PERFORMANCE EVALUATION OF RECYCLED LITHIUM-ION BATTERIES IN IRRIGATION SYSTEM

Isyaka A. A.¹, Hassan S.M.¹,²*, Haruna Y. S.¹, Hassan M. A.¹, Nasiru A.¹ and Musa I.²

¹Department of Electrical and Electronics Engineering, Abubakar Tafawa Balewa University, P.M.B. 0248, Bauchi Nigeria
²Department of Mechatronics and Systems Engineering, Abubakar Tafawa Balewa University, P.M.B. 0248, Bauchi Nigeria

*Corresponding Author: smhassa@atbu.edu.ng

Abstract

Water pumps, being the most essential part of any irrigation system require fuel or electricity to be operated. The fuel is often expensive, and majority of rural areas are not connected to the grid. This necessitated the need for an alternative source of energy to power the pumps. Solar energy is one of the most easily accessible forms of energy and has the advantages of being environmentally friendly and durable. The energy is also in abundance and readily available. A key concern is the high cost of batteries to store the solar energy. This paper analyses the performance of solar irrigation system using recycled laptop batteries. The use of recycled laptop batteries is expected to cut the cost of deep-cycle batteries by more than 60%. Experimental results have shown that the recycled lithium-ion batteries can effectively power irrigation pump hence, can handle the irrigation process satisfactorily.

Keywords: Irrigation; solar; Lithium-ion batteries; Performance; Battery Management System (BMS); Control.

1 Introduction

According to author in [1], Nigeria has a total area of about 34 million hectares of arable land. It is the largest producer of sorghum in the world after United State, and the fifth in the production of palm oil, beans, and cocoa. At the same time, agriculture accounts for about 23 percent of Nigeria’s Gross Domestic Product (GDP). At the grassroots level, agriculture is almost the sole employer of labor in Nigeria with about 75% of the nation’s population living in the rural areas. However, the world’s population that uses laptop computers and tablets worldwide are close to 1.5 billion. This necessitates the rising demand for lithium-ion batteries to grow significantly over the last decade. The demand will not only remain high, but it will also increase even more due to migration from fossil-based consumer electronics that produces greenhouse gas emissions in energy harvesting process which contributes to global warming. Some of these climate change impacts can be mitigated by adding more renewable sources.

A Lithium-ion (Li-ion) battery is constructed by connecting the basic Li-ion cells in parallel (increase current), in series (to increase voltage) or combined configurations. Multiple battery cells can be integrated into module [1]. Multiple modules can be further integrated into a battery pack.

Therefore, the production of electricity is very paramount for attaining progress. In recent times, attentions were directed in using renewable energy sources such as solar, wind, biomass, and running water for power production to run farm equipment. There are technologies available for converting renewable sources such as the wind, hydro, solar and many others into useful power and these technologies are presently receiving widespread attention.

Consequently, water pumps being the most essential part of any irrigation system require fuel or electricity to be operated. The fuel is often expensive and not readily available in most rural areas. On the other hand, majority of the rural areas, that contribute greater percentage of food supply, are not connected to the national grid. This necessitated the need for an alternative source of energy to power the irrigation pumps. Hence, solar energy being one of the easiest accessible forms of energy available to the farmers in rural areas is a good alternative. The energy if harvested using photovoltaic cells, has the advantages of being environmentally friendly, durable, and requires minimal maintenance.

The harvested energy from the solar needs to be stored for future applications using batteries that are equally expensive as fossil fuel. However, used lithium-ion batteries obtained from laptops are often discarded.
This leads to increase in electronic waste (e-waste) and other hazardous chemical substances that poses a great threat to the environment. It was established that not all cells within the laptop battery packs are unusable. Therefore, there is need to recycle the reusable ones which in turn optimizes economic and environmental benefits of the batteries.

The remainder of this paper is organized as follows: Section II reviews the related works, while section III presents the methodology or development of the proposed system. In section IV, experimental results are presented and discussed. Lastly, conclusion is presented in section V.

2 Literature review

Despite emergence of new economic sectors such as information technology and manufacturing, agriculture will continue to be an important employer of labor across the globe. However, the recent unpredictable and uncertain nature of our rainy season necessitates the need for efficient irrigation systems in our farms. To address these challenges, several researchers have attempted to develop irrigation systems based on renewable energy sources such as solar and wind. This is because, the abundance of sun and wind makes it a powerful source of energy that can fuel life on earth. It can also provide a sustainable and clean energy to the world populace at cheaper and affordable rate than other forms of energy from fossil fuels. For example, [2] and [3] both attempted to develop smart irrigation systems focusing on water management. However, in both cases consideration has not been given to the effect of weather conditions on the solar PV cells and its effect on the overall efficiency. In a related development, [9] also developed a smart irrigation system for monitoring ground water usage. The authors did not address the earlier stated problem of solar system non-functioning optimally due to effect of weather conditions.

On the application of IoT technology for smart irrigation, [4] attempted to monitor and control a solar powered smart irrigation system using sensors and environmental data from an Internet of Everything (IoE). Data collected was used to predict environment conditions using the Radial Basis Function Network (RBFN) while the predicted data was used to control the irrigation system. However, the approach only considered solar system and was limited to simulation environment. In another study, [5] also proposed a concept of IoT as a basis for monitoring and control systems. While [6] was aimed at addressing the water management in irrigation system, thereby minimizing human intervention due to manual labor thereby optimally improving crop yield due to apportioning the exact water according to the crop demand, and economically add value. In addition, the work reported in [7] was also a sensor-based irrigation system that explore the use of temperature, moisture, and humidity sensors to monitor the state of the environment before communicating with microcontroller thereby engaging or disengaging pump. Furthermore, it prompts the end-user at real time using Zigbee technique. Perhaps, both water consumption, dry and flooded irrigation have negative impact on crop production economically and otherwise. Solar energy has been the major player in renewable energy harvesting. It became paramount due to its abundance and durability. As part of this research credence, it controls the Ph and salinity of water and the LDR using stepper motor in navigating the PV module for proper tracking of maximum solar radiation. It maintains the soil Ph at (6.0-7.0) for grains and (6.8-7.0) for forage and legumes. Moreover, the main purpose of this research is to use solar PV system to address watering and irrigation system capable of integrating soil moisture sensor as an input from the root of the crop or field, and a PIC18F4550 timer, as well as HSAT (Horizontal single axis tracker) on the feedback of two LDR and relay to operate automatically under the influence of soil moisture sensors after comparing its output with a predefined level. Furthermore, it uses lead acid battery as a storage as against the lithium-ion recycled laptop batteries. Finally, [2] explores the use of drip irrigation system by collating data through humidity, temperature, flow, and soil moisture sensors. The two modes of operating systems are: closed loop system where microcontroller operates the system based on soil moisture demand, whereas the other mode is by remotely activating the system by end-user. Hence, the system consists of electrical aspect which involves solar PV panels, MPPT, BMS, and battery bank. While the mechanical aspect consists of pumping machine, and the medium in which water is conveyed to and outside the pump. In a nutshell, this research work ensures sufficient level of water in the soil avoids over and under irrigation. Therefore, research into solving the problem of single energy source while applying used laptop batteries has the potential to greatly improve farmers yield and will help towards solving problem of food insecurity in our country.

According to [8] as technology advances in storage systems, recycled laptop batteries known as Lithium-ion batteries (LIB) are the bedrock of digital electronic revolution through mobile phones, tablets, laptop computers, and many other consumer electronic devices. The device has gained prominence due to their increased performance and efficiency, coupled with the increasing demand for energy storage, mainly driven by the implementation of electric vehicles, as well as several economic and environmental issues that are tantamount to environmental degradation and related hazards to humanity. However, many technologies have been developed to allow these devices to be reused or recycled instead of discarding, to provide a second-life opportunity to the lithium-ion batteries. In dealing with Lithium-ion batteries, Battery Management System (BMS) is essential to validate voltage, current, temperature, State-of-Charge (SoC) and State-of-Health (SoH) as well as Depth-of-Discharge (DoD) and prevent
dangerous situations by maximizing the performance and life cycle of batteries. According to [2], in automotive applications, lithium-ion batteries do not have optimal operating conditions, they typically endure more than 1000 charge/discharge cycle for 5 to 8 years and are also subject to a wide temperature range between 200°C and 700°C, a high depth DoD, and high charge and discharge rates.

3 Methodology

This section will first present the proposed irrigation system followed by the methodology for proper sorting and selection of used laptop batteries, then the battery pack design and management system followed by the lithium-ion battery model. Finally, the practical implementation of the system will be presented.

3.1 Proposed Irrigation System

The proposed irrigation system consists of Photovoltaic (PV) array, charge controller, battery management system, battery bank of recycled laptop batteries to be precise, with 2kW inverter. The system operates 0.5Hp A/C pump and channeled water from the reservoir through the sprinkler system.

3.2 PV cell array and Charge Controller

In this work, four 185W solar panels each with Short circuit current ($I_{SC}$) of 5.43A, Open circuit voltage ($V_{oc}$) of 45V and Voltage at maximum power ($V_{mp}$) of 36.4V arranged in parallel are used alongside 60A MPPT charge controller. The PV arrangement is shown in Fig. 2. Consequently, the MPPT charge controller including the dump load are presented in Fig. 3. The function of the dump load is to prevent the wind turbine and PV cells from excess voltages that might be produced once the batteries are fully charged.

3.3 Sorting of Used Laptop Batteries

The steps needed to be followed to ensure proper sorting of used laptop batteries are as follows:

1. The discarded laptop batteries need to be procured and dismantled using the appropriate tools.
2. Pull-out the assembly of cell array and carefully disconnect the charging circuit using the right tool to avoid short circuit due to polarity.
3. Ensure proper separation of 6 or 4 lithium-ion batteries connected in series-parallel for desired voltage and milli ampere hour (mAh).
4. Keep the battery tabs in position to enable smooth and safer running of solder after arranging the discarded batteries for yet another battery bank build-up.

The following flowchart shows a step by step working model of the entire cell sorting and selection process.
3.4 The Lithium-ion Battery Model

The storage used in this research work is the recycled cylindrical Li-ion cells with 410AH, and a protective circuit of 40A 3S BMS respectively. The protection is an electronic circuit that is synchronized with the battery flat, whose aim is to provide an utmost protection on the battery to be charged and discharged optimally. The battery has a maximum voltage of 4.2V and a nominal voltage of 3.7V, likewise one or more Resistance-Capacitance (RC) networks are introduced to model the dynamic behavior of the battery. The Thevenin’s equivalent circuit model of the battery [10, 11, 12, 13] is a first order RC shown in Fig 5. The circuit consists of a voltage source, a resistor in series with an RC link. $U_{oc}$ is the open-circuit voltage of the battery, $R_0$ is the battery ohmic resistance, $R_1$ is the polarization resistor while $C$ is the polarization capacitor. The current supplied by the battery is I while $U$ is the battery voltage and $U_1$ is the voltage across the RC network.

\[ U_1(t) = U_1(0)e^{-t/\tau} + IR_1\left(1 - e^{-t/\tau}\right) \]  

(3)

as reported in [14] at $t = 0$, $U_1(0) = 0$, hence the initial term is zero. Therefore, (3) reduces to

\[ U_1(0) = IR_1\left(1 - e^{-T/\tau}\right) \]  

(4)

Thus the polarisation resistor and capacitor can be determined for (4) as follows:

\[ R_1 = \frac{U_1(0)}{I\left(1 - e^{-T/\tau}\right)} \]  

(5)

where $\tau$ is the time constant of the RC link given as

\[ \tau = R_1C \]  

(6)

subsequently from (6) the polarisation capacitor $C$ can be obtained as follows:

\[ C = \frac{\tau}{R_1} \]  

(7)

The RC networks analyses the diffusion process in the electrolyte, thus, with larger number of RC elements, the battery model will be enriched with adequate precision. It should be noted that the time constant is the function of both the capacitance size and resistance in the network [17].

3.5 Battery storage design

The battery storage consist of the arrangement of batteries and the management circuit. Battery bank is designed to have a terminal voltage of 24. The operation of the BMS and the battery arrangement will be discussed subsequently.

3.5.1 Battery management system

Based on [12] Li-ion batteries have high power density, robust SoC and SoH estimation that sustains its life cycle with excellent precision, low self-discharge factors of performance under unusual temperatures, safety, and efficiency, with no effect of memory compared to other energy storage technologies. However, these batteries have had accident-related cases that causes a serious outcry in the society. This is mostly due to overcharging if no control measure employed. Hence the need for an effective battery management system (BMS). Its functions among other things are data acquisition, charge and discharge management, SoH and SoC-controlled estimation, cell balancing and other unforeseen circumstances. Fig. 6 shows the block diagram of a typical bms system.
The main sensors present in BMS are Temperature, voltage and current sensors, and any of these three sensors that is not functioning, it will amount to cell damage permanently [15]. In the current aspect, the long current overcharge can cause serious damage, hence the need for BMS to arrest the undesirable situation. This can be achieved by estimating several parameters of the SoC, impedance, and SoH of the Li-ion batteries of undesirable situations. However, depending on capacity of the cell, the voltage is kept at a reference point such that the range of the voltage is associated with the SoH of the battery pack or individual cell. The voltage serves as the information that improves and compliments the SoH and SoC estimation accuracy. Finally, the range of temperature range of lithium cells is between $-20^\circ C$ to $60^\circ C$, hence violating these limits can be tantamount to cell damage, or thermal runaway may occur with high risk of fire explosion which can be prevented, courtesy of temperature sensor control of BMS.

However, if the cell voltage is below 2V in the cause of discharging, the battery flat will instantly be disengaged since the integrated monitoring circuit has a hysteresis voltage of 2.2V to prevent risk of cell destruction and intermittent operation of the cells.

### 3.5.2 Battery Bank Arrangement

Fig. 7 shows four flats of lithium-ion batteries connected on a particular BMS each. Each floor consists of 3 blocks of 18 cells connected in series-parallel, thereby having 18P3S arrangement in the flat. As the first block attains its maximum load i.e. 4.2V, the BMS will automatically switch off the charger and initiate balancing procedure on other two remaining blocks of 8.4V and 12.6V respectively. This is done to maximize their capacity. By disabling the charger as explained earlier, the system balances the other two blocks from the first one that is fully charged, until it's low enough to receive the charging load current again [16]. The type of BMS considered in this work is the 3S − 40A as seen in the configuration of Fig. 8. The consideration is mainly due to availability. Hence different configuration of the batteries could have been obtained if a different BMS has been considered. The BMS used here has been fortified with cooling system to prevent overheating of some sections of the circuitry. This is done through the use of LM 35 as a temperature sensor, such that once the BMS temperature exceeds 30°C, a fan is turned on to cool it down.

### 3.6 Implementation

As technology advances discarded laptop batteries known as Lithium-ion batteries (LIB) are recycled and used as a storage after rigorous sorting, selection, and testing of individual cell to ascertain its well-being or otherwise. Fig. 9 shows the entire system involving the solar PV panel, the battery bank, the inverter, and the pump with associated pipes and sprinkler that convey the water to the field or irrigation farm. Thus, the figure depicts the implementation of the entire system.
that facilitates energy harvesting from the photovoltaic panel through the inverter, to enable smooth running of a/c pump. Furthermore, the same power harvested will be stored for autonomy period through the BMS.

Figure 9: Complete System Implementation

4 Results and Discussions

Two resistive loads and an inductive load were considered for the experiment to evaluate the viability of the recycled laptop batteries as follows:

1. Resistive Loading: Resistive load of 400W and 350W were applied on the battery bank, and the readings were taken as shown in Fig. 10.

2. Inductive loading: A 0.5 horsepower (373W) pump was powered by the battery bank, and carefully monitored at various loading conditions to ascertain the desired results as shown in Fig. 10.

Figure 10: Battery collapse time with various loads

Figure 10 shows the battery collapse time of the battery bank after being subjected to various loading conditions, the 400W resistive load takes about 51 minutes to collapse, while that of 0.5 horsepower (hp) pump which is equivalent to 373W load takes about 82 minutes before collapsing, and finally the 350W resistive load takes about 56 minutes to collapse. Remember, the intermediary load of 373W is an inductive load, and the later was resistive hence the clear distinction on its collapse duration. This clearly shows that the system has the capacity to power the intended irrigation system for more than one hour. The Voltage regulation is given as follows

The voltage regulation is given as follows

\[ \text{Percent } V_R = \left( \frac{|V_{NL}| - |V_{FL}|}{|V_{NL}|} \right) \times 100 \]  

where \( V_{NL} \) and \( V_{FL} \) are the no load and full load voltages respectively.

Thus from the values obtained in Table 1 the percentage regulations for the various loads considered is given in the table below

Table 2: Voltage regulations for loads

<table>
<thead>
<tr>
<th>Load (Watt)</th>
<th>( V_R ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>4.27</td>
</tr>
<tr>
<td>373</td>
<td>8.02</td>
</tr>
<tr>
<td>400</td>
<td>3.40</td>
</tr>
</tbody>
</table>

Based on the significance of the voltage regulation as shown on Table 2 the percentage regulation of 373W is 8.02% which is an inductive load, while that of 350W and 400W is 4.27% and 3.40% respectively. It can be seen that the pump being an inductive load has a higher regulation compared to the resistive loads.

Figure 11: Comparison of Voltage loading conditions

Plot of Voltage Against Time: The comparison of voltage loading conditions on voltage no load \( V_{NL} \) voltage full load \( V_{FL} \) and the collapse voltage \( V_{CLPS} \), the
nominal voltage of our Li-ion batteries is 3.7V with a maximum voltage of 4.2V and since each of the 4 flats of the battery bank consist of 3 cells connected in series, and 2 of the flats are connected in parallel each to obtain 12V voltage on each 2 flats, then the two flats are cascaded to obtain 24V terminal voltage. This analogy gives a collapses voltage at 20V from the full load voltage profile of 23.7V on inductive load and the scenario plays out on the two resistive loads of 350W and 400W respectively.

Finally, the average current drawn by each load is 4.68A for 373W inductive load, whereas 4.85A and 7.52A on each resistive loads of 350W and 400W. This categorically shows that the resistive loads draw much current compared to inductive loads of the same power rating.

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Conclusion

This paper has evaluated the performance of recycled Li-ion laptop batteries based on charging and discharging process. The state of health and state of charge of the batteries, as well as control of the charging process to attain cell balancing were ensured by the BMS. Experimental results have demonstrated the viability of reusing discarded laptop batteries thereby extending further their useful life. Consequently, the economics of using recycled 18650 Li-ion batteries could lead to drastic reduction in cost by up to 60% compared to deep cycle batteries. The recycling will at the same time curtail environmental degradation due to e-waste.

References


