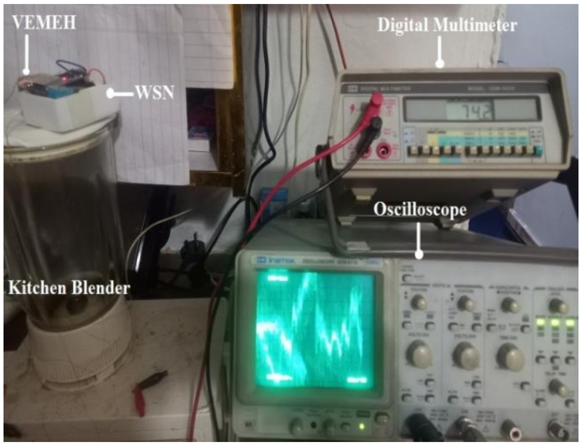

Figure 13: Prototype testing on a running kitchen blender

The VEMEH along with the fabricated WSN is placed on domestic water pump to measure the acceleration level of vibration (Figure. 14). As shown in Figure. 14 (a) a wooden block is used to isolate the VEMEH from the body of water pump and thus avoid any interaction between the magnetic field of the water pump and that of VEMEH. It has been observed that the output voltage of a home water pump was 95.7 millivolts as measured on the digital multimeter and shown in Figure. 14(b). The acceleration readings as measured by the acceleration sensor of WSN and given on mobile-app was 0.85 g.

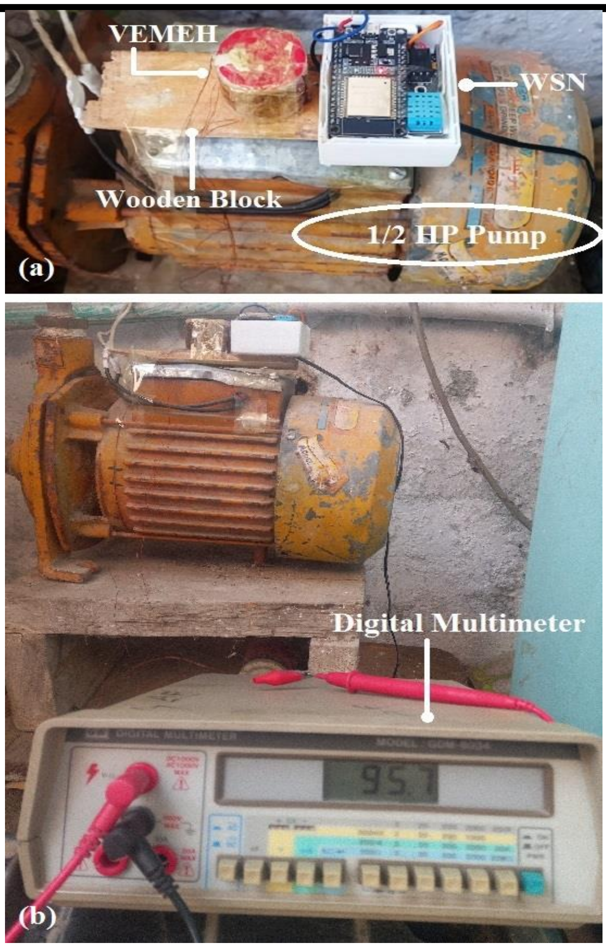

Figure 14: Prototype testing for monitoring of a domestic water pump (a) VEMEH and WSN placed on water pump, (b) Actual reading during pump running

VIII. CONCLUSION

This paper describes real-world testing and experiments on a novel wide-band vibration-based electromagnetic energy harvester. Using a freely moving cylindrical magnet in a bobbin, the suggested harvester operates outside of a narrow frequency range. The harvester can respond to ambient vibrations across a wide frequency spectrum, making it suitable for human body monitoring, domestic appliances, industrial gear, and transportation systems. A major challenge for energy harvesting systems is their ability to provide continuous, on-demand direct current electricity. Energy harvesting systems that rectify and store output power from ambient energy sources are difficult to design due to low and inconsistent input energy. Additionally, vibration electromagnetic energy harvesters produce modest output voltages of a few millivolts to several hundred millivolts. The output voltage is increased using a three-stage Cockcroft-Walton (CW) voltage multiplier to provide more steady and reliable power to the load. Wireless sensor node was built for appliance monitoring systems. A smart-phone app may monitor appliance status and ambient conditions in real time by receiving sensor data. Real-time automotive engine compartment monitoring was achieved by integrating the vibration energy harvester prototype with a wireless sensor network and rechargeable battery. This autonomous condition monitoring system powers the wireless sensor node by continuously recharging the energy harvester battery. The device was tested in wearable applications, including running with the harvester in a pants pocket. Like the washing machine, kitchen mixer, and home water pump, the harvester was linked. At 0.65 g acceleration, washing machine vibration produced an open-circuit DC output voltage of 92.6 mV. At 0.51 g acceleration kitchen blender produced an open-circuit DC output voltage of 74.2 mV. At 0.85 g , the home water pump produced 95.7 mV open-circuit DC output voltage. Because of its practical implementation, the VEMEH is well-suited for use in WSNs and IoT applications that make use of ambient vibration sources.

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