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ABSTRACT
This paper develops a universal Real-Time Graphical User Interface for the first time for low-voltage energy Harvesting. The proposed GUI is built in LabVIEW with NIUSB 621 DAQ that synchronized the data to perform real-time analysis through the use of power electronics. A hybrid Vertical Axis Wind Turbine adapted to a 200 W Permanent Magnet Synchronous Generator is used for incorporating the supercapacitor-based battery charging energy harvesting system. The GUI displays the real-time energy harvesting output readings both graphically and digitally along with wind speed and angular velocity of the turbine. The model is built in such a way so that it could be used as a universal GUI for both wind and solar energy harvesting with minimal adjustment.

KEYWORDS
Graphical user interface (GUI); LabVIEW; real-time monitoring; energy harvesting; wind energy

1. INTRODUCTION

Numerous countries worldwide are conscious of the fact that the past and current trends of energy system are not sustainable towards global energy demand. In order to search for an alternating source, the world is turning towards renewable energy. Wind power is the next promising source along with hydro and solar. Wind energy is gaining more interest each year [1]. Asia captured the largest market for wind power for the last few years. China, followed by the United States and Germany is leading from front [2,3]. Wind energy has generated more than 20% of electricity in quite a few countries including Denmark, Nicaragua, Portugal, and Spain. Moreover, World Wind Energy Association (WWEA) reported that wind production in China increased considerably by adding another 23.3 GW in the year 2014 followed by Germany and USA [3]. However, most of the research on wind power focused more on the grid-connected system [4,5]. In 2013, a 1.5 KW Permanent Magnet Synchronous Generator (PMSG)-based standalone Vertical Axis Wind Turbine (VAWT) was developed but it was too heavy and bulky in size for the small-scale off-grid system [6]. In 2014, a laboratory prototype of a 300 W PMSG-based 8 bladed VAWT was created in order to observe the off-grid performance of small-scale VAWT system [7]. After getting satisfactory performance, a small-scale VAWT integrated to PMSG fabricated with battery charging energy harvesting circuit [8] is developed and tested in 2016. This paper describes the real-time output characteristics of the turbine with the 6V battery charging energy harvesting circuit (EHC). The universal GUI is developed in such a way so that it could be incorporated both into solar and wind power. A universal graphical user interface for the real-time monitoring has been developed. A Hybrid Vertical Axis Wind Turbine (VAWT) integrated to Permanent Magnet Synchronous Generator (PMSG) is used for incorporating the EHC system. However, instead of using a wind turbine; a solar panel could also be used pertaining to the dynamic loading issues. As far as low voltage concerns, there has not yet example of developing a GUI incorporating both solar and wind and could display both digital and analog data for off-grid low voltage energy harvesting profile.

2. REAL-TIME MONITORING IN RENEWABLE ENERGY

Few works in the renewable energy sector regarding real-time monitoring system. Bahl *et al.* [9] designed an atmospheric wind profiler that could able to measure atmospheric horizontal and vertical winds. In 2013, Aiswarya and Prakash [10] created an interface in Labview to measure wind speed, direction, pressure and temperature. Bayon *et al.* [11] also worked on real-time optimization of wind farms. In the same year, Sahoo *et al.* [12] developed a Wind Turbine Emulator using Labview that displayed the static and dynamic characteristics of a typical wind turbine. Zheng *et al.* [13] also worked with real-time monitoring of wind power. However, all of their interests were more into environment comfort. In 2015, Toper [14] introduced a wind turbine emulator for multiple power plants. However, the system was too complex and it is improvised with advanced FPGA controller, which was also designed in Labview. Consequently, in the same year, Joshi *et al.* [15] created a digital subsystem with programmable computer and transducer to record the frequency distribution of wind direction in the separate sector. Having discussed the real-time monitoring system implemented in wind energy, no significant graphical user interface for off-grid wind energy harvesting circuit (ECH) is available in literature [16]. Nevertheless, energy harvesting through renewable sources is not a new idea. Babazadeh [17] invented a hybrid energy storage system for a PMSG wind turbine with a large variable wind speed between 6 and 21 m/s. The system helped to smoothen and regulate the output. Currently, the available electric vehicle (EV) such as Tesla Model S, Toyota Prius, and Chevrolet Volt use battery banks as energy storage. The average urban driving patterns cause rapid discharging of battery banks while accelerating. This research results reduction in the battery bank lifespan, making supercapacitor beneficial for this case. Since supercapacitors are able to charge and discharge at a fast rate, it can provide a boost of power during acceleration and absorbs power during regenerative braking [17–19]. For instance, Li and Joos [20] proposed a power electronic interface including a battery and a supercapacitor. The interface developed for grid connection, which is in Mega Watt power range. Worthington [21] developed a novel synchronized switch harvesting on inductor technique that is connected to a load capacitor directly to harvest energy. Experimental results showed that this idea was capable of harvesting three times more amount of energy compared to the usual bridge rectifier circuit [21]. This paper introduces a novel approach of bringing energy harvesting into wind power technology and delivers a standard and user-friendly LabVIEW-based GUI real-time monitoring for switched controlled wind energy harvesting system. Not many attempts are observed in this field for a universal GUI-based system. Sarker and few other researchers developed a control system in 2013 for low energy which was being harvested from the environment with the help of vibrating piezoelectric element through diode bridge rectifier (ac–dc converter). A switch mode step-down dc-dc converter was used for the low powered circuit to control the amount of energy stored in the battery. However, the input ac voltage with 0.4 V amplitude was rectified and stepped up to 3.3 V dc. This research aims to develop a system that can step up any voltage as low as possible considering the small voltage drop in the control system [22]. Therefore, the contribution may impact significantly in the energy harvesting sector with a novel real-time control monitoring interface.

3. HARDWARE DESIGN

MD S. A. Khan (2017) described the hardware architecture in his PhD thesis as follows.

3.1 VAWT

The following Table 1 shows the configuration of the VAWT along with PMSG used in this experiment.

3.2 EHC

In this experiment, Battery and Supercapacitors (Supercap) are used together to form a hybrid system. The battery has higher equivalent series resistance (ESR) comparing to supercapacitor which results in a high internal loss, thus less efficient compared to supercapacitor [22–25]. In addition, the voltage coming from the generator of the turbine is not constant, wind dependent and may fluctuate. Therefore, a combination of supercapacitor and battery is needed to be employed. Moreover, it is observed from Table 1 that the highest open circuit voltage ranges from 3.5 to 8 V for low wind speed configuration. As far as low voltage concerns, two choices were there; either to work with a battery 6 or 12 V. Since the open circuit voltage range was low, it is decided to use a 6V battery for charging. A supercapacitor bank was to be placed before the battery which charged up by taking the voltage generated from the turbine and subsequently would be discharged through the battery. Since the battery needed a constant voltage for charging up, the system required a DC–DC boost converter in between the supercapacitor Bank and Battery that would give a constant stepped up the voltage to the battery [26].

Table 1: VAWT configuration

Hybrid VAWT	Wind speed range	3–5 m/s
	Height	60 cm
	Radius	14.5 cm
	Number of blades	9
PMSG	Phase	3-Phase
	Rated power	200 W
	Rated voltage	12 V
	Diameter	16 cm
Top net weight	Entire system	12.5 kg
Generator performance	PMSG open circuit analysis	8.0 V (Case A) 6.5 V (Case B) 3.5 V (Case C).

Note: m = meter, s = second, W = Watt; Case A indicates 5 m/s wind speed, Case B indicates 4 m/s wind speed and Case C indicates 3 m/s wind speed

Figure 1: 6V Yokohama lead-acid battery

As a part of the hybrid energy harvesting, Supercaps were used to store the charges initially generated by the turbine. To form a Supercapacitor bank, four Supercapacitors of 35F each, manufactured by Cooper Bussmann with a voltage rating of 2.7 V were placed in a series connection. When four Supercapacitors are linked in series, total operating voltage, Vt and total capacitance, C_{total} was calculated as follows [26]:

$$\text{Vt} = 10.8\text{V} \quad \& \quad C_{\text{total}} = \frac{1}{(1\backslash C_1) + (1\backslash C_2) + (1\backslash C_3) + (1\backslash C_4)} = 8.76\text{F}$$

As a result, a supercapacitor bank with 8.75F capacitance and voltage rating of 10.8 V were assembled. Although there were a few better batteries found in the research they were excluded from the list due to the cost-effectiveness and maintenance difficulties. For example, Li-Ion batteries were omitted; even though have high efficiency and cycle life [1617]. Considering all the facts, because of having the optimum characteristics, lead-acid battery remained as the best choice. Throughout this experiment, a 6 V (3.2AH/20HR), 3 cells, lead-acid battery (Figure 1), manufactured by Yokohama, was chosen [26].

3.3 Power Electronics and Encoder

3.3.1 DC-DC Boost Converter

A DC-DC Boost Converter was used in the system to give a constant voltage of 7.5 V to the 6 V battery. The "LT1303" micro-power step-up high-efficiency DC/DC converter was chosen as they were ideal for use in small, low-voltage battery operated systems. An adjustable version of it is LT1303 which can supply an output voltage up to 25 V. The schematic diagram of the LT1303 converter is shown in Figure 2, whereas Figure 3 shows the fabrication [26].

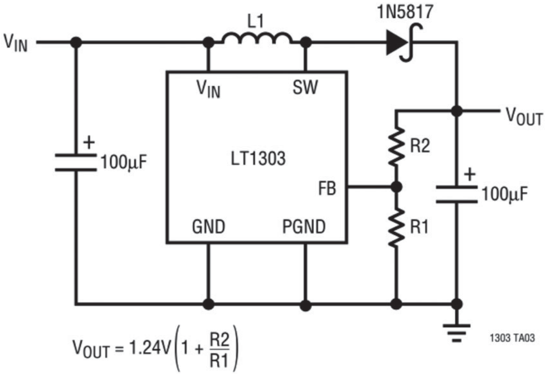

Figure 2: Circuit diagram of LT1303

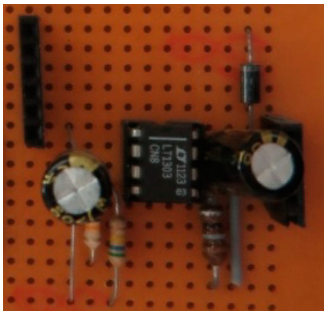

Figure 3: Configuration of LT1303CN8 on stripboard

Since the constant charge cycle of the battery ranges from 7.4 to 7.5 V, it was therefore set to 8.18 V. The voltage was expected to drop-down; therefore, the output at DC-DC converter was set at little high. By setting the $R_1 = 100\text{k}$ and $R_2 = 560\text{k}$, the output voltage can be calculated as shown below [26].

$$\text{V}_{\text{OUT}} = 1.24\left(1 + \frac{560k}{100k}\right) = 8.18\text{ V}$$

3.3.2 Current Sensing Circuit

Current monitoring is a fundamental technique in many electronics systems. For a high-side current sensing circuit, a sense resistor is placed on the high side, located in between the supply voltage and load. For a low-side sensing, a sense resistor is placed on the low-side, which is connected to the load and grounded on the other side [24–26].

A high-side current sensing is preferred if the generated current from the wind turbine is basically the measured current flowing through the load. Therefore, for the energy harvesting circuit, a high-side current sensor was chosen. Here, a low offset high-side current monitor, namely ZXCT 1022, was used to read the value of current. The circuit diagram and the stripboard form are shown in Figures 4 and 5, respectively [26]. It is noteworthy to remark that value of R_{sense} was set to the 0.1 Ω and Vout was connected to the analog input pin of the Arduino (single-board microcontroller).

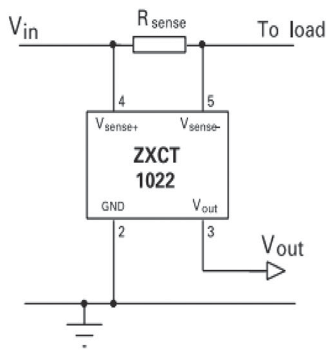

Figure 4: ZXTT current sensor pin configuration

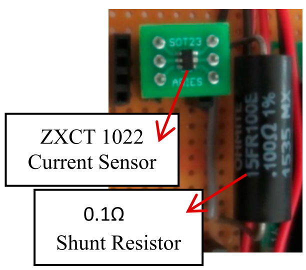

Figure 5: Circuit on stripboard

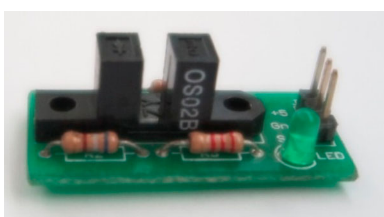

Figure 6: Rotary encoder RE08A

Figure 7: Rotary encoder installed on wind turbine

3.3.3 *Rotary Encoder*

To measure the rotational speed of the wind turbine, a rotary encoder (Figures 6 and 7) was used for this project [26]. It was installed at the base of the turbine. It could sense the rotation and send the signal to Labview through DAQ. It sent logic high whenever the marked turbine blade cuts through the encoder; or else logic low. To count the number of logic high per minute, the counter was used in LabVIEW [26].

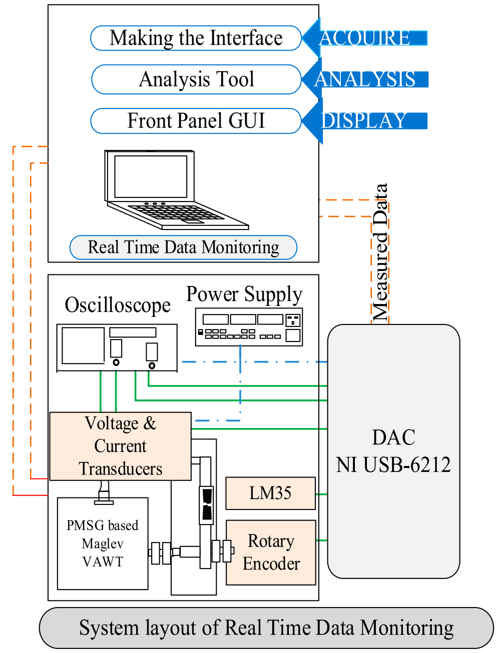

Figure 8: Layout of the entire system

4. SYSTEM LAYOUT

MD S. A. Khan (2017) explained the system layout in his PhD thesis [26]. A novel design of a small vertical axis wind turbine (VAWT) has been used to charge batteries for energy storage. This design of VAWT uses magnetic levitation concept, making it gearless and lightweight which result in significant reduction in friction and start-up wind speed. The charges generated are desired to be stored in a 6 V lead-acid battery. The charges generated from the turbine are not constant because it depends highly on the wind speed. Therefore, supercapacitor bank followed by a boost converter is used to provide a constant current supply to charge the battery through discharging the supercapacitor; thereby, able to lengthen the life cycle of the battery. Since Supercapacitors are able to hold charges for a long time, hence it will not deplete its charges comparing to normal capacitors. A control system using Arduino (single-board microcontroller) is implemented to control the charging and discharging circuit so that the system is able to perform efficiently. Encoder, current and voltage transducers are to provide real-time to monitor data. DAQ interfaced the laptop through LabVIEW-based GUI for data acquisition. Figure 8 provides the system layout of the entire experiment [26].

5. CONTROL SYSTEM

In this harvesting system, switch plays a vital role. Two N-channel MOSFETs, P36NF06L, programmed by Arduino

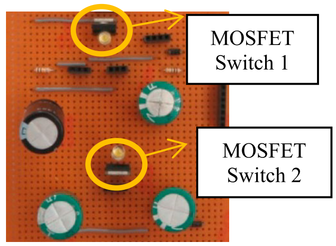

Figure 9: Configuration of switching circuit on stripboard

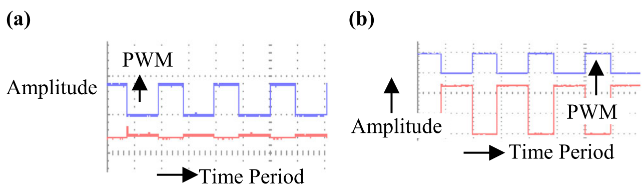

Figure 10: (a) Analysis of MOSFET when it is turned off using oscilloscope. (b) Analysis of MOSFET when it is turned on using oscilloscope

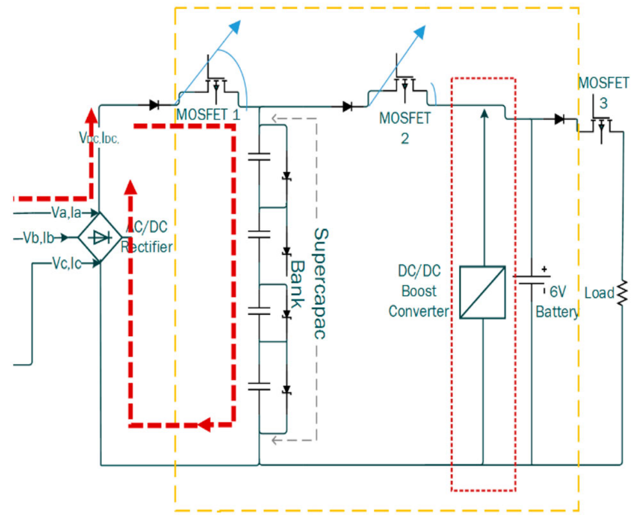

Figure 11: Schematic diagram of the system circuit at condition 1

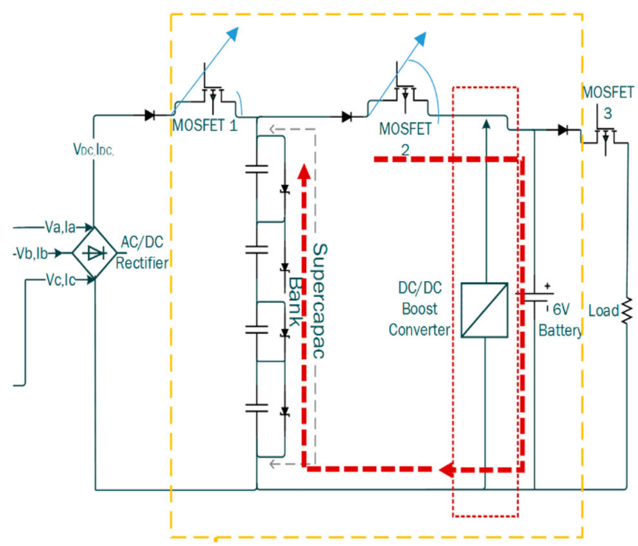

Figure 12: Schematic diagram of the system circuit at condition 2

UNO, were used here (Figure 9) to create the switching condition in the energy harvesting circuit [26]. An LED was placed in parallel to the gate–source pin of the MOSFET for testing purpose [26].

To control the charging and discharging algorithm of the supercapacitors bank and rechargeable battery, two N-channel MOSFETs were used to act as a switching circuit in this project. In order to verify the suitability and validity of the use of N-channel MOSFET several tests had been carried out (Figure 10). When a PWM pulse with an amplitude of 1V was connected to the gate to the source; the MOSFET was off. On the other hand, when a 4.8 V PWM pulse was applied to the gate to source, it can be seen from the figure that the MOSFET was switched on. In this project, a 5 V PWM was used from Arduino to turn on the MOSFET and 0 V to turn off.

Condition 1- Charging Supercapacitor from Wind Turbine Circuit: This condition occurs when $V_{Supercap}$ was less than 4V. MOSFET 1 was turned on so that the wind turbine could charge up the supercapacitor bank. In this period of time, MOSFET 2 was turned off which basically isolated the battery from the Supercapacitor. Figure 11 shows the schematic diagram of the system circuit at condition 1. Here, Vac and Ia-c are the AC voltage and current coming from the 3-Phase PMSG.

Condition 2: Discharging Supercapacitor Bank to Rechargeable Battery: This condition occurs when $V_{Supercap}$ is greater or equal to 7.5V, MOSFET 1 then was turned off to prevent overcharging from the wind turbine, while MOSFET 2 was turned on (Figure 12). At this point in time, the rechargeable battery was charged up to the battery rated voltage, 6 V. MOSFET 1 would be switched on again as soon as the voltage of supercapacitor dropped to 4V.

Until the battery was charged up to 6 V, the charging and discharging process would be continued. Two LEDs are put aligned with the bias voltage. To indicate its logic high close circuit status, LED would light on whenever the MOSFET was turned on and vice versa. Figure 13 shows the energy harvesting circuit on stripboard [26].

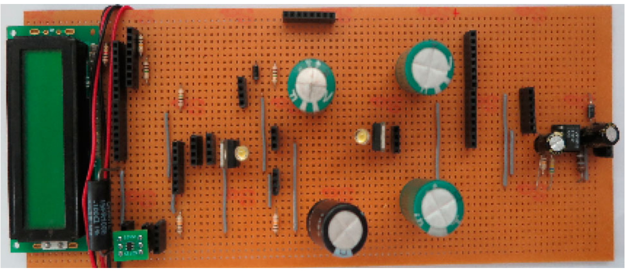

Figure 13: EHC on stripboard

6. LABVIEW-BASED GRAPHICAL USER INTERFACE

The graphical user interface (GUI) for this project was created using LabVIEW [26]. A user-friendly GUI enabled the user to be able to monitor and analyze data. The front panel of developed LabView GUI is shown in Figures 14 and 15, respectively, whereas Figure 16 shows the block diagram of Labview interface. The parameters that are monitored from this GUI are the supercapacitor and battery voltage, current drawn by the supercapacitor while charging, current drawn by the battery while the supercar being discharged and the rotational speed of the turbine through the encoder. Programmable load reading was the additional feature for further use. The data from the graph could also be exported to Excel. This enabled the user to keep track of and acknowledge the current status of the system.

7. EXPERIMENTAL SET-UP

The experiment was carried out at the University of Nottingham Malaysia Campus, located in Jalan Broga, Semenyih. The research is performed in the Research Building, N block. Figure 17 displays the experimental set-up of the system. The set-up consists of the 9 Bladed Hybrid Vertical Axis Wind Turbine connected to a 200W Permanent Magnet Synchronous Generator. The figure also displays Labview-based graphical user interface incorporated with energy harvesting circuit. Anemometer reads the wind speed which was varied accordingly.

8. RESULTS

As stated in section 7, the experiment was conducted at the Research Building of University of Nottingham Malaysia Campus during PhD research period of Dr. MD Shahrukh Adnan Khan (2011–2016) and data was taken from his PhD thesis [26]. Figures 18 and 19 here show the Labview GUI while the system was operational. Figure 18 gives the digital reading of energy harvesting supercapacitor bank and battery charging values for a fixed wind speeds and angular velocity. On the other hand, Figure 19 provides the graphical analysis of supercapacitor bank current and Voltage reading along with battery charging progress. Data was imported directly into excel and after analysis, they were plotted for efficiency comparison (Figure 20). For a wind speed of 5 m/s,

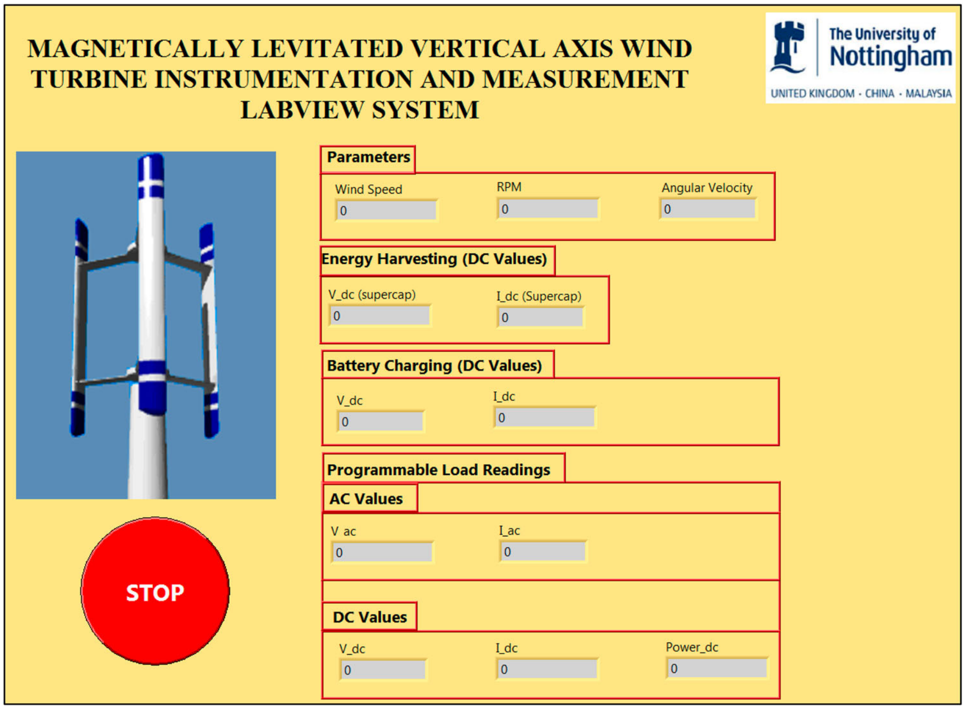

Figure 14: Developed front panel of LabVIEW GUI – Part 1

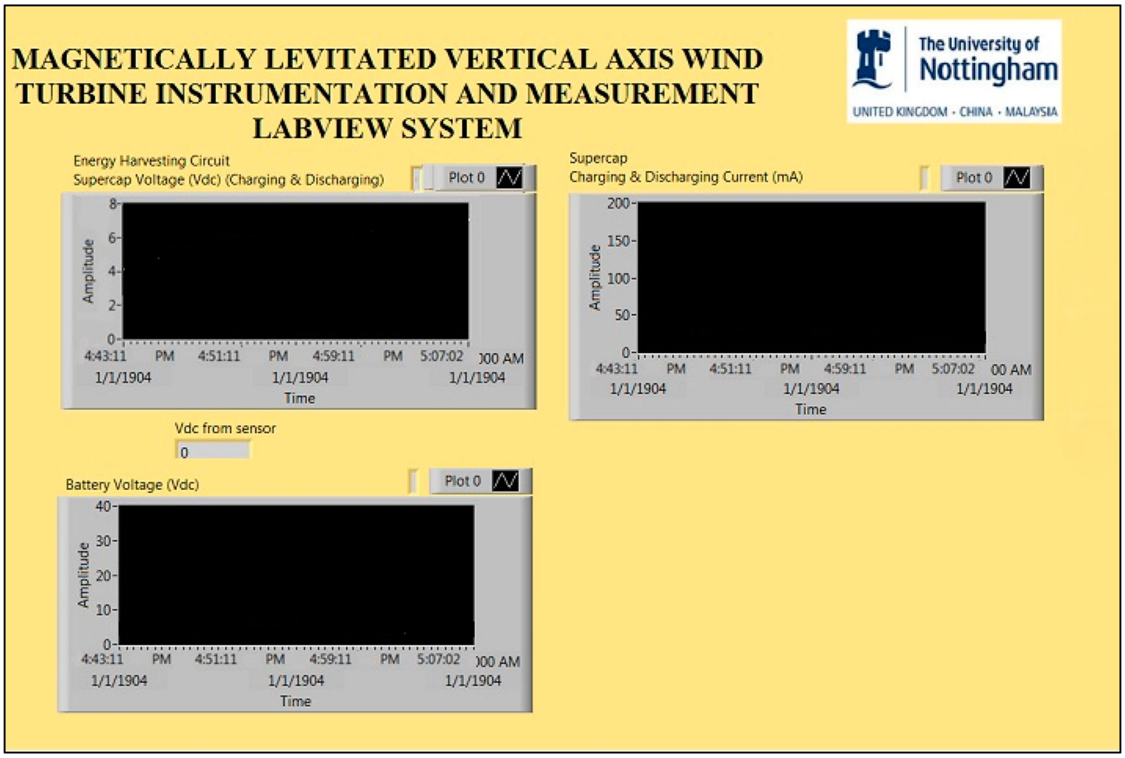

Figure 15: Developed front panel of LabVIEW GUI – Part 2

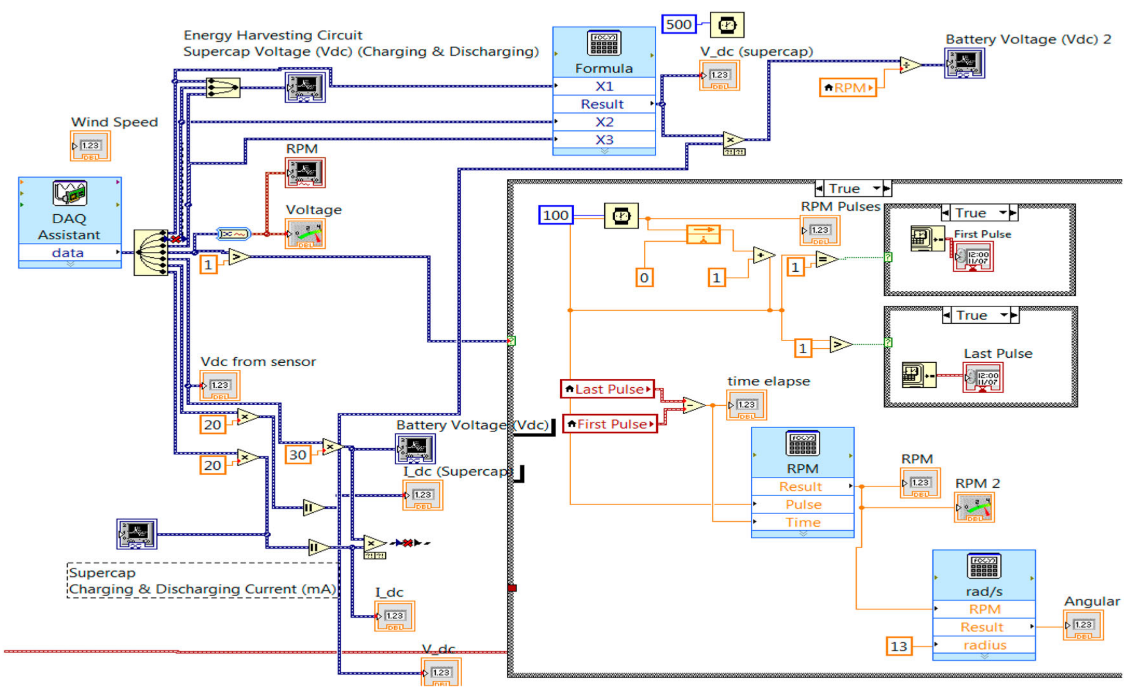

Figure 16: Back panel of developed LabVIEW GUI

the result showed an increase of 19% of the charging time while charging through the supercapacitor [26]. It took only 8.1 h whereas direct charging converter took 10 h. For wind speed 4 m/s, the energy harvesting circuit, taking only 10.4 h to charge up the battery, again showed an excellent performance of 31% efficiency. For 3 m/s, energy harvesting circuit still held the top position handsomely with 28% efficiency. The novelty of the GUI-based interface is the ability to harvest energy even if the output is as low as 2–3 V and so with the help of charging the battery through MOSFET-based Supercapacitor bank control profile [26].

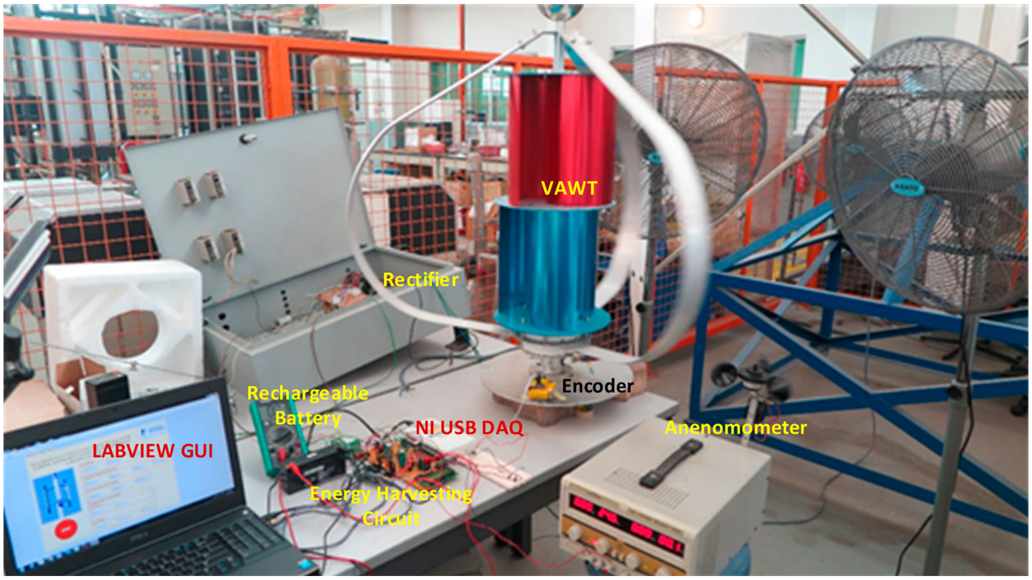

Figure 17: Experimental set-up

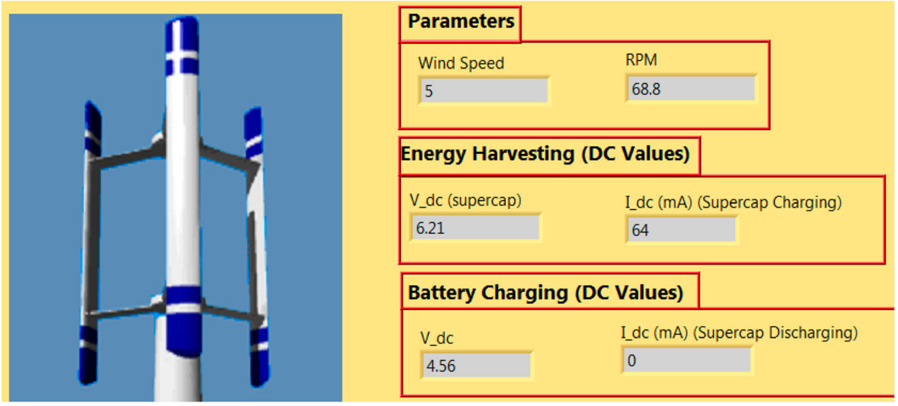

Figure 18: LabVIEW GUI reading at operation – Part 1

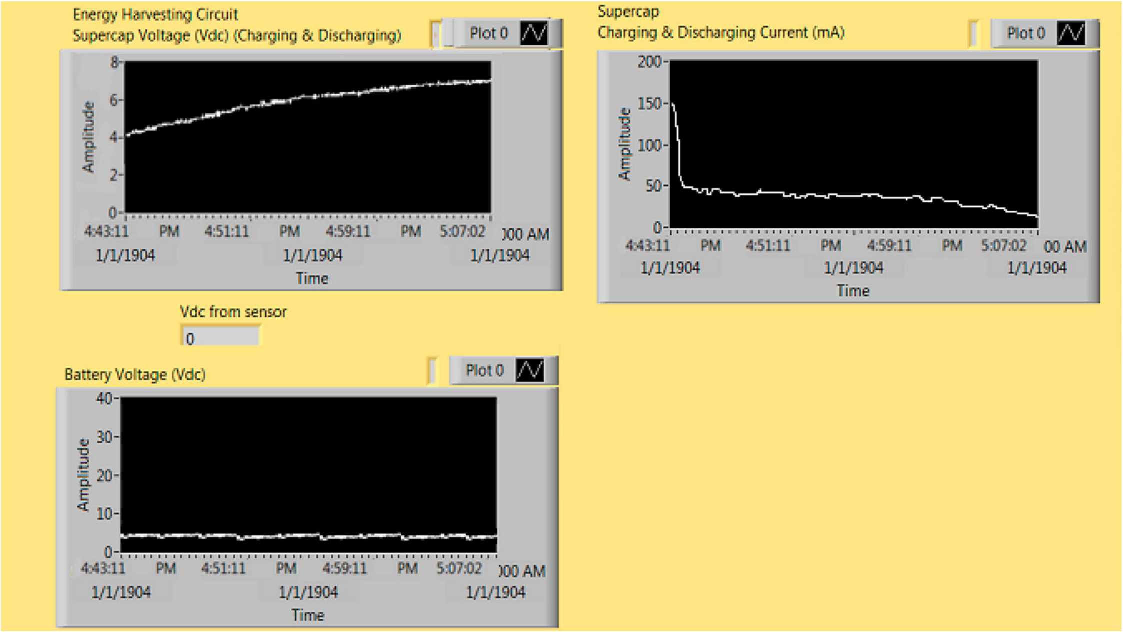

Figure 19: LabVIEW GUI graph at operation – Part 2

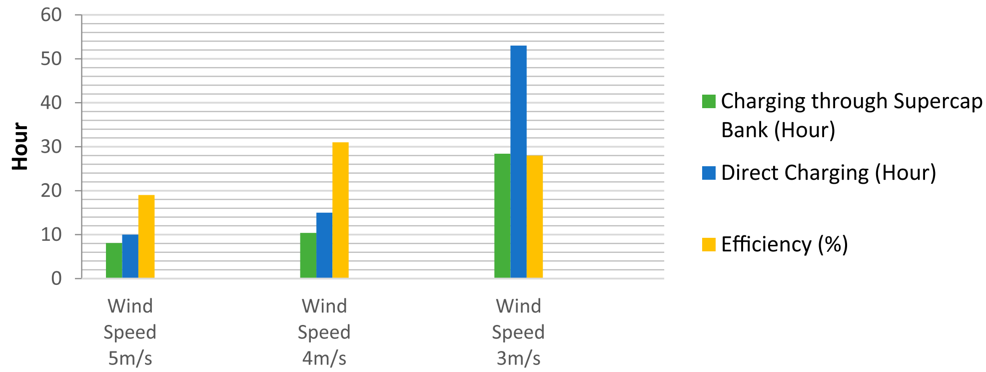

Figure 20: EHC efficiency comparison

9. CONCLUSION

As a conclusion to this paper, the aim of this experiment was to provide a Labview-based GUI that can work with a standalone off-grid wind turbine incorporated with energy harvesting circuit. For the first time, a universal graphical user interface has been developed for energy harvesting. Not only it can be incorporated into wind turbine but also it is designed for the solar panel. The originality lies in the fact that it is capable of harvesting energy even in low voltage output. The proposed interface provides an easy, less complicated access to energy harvesting data without much difficulty. There is a vast scope to extend this work further. The GUI developed in the Labview is universal and can be integrated with any sort of energy harvesting with a minimal adjustment. This surely can bring a revolutionary change for real-time data monitoring for off-grid wind power application and can be a replacement of SCADA (Supervisory Control and Data Acquisition) for small-scale real-time system.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

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