HYBRID ENERGY HARVESTING AND STORAGE FOR WIRELESS SENSOR NETWORK

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***Abstract*- Advanced development of wireless sensor network is comprised in the expansion of the research acquisitions. In case of integration, self-energy harvesting and long-lasting energy management have become challengeable topics in the development of wireless senor networks (WSN). In addition, continuous dataflow is a vital requirement of a successful product by means of WSN. Therefore, this research paper outlines a system that can overcome drawbacks in existing studies, and it introduces new features to WSN deployment. The proposed system introduces a wireless sensor node which consists of three components; Hybrid self energy harvesting system, Hybrid energy storage and uninterrupted wireless data transmission between nodes and the end user. Solar and wind energies are used as harvesting bases to fulfill the continuous power requirement of the sensor node. The hybrid energy storage assists to store the energy in the middle of the power flow from the harvester to the node. In an instance, Lithium-ion batteries and Supercapacitors are combined as energy storage resources. Moreover, the system supports to analyze and transfer the health status of each key element of power management in both energy harvester and storage. The WSN is developed by constructing a direct communication link to the remote monitoring server instead of an Internet connection. That ensures the hundred percent real time data delivery to the end user without any data losses. Additionally, a special node failure detection is included. The consolidation of the three components executes as a smart system that can be used to aggregate required sensor data and transfer them to the end user. The prototype is decided to test in a demonstrative over the bridge and uses the accelerometer as the sensor to collect risk predictable data from it.**

Keywords – WSN, Hybrid energy storage, Hybrid self-energy harvesting, RF Protocol

I.INTRODUCTION

WSN is a fast advancing technology and it mainly uses for remote sensing and environmental monitoring [1]. Past researches are contributed to developing systems with the use of WSN for prevention of natural disasters in dams, buildings, and bridges; based on comprehensive analyzing of risk predictable parameters like vibration, acceleration strain, strength and displacement [2] [3]. Because these disasters can be caused to harm the public assets and human beings. Typically, a WSN system is responsible for collaborating with environmental sensing and deliver those variable data to human accessible locations. That comforts to monitor, predict and make decisions quickly from a remote location before occurring a disaster.

In the integration level of the WSN, the technology adoption concerns self-energy generation to power up each node independently. Since each node is equipped with self-energy methodology, energy storage is acquired as the next key characteristic. However, limited lifetime and frequent replacements are the adaptive challenges regarding energy storage solutions. The number of charging cycles and the overcharging could be the main affect to degrade the lifetime of such storage cells like batteries, capacitors. Because of those challenges, as a commercial product, there should be a capability to measure performance and operation fluctuations in real time in a container of energy harvesting and energy storage. On the other hand, the study of the wireless communication advancement in the sensor network, every commercial WSN systems were tended to use pre-define wireless protocols, such as ZigBee, Z-Wave, Wi-Fi to make communication bridges between nodes. Furthermore, to interconnect the remote user and the sensor network has been incorporated with a cloud connection.

Last, when examining all above particulars, past inventors have shown their aim was to develop reliable, low power consumption, durable and highly autonomous sensor nodes in such risk prediction applications based on the sensing of environmental phenomena. Because those aids lead to solving accessibility, maintainability, uninterrupted power supply difficulties and communication drops. Although this paper will be focusing on the drawbacks behind those past research outcomes and existing systems. The next section will describe proposed architecture's competitive advantages over existing systems regarding the WSN developments in terms of energy harvesting, energy storage and the design of the sensor network.

The remaining of the paper assists to discuss the above factors in intensely manner. The wireless sensor architecture is detailed in section 3, integration of sensor node with Hybrid Energy Sub Systems in section 4. The section 5 will conclude the append of a test environment with experiments and final section 6 evaluates the conclusion of the system.

II. BACKGROUND

The primary way of power input practice to the WSN enabled design was using external electricity power through the grids. Practically, the use of external power resources is more inefficient since the installation locations of nodes in the asset is a considerable factor. Nevertheless, it raises laying and accessibility, maintainability, and uninterrupted power supply difficulties in terms of using external power sources. With the rapid growing of technology, the inventers are currently moving to self- energy harvesting practices. Worries with the above facts, the optimal approach is to implementing energy harvesting sub system for each sensor node separately. The research decided to use ambient energy sources; solar and wind power to satisfy the power requirement of the node by expecting to work in smoothly even in environmental weather alterations.

Almost WSN systems are incorporated lithium-ion batteries as in terms of self-power storage. That is not a feasible approach where a large scale WSN [4]. The research concludes in part use of both Lithium-ion batteries and Supercapacitors to compile hybrid storage sub system. Because supercapacitors can guarantee more years of operation rather than batteries. Their lifetime is more than 10 years. In addition, the system consolidates heath status of both energy harvesting and energy storage sub systems such as battery bank heath, battery lifetime, charging status between the battery bank and supercapacitor bank, node power consumption and power generation status from both energy harvesting sources.

When examining past research outcomes, every commercial WSN systems are based on a cloud connection for delivering sensor data to a remote system user [5]. Although the conflicts of obstacles may impact negatively because of the line of sight signal propagation. Furthermore, Incidentally Internet connectivity results downtimes due to various malfunctions cause of environmental conditions. Those drawbacks lead to degrading, reliable communication among nodes and end user. Hence, the research is intended to make up direct radio frequency (RF) Communication Bridge to close end user and WSN together. It is based on the development of distinctive RF protocol and ensures direct data transfer more than 1Km. Moreover, it expresses different conveniences in distinctive RF protocol instead of the usage of pre-define protocols [6].

III. WIRELESS SENSOR NETWORK

The following Fig. 1 is illustrating the overview of the entire system incorporation with the remote user.

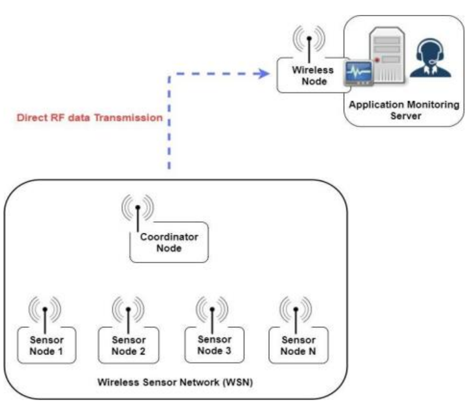

Fig. 1 System context

A. Hardware design of WSN

In fact, WSN is a combination of three components; sensors, sensor node and sensor network [7]. Typically, sensors convert physical phenomenon into electrical signals. According to the prototype perspective, the research decided the accelerometer as the sensor which attached to each sensor node to aggregate sensor data. It measures acceleration with respect to the tri-axis to capture sideways movement [8]. Its other benefits are low power consumption, low cost, and higher accuracy. The sensor data can be used to study hazards that may arrive from the applied over the bridge. The sensor nodes are installed to appropriate locations in the bridge in order to consider the better risk data input. Thereafter, the sensor node is responsible to process and analyze those aggregated data. The sensor network interconnects nodes and direct data towards the end user.

Traditionally, Each WSN enabled systems have been used a cloud connectivity to transfer sensor data for remote accessible locations which cannot ensure reliable and continuous data transmission because of Internet connectivity might be loss due to a lot of reasons. Thus, the research captures this issue and propose a radio frequency data transmission mechanism. Unlike the Internet, RF is not a line of slight so that obstacle's impact is minimal to the data flow. In this case, develop RF based protocol using the NRF24L01 transceiver module that comes with two types; (1) NR24L01+ that supports up to 100 m signal propagation range [9]; Therefore, the system was decided to integrate this type to sensor node to node interconnections; (2) NRF24L01 with internal amplifiers; Power Amplifier (PA) + Low noise Amplifier (LNA) [10]. PA is assigned to the data transmit path meanwhile LNA is assigned to data receiving path. The main advantage of this arrangement is to provide more than 1km data propagation than the NRF24L01+. That can be assigned to implement a long distance of data carrying. Instead of cloud connectivity, the research identified this module can use to transfer sensor data from the sensor network to the remote end user directly. Also, the system identified several advantages in terms of NR24 rather than other wireless technologies. It proved license-free, ultra-low power consumption (12.5mA), higher data rate (2Mbps), low cost, enhanced signal range, etc. [9]. Furthermore, the research suggests that modules can be used as repeaters if the remote location is situated more than 1 Km.

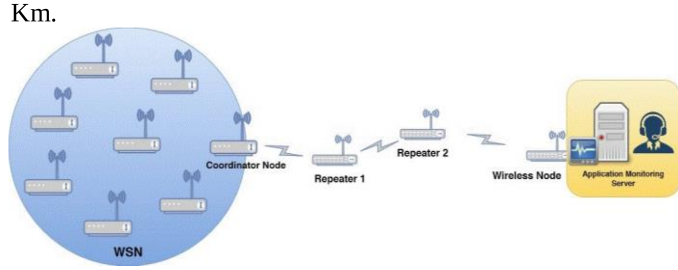

Fig. 2 Expanding of RF transmission distance using repeaters

As shown in Fig. 1, each sensor node and coordinator node are networked as a star topology. Primarily, sensor data is sent to the coordinator node and it will transfer those data to the remote user. Hence sensor data takes only one direction towards the coordinator node. Related work regarding WSN design, each sensor node entails an RF transceiver module and a controller unit. The development programs the Arduino Uno Microcontroller as the controller unit to control all sub-component associated with it since support ultra-low power consumption, easy programming. To prove long distance data transfer, central node and the wireless node at the remote server, integrate high power NRF24L01+PA+LNA module with an antenna. Other sensor nodes use the NRF24L01+ module to the short distance signal range (100m). This is the basic hardware arrangement which is designed for reliable data delivery [9].

B. Software design of WSN

In programming perspective of a microcontroller unit (MCU), the node to node communication is established using RF protocol development. It makes logical communication pipes to the node to node data exchange and several features have added to expect reliable data delivery, such as set highest data rate (2Mbps), set power amplifier level to high.

Next, the development progress recognized that there should be a methodology to detect faulty nodes in the WSN. Because most of the WSNs are used to make security monitoring purposes so that the identification of faulty nodes is an essential task. There are two types of faults; soft and hard. The “soft faults” means to continue communication with other nodes, but the transmitted data is incorrect. The “hard faults” means that the sensor node cannot communicate with other nodes. To overcome both soft and hard faults, monitoring server node’s MCU initiates a timer to determine that valid data is coming or not from a particular node before expiring the timer count. If a one or more node is not sending data before expiring the timer, that node is recognized as a faulty node (hard fault). Then system user can determine the faulty node and can take necessary actions. Furthermore, if receiving data is not correct (soft fault), the server’s controller unit identifies the incorrect data receive from the particular node.

IV.INTEGRATION OF SENSOR NODE WITH HYBRID ENERGY SUB SYSTEMS

A. Sensor Node

The system arrangement uses Arduino Pro Mini the MCU [11] to act as the controller unit in the node. Though, Pro Mini Provide low power consumption than Uno. It consumes 23µA with 5V version. That is more energy efficiency selection for controller unit than using other microcontrollers. NRF24L01+ transceiver consumes low power consumption to transmit (11.3mA) and receive (13.5mA) [9]. Accelerometer also consumes low power consumption. Therefore, the research identification has shown that total consumption of the sensor node can be kept in a minimal value. Further developers can use this common sensor node structure to connect their own sensors to the MCU respect to the harvested energy.

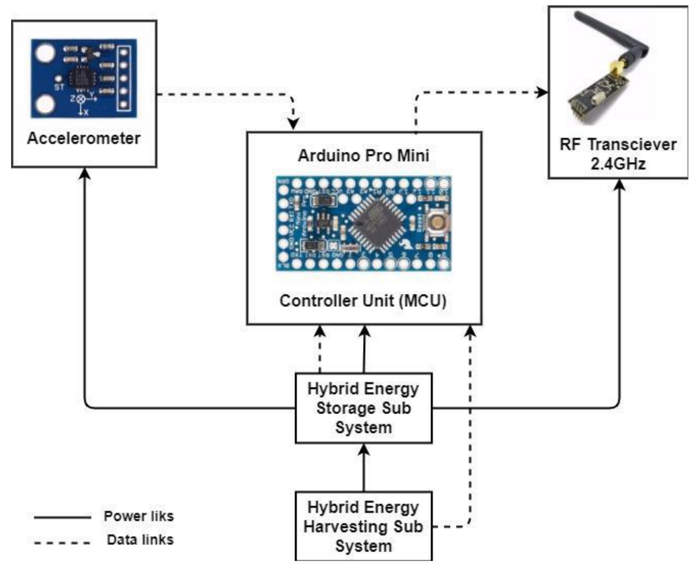

Fig. 3 Sensor node design

B. Hybrid Energy Harvesting Sub System.

A remarkable study of this development is to arrange energy harvester and energy storage as hybrid solutions to expect more year of operation to satisfy the power requirement of the WSN nodes with minimal maintenance by two achievements;(1) Increase the energy density of power sources; (2) Minimize the power consumption of the node either by choosing the right components or firmware optimization. As mentioned in before sections, hardware and software vise optimization for low power consumption is already implemented. The first achievement can be realized by two options: develop self energy harvesting technique which allows to power up the WSN node itself by ambient energy such as wind and solar; and attach durable power storage with increased capacity to the harvester. The second option will be discussed in the next section (C). When the research is realizing self-harvesting, primarily, the solar energy source is used as the main harvester meanwhile wind as the backup energy source. In this study, the important concern is to provide a stable DC output from the energy harvester. According to the system requirements, 5v with 50mA power supply should be needed. A 6V, 240mA solar panel, and a micro wind turbine are coupled in parallel and connected to hybrid energy storage via two current measurement circuit modules called ACS712 by Allegro [12] which consumes about 13mA current over 5V voltage.

As shown in Fig. 5, those current measurement modules are connected to the MCU and can measure current input from each power sources separately. Thus, that is a valuable method to get an idea about the performance of energy to report the end user by solar and wind vise. On the other hand, the wind turbine generates an alternative current (AC) while solar panel is giving DC current. Approximately, about 200mA can generate in noon-time sunlight from the solar panels. Consequently, AC to DC converter had to be used with a wind turbine as shown in Fig. 4, to feed DC to the charging controller unit. It is constructed using four IN5408 diodes and a 1µF capacitor to do current rectification. Both sources can generate 200mA current flow at the maximum energy harvesting which is pretty much enough to run the entire sensor node. At this stage, research's challengeable concern was to solve the effective wind energy harvesting problem. Results of experiments use aluminum three bladed horizontal axes with the rotor in wind turbine to expect peak voltage of 6V. The reasons for using a turbine instead of DC motor are like, continuous operation gives maintenance cost due to wear of its commutator and brush gears. Moreover, the altitude effect to the rotation of the blades. Therefore, sensor node installation at hilly location proofs the power output is maximizing.

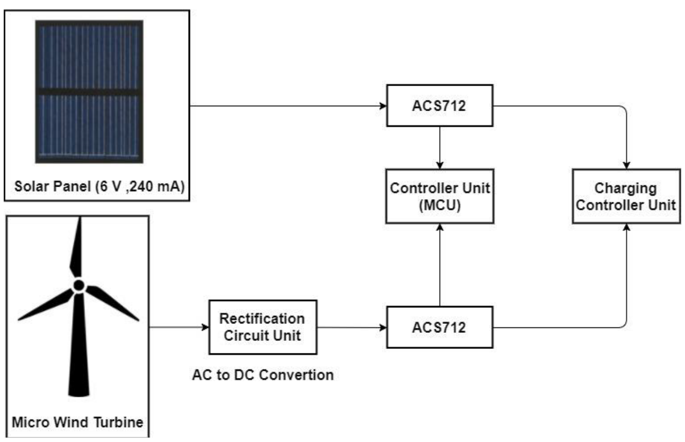

Fig. 4 Energy harvesting design

C. Hybrid Energy Storage Sub System

The harvested energy is stored in a Supercapacitor bank and a Lithium-ion battery bank by presenting a special power management unit. Integration targeted that battery bank as the primary energy storage and supercapacitors as backup storage. The research investigated that almost past storage systems were integrated supercapacitors in a series manner. However, when the supercapacitors are charging respect to the series manner if happen leakage current charging in one or more caps that cause to overcharge that particular supercapacitor and it might be a reason to damage them. Also, supercapacitors have low power density so that it can provide power for a few hours only if a case of energy harvesting failure. Therefore, the system cannot depend on supercapacitors only. Due to those influences, the research performed both lithium-ion batteries and supercapacitors as storage banks to achieve higher power density to ensure a few days of the power supply. As before discussed, supercapacitors are paralleled to each other rather than connecting series manner, and lithium-ion batteries are also connected in the same manner. Here it is used two 500F, 2.7 V supercapacitors to make supercapacitor bank. For the battery bank, two of 2700mAh lithium-ion batteries are used. The parallel connectivity doubles the capacity. As a result, it proved higher energy capacitance. The calculation has shown in conclusion section will be given a clear idea of how much time that the system can run since the harvesting energy is nonoperational.

The research developed a special power management unit which consists of three elements; charging controller unit, energy storage unit and power distribution unit. It achieves a smart power management between Supercapacitor bank and battery bank.

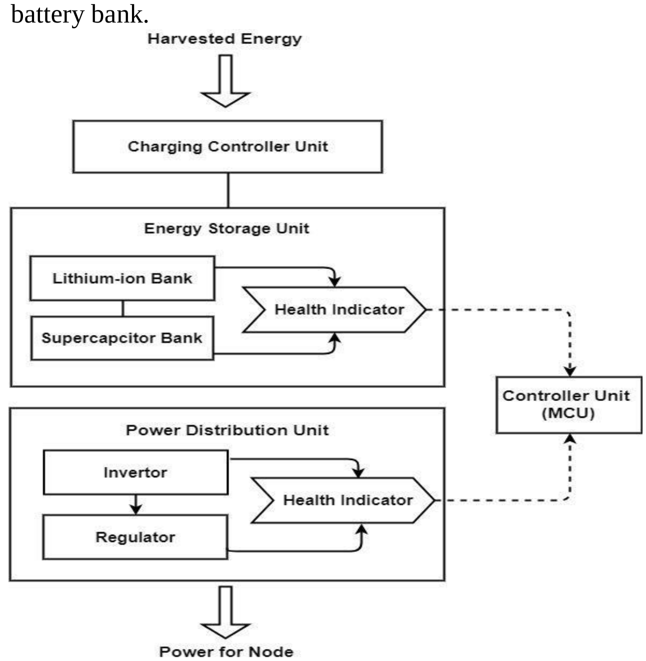

Fig. 5 Energy storage design

The Fig. 5 illustrates that how to collaborate three components of the storage sub system with indicators. Here, the charging controller unit acquires the harvested energy as a DC current flow from energy sources. Primarily, its indicator notifies voltage levels in both banks separately. During the charging process, the supercapacitor bank is charging up to the 2.7V voltage level. Since that point, the controller unit limits the overcharging. Also, the battery bank can be charged up to 4.2V. And then stop the overcharging the batteries. Now, storage banks are fully charged. Consequently, the sensor node can consume the harvesting energy directly without involving energy storage banks, until the harvesting sources are giving stable energy.

The energy storage unit developed energy banks provide stable power to the distribution unit. It makes sure to use supercapacitor bank to the supply the power as a backup when the battery bank voltage level less than 2.1V. Moreover, in part health indicator which measures voltage levels in the banks and indicates and feed those values into the microcontroller to report the end user. The power management in the charging unit and the energy storage unit is shown in Fig. 6 as a flow diagram.

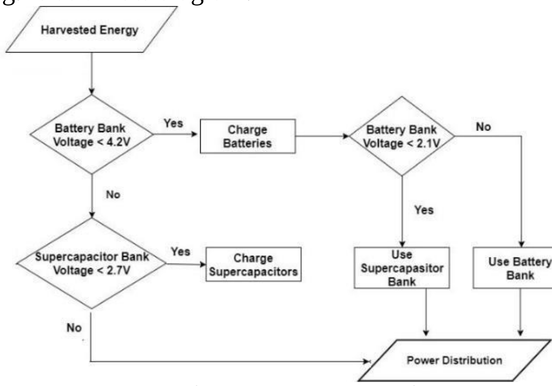

Fig. 6 Flow diagram of energy management of charging unit and energy storage unit

The power distribution unit contains two major components; Invertor and regulator. In fact, the voltage invertor converts the voltage level that is supplied from energy storage into 9V. Therefore, this acts as a step-up module. Thereafter, the Regulator converts that voltage level into 5V as input to power up the node. In this circumstance, the distribution unit can provide a stable 5V output voltage level until up to minimum 2V input from the energy storage to distribution unit. Furthermore, the power distribution unit has a health indicator to measure the current of its output voltage. That is done by ACS712 current sensor module which was used the same as in harvesting sub system.

V.TESTING AND RESULTS

Just as prototype perspective, gathering, and processing sensor data are prepared based on accelerometers and a handcraft over-bridge. The accelerometer is responsible to measure physical sideways movements and according to the experiments, on over the bridge, the system states threshold values for sensor data. Whenever exceed those analyzed values, the system indicates a risk status and end user will be notified in real time. The sensor nodes were mounted in that bridge in order to several suitable places and capture accelerometer's sensor data according to the changes in 3-axis at each of those places. After that, recognized and initiated the threshold values that can be changed maximally. Accordingly, exceeding values results to generate alerts to risk the possibility to happen a disaster and inform the end user.

The observation on the harvesting sources, solar cell power depends on the load across its terminals. Because it does not produce electrical power when the solar cell at the open circuit or short circuit. If an optimal load is applied, the power reaches to the maximum value. Results show that solar cell can reach maximum power point (MPP) at 5.5V, meanwhile, the micro turbine verifies that minimum wind speed of 5m/s can reach maximum peak voltage (6V).

Proved in testing results, the entire sensor node is consuming about 65mA in order to accelerometer function when after beginning delivery of real time data. The result includes the power consumptions of the controller unit (MCU), accelerometer, RF transceiver, and ACS712 current sensors. Next, the test setup decided to full charge the battery and supercapacitor bank. Then, calculate the total uptime that can be run the system normally by disconnecting the harvesting energy supply. Before that, following theoretical calculation is exposed that total uptime when after disconnecting the harvesting energy input.

Assume that the average power consumption of one node (power requirement) is 65mA and energy banks are parallel, Q = CV equation can be used to calculate the total uptime from each energy banks

Regarding the battery, assume that when battery capacity = $C_{(bat)}$, number of batteries = N, power requirement = $P_{(req)}$, the operation time from the battery bank ($T_{(bat)}$) will be; However, the test setup realized that battery bank can be only operated roughly 63 hours where voltage level at 2.13V. The test result of voltage dropping has depicted in Fig. 7.

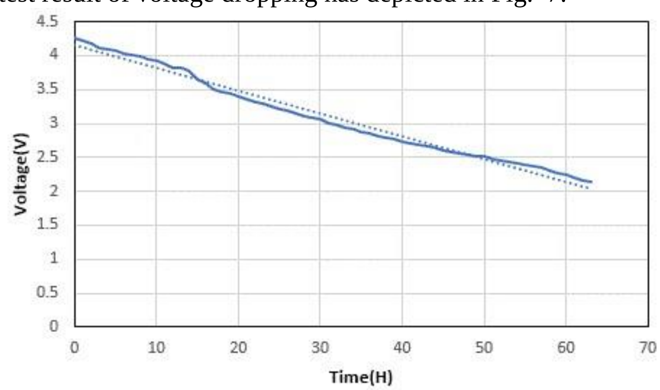

Fig. 7 Voltage dropping of battery bankthe

After that, starts to operate the system from the supercapacitor bank. Regarding the supertor bank, working voltage range of is between 2.0V and 2.7V. Assuming, the maximum voltage = $V_{(max)}$, the capacitance at the maximum voltage = $C_{(max)}$, the coulombs of charge at the minimum voltage level ($Q_{(max)}$),

$$Q(max) = C(max) \times V(max)$$
$$Q(max) = 1000F \times 2.7V$$
$$Q(max) = 2700.00C$$

Where, the minimal voltage = $V_{(ref)}$, the capacitance at the minimal voltage = $C_{(ref)}$, the coulombs of charge at the minimum voltage level ($Q_{(ref)}$),

$$Q(ref) = C(ref) \times V\ (ref)$$
$$Q(ref) = 740.74F \times 2\ .0V$$
$$Q(ref) = 1481.48C$$

Thereafter authors need to find out c to coulombs of charging at the working voltage rage ($Q_{(work)}$). To do that, should deduct the $Q_{(ref)}$ from the $Q_{(max)}$

$$Q(work) = Q(max)Q(ref)$$
$$Q(work) = 2700.00C - 1481.48C$$
$$Q(work) = 1218.52C$$

Although, 3.6C equals to 1mAh. Therefore, power of the capacitor (P(cap)) $.6C$ can calculate by dividing Q(work) from 3.6 coulombs;

$$P(cap) = 1218.52C \div 3.6C$$
$$P(cap) = 338.47mAh$$

Now, the operation time from the capacitor bank ($T(cap)$) will be;

$$T(cap) = P(cap) \div P(req)$$
$$T(cap) = 338.47mAh \div 65mA$$
$$T(cap) = 5.2h$$

Although, the practical setup assists that the voltage dropping of caps are getting isr value than the value calculation. The result gets proof that super capacitor bank lasts about three hours where the minimum voltage level at 2.14V.

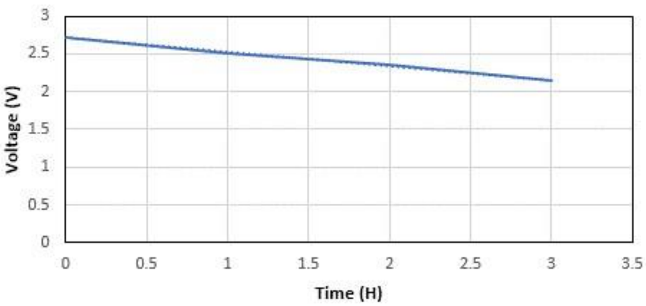

Fig. 8 Voltage dropping of supercapacitor bank

When compare total uptimes in between theoretical and practical values, theoretically,

$$T = T(cap) + T(bat)$$
$$= 5.2h + 83.07h$$
$$= 88.27h$$

However, the practical setup has shown that the system can only operate around 66 hours.

$$T = T(cap) + T(bat)$$
$$= 3h + 63h$$
$$= 66h$$

VI.CONCLUSION

The outcome found out a hybrid approach is the most appropriate solution for it. As well as, should hang a hybrid energy storage unit that entails the supercapacitor bank and lithium-ion battery bank together. This container has has been achieved the goals of the authors, a long lasting and durable sensor nodes to their autonomous operation and to minimize physical maintenances. The performance of the energy storage was investigated by how much time that a node does operate whenever a harvesting energy is insufficient or non-operational due to varying of weather phenomena. The experiment setup has exposed that the node can function roughly two and a half day. Meanwhile, devoid of cloud connectivity have gained enhanced architecture to guarantees a hundred percent of real time data delivery for the end user without any data losses. At last, the system provides a monitoring application server that use to analyze and take a necessary decision based on the data logging. This prototype level system can be based for WSN enabled disaster recovery application is requesting low power, durable and highly autonomous sensor nodes. For further developments, suggest solid state thin film batteries as an alternative to lithium-ion batteries because of its having more life cycle time rather than lithium batteries. Future developers can use this autonomous sensor node structure to connect their own sensors to measure environmental phenomena.

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