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Development of a Model for Improving Reliability Performance of a Microgrid Lithium-Ion Battery Energy Storage System (BESS)

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ABSTRACT
There is a global increasing demand for storage of renewable energy; this cannot be achieved without an efficient and reliable battery energy storage system. The energy obtained from any source can either be used at that moment or stored for future use. This condition has motivated many researchers to work on improving the reliability performance of different types of battery energy storage systems (BESS). The study examined the possible and available modalities for improving the reliability performance of a microgrid lithium-ion battery energy storage system. A mathematical model was developed to improve the BESS performance reliability of lithium-ion batteries. The modified model achieves percentage accuracy of 98.88% when tested using the percentage accuracy prediction error method; it demonstrates a root-mean-square error (RMSE) value of 1%, and it achieves a mean absolute error of 1%. A MATLAB program was developed for improving lithium-ion battery reliability performance analysis.The results demonstrate that a lithium-ion BESS functions well between 25°C and 45°C; at this temperature range, the internal resistance of the BESS becomes lower, allowing electrons to freely flow within the BESS. The MATLAB program was run at different numbers of battery cycles, such as 2000, 3000, 4000, 5000, and 6000 cycles with temperature variations and capacity degradation rates to analyze the BESS reliability performance in the MATLAB environment. The outcome clearly indicates that the higher the number of battery cycles, the higher the state of health (SOH) and the less capacity degradation.

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INTRODUCTION

Battery energy storage systems (BESS) are exponentially growing, the commercialization of Battery Energy Storage Systems (BESS) is predicted to soar after 2017, according to researchers at US consultancy Frost & Sullivan, who wrote a report titled The Global Market for Grid-Connected (BESS)[1]. They assert that we are in the midst of this "dynamic growth". There will be a significant "boom" in storage systems after 2020, when their costs will have reduced sufficiently for the facilities to be paid off in five to six years[2]. Today, there are many countries that have been slowly shifting the generation of electricity from non-renewable energy source (NRES) to renewable energy source (RES) such as wind and solar energy[2]. The energy obtained from these sources must be stored for future use when such natural sources are not available. This condition has given an added advantage toward the rapid growth of BESS deployment. There is active international, national, state, and local dialogue on policy considerations pertaining to future pathways for reducing greenhouse gas (GHG) emissions.

There is even global plan to reduce the global temperature rise to 1.5°C by 2050 [3]. However, the resource sufficiency of these

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systems may eventually be compromised when more RES, such wind and solar energy, replace dispatchable units. In tiny island grids that are overloaded and subject to security and technical restrictions that eventually place a cap on the amount of renewable energy that can be stored in such systems, the introduction of energy storage is currently a key aspect in enabling RES uptake.[4]–[6] Electric energy storage (EES) is a set of technologies that stores previously generated electric energy and releases that energy later. Storage uses forms of energy such as chemical, kinetic, thermal, or potential that can be converted to electricity on demand, which have an average storage capacity of more than 10% of their daily consumption[7].

Additionally, without storage, the grid must produce, deliver, and consume electricity very instantly in order to maintain balance. In spite of the fact that consumer power demand varies greatly during the day and throughout different times of the year, this necessitates that the whole electric value chain, including the generation, transmission, and distribution networks, be sized at annual peak use. Because the entire electric value chain had to be sized to accommodate peak demand, there were inefficiencies in the system, underuse of assets, and excessive costs for ratepayers[8]. A power system known as a PV system uses PV cells to produce electricity directly from sunlight. By creating a potential energy differential between photons and electrons when sunlight hits a PV cell's surface light energy is converted into electrical energy.

PV modules/arrays are made up of a combination of PV panels and PV cells, respectively [2], [7], [9]. PV modules that are connected to the utility grid are called grid-connected PV (GCPV) systems. while a PV module that is not linked to the utility grid is called a stand-alone PV system. During the peak-demand, the BESS connected to PV system supply excess electricity generated from the solar module to the grid [10]. However, a stand-alone PV requires batteries to store any extra electricity produced by the solar panels, and this sort of BESS is often intended for consumers who reside outside of urban areas. Most GCPV systems are related to the microgrid.

Nowadays, BESS are modeled and simulated using different software to predict the reliability performance of systems. The research work in [11] reviews the efforts in the modeling and simulation of lithium-ion batteries and their use in the design of better batteries. There is currently much research going on regarding stand-alone BESS and grid-connected BESS in order to increase the system efficiency and improve its reliability performance. Battery energy storage systems (BESS) remain the only solution toward achieving a clean energy future. As demand for electricity continues to grow, many challenges are also arising, ranging from the risk due to the integration of electric energy from BESS to the grid to natural and artificial hazards that can seriously affect the successful operation of BESS. The reliability performance of the BESS system is one of the key solutions to these problems.

LITERATURE REVIEW

Research on battery energy storage systems (BESS) continues to arise as the need to store electric energy for future use is increasingly evolving. All electrical appliances need a specific amount of electric power, called rated power, to effectively operate under normal working conditions. This can only be achieved if there is a constant power supply or uninterrupted power supply (UPS), There is no doubt that in most developing countries, there is no constant power supply. This power disruption has posed a serious challenge to the operation of many electrical devices, hence the need to create a reliable energy storage system that will be used for continuous operation even when there is no supply from the grid. There have been so many research studies on BESS. BESS have seen rapid growth in the last few years. For example, in 2019, the accumulated power of all BESS in Germany was more than 450 MW [12].

By 2022, the total power capacity of authorized projects with electrochemical storage in the UK will be 5499 MW [13]. In 2018, 6MW battery energy storage system (BESS) using lithium batteries was installed in the city of

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Budapest, Hungary[13]. Many countries are moving toward renewable energy and continue to install more energy storage systems to accumulate the energy produced during the day.

MATERIALS AND METHODS

The method we used to developed some mathematical model involved the use of both primary and secondary data that was used by some researchers to developed mathematical models thus improving on their work. These models were simulated in Matlab environment to test it is performance reliability.

Model for Improving Reliability Performance of a Microgrid Lithium-Ion Bess

A state of health model developed in [31] was modified to improve the reliability performance lithium-ion battery energy storage system.

$$\mathrm{SOH} = [\mathrm{SOH}_0 - \frac{\mathrm{I}}{2 \times \mathrm{n} \times \mathrm{Q_r}} \int_0^t |\,\mathrm{i(t)dt}|\,]100\% \quad (3.1)$$

From the equation above SOH_0 is the original state of health of the BESS or is the initial capacity of an individual battery, n is the number of cycles expected for battery to reach its end of life, $i(t)$ is the electrical current which flow through the battery, dt is the change in time.

$$SOH = \frac{C_{now}}{C_{initail}}\ 100\% \quad (3.2)$$

Where C_{now} is the available battery capacity and $C_{initial}$ is the original battery capacity, but electric charge
(C) = current (I) X time (t)

$$C_{now} = \mathrm{I} \times t \quad (3.3)$$

SOH_0 is the original state of health of the BESS or is the initial capacity of an individual battery, n is the number of cycles expected for battery to reach its end of life, $i(t)$ is the electrical current which flow through the battery, dt is the change in time. From time t = 0 to time t = t, battery charge changes.

$$C_{now} = \int_0^t I\, d(t) \quad (3.4)$$

for n number of cycle $C_{now} = \int_0^t nIdt$, ... eq (3.4),

Recall that V = IR=> $\frac{V}{R}$ = I (3.5)

We can put the above equation into eq (3.4) $C_{now} = \int_0^t nI\, dt$

$$C_{now} = \int_0^t n\, \frac{V_{(t)}\, dt}{R_{int}}$$

$$C_{now} = \int_0^t n \left(\frac{V_{(t)}}{R_{int}}\right) dt \quad (3.6)$$

From eq (3.6) the higher the value of R_{int} the lower the value of charge at that instant, and the lower the value of R, the higher the value of charge. This means that our focus for improving the overall BESS performance can be done on this internal resistance (R_{int}).

Internal Resistance (R_{int}).

Battery is made up cathode and anode which is positive terminal and negative terminal respectively and at each terminal there is an internal resistance which can be reduced by dissolving the side product accumulated at both cathode and anode. therefore,

$$R_{int} = (R_{an} + R_{ca}) \quad (3.7)$$

equation 3.6 can be written as

$$C_{now} = \int_0^t n \left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right) dt \quad (3.8)$$

Internal resistance can be altered by charging at different temperatures thus, charging multipliers (k) and temperature coefficient (T_c) can be introduced to reduce the internal resistance using neuro-fuzzy method thereby modifying eq (3.1) for improve reliability performance.

Temperature Coefficient (T_c) and Charging Multiplier (K)

Temperature coefficient (T_c) and charging multipliers (k) can be used to reduce the internal resistance using neuro-fuzzy method thereby modifying eq (3.1) for improve reliability performance.

$$C_{now} = \int_0^t n \left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right) x\ K\mathrm{Tc}dt \quad (3.9)$$

Where K = charging multiplier and is always less than one (K< 1), and T_c = Temperature coefficient which also always less than one (T_c < 1).
But we know that from eq (3.1)

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$$SOH_0 = \frac{C_{now}}{C_{initial}}$$

$$SOH_0 = \frac{\int_0^t n\left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right) KTcdt}{C_{initial}} \qquad (3.10)$$

$$SOH_{modified} = \left[\frac{\int_0^t n\left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right) KTcdt}{C_{initial}} - \frac{1}{2_n Q_r} \int_0^t |i(t)\, dt|\right] X\ 100\% \qquad (3.11)$$

Mathematical Implication of Developed Model

Based on the latest advancements in battery modeling research, WE have developed a comprehensive mathematical framework aimed at improving the reliability and performance of lithium-ion batteries, with the State of Health (SOH) as the central subject. The foundation of any reliable SOH model lies in its precise definition. SOH is defined as the ratio of the current maximum available capacity to the rated initial capacity

$$SOH = \frac{C_{now}}{C_{initail}}\ 100\%$$

Upon Validation of the model developed using experimentally measured parameters on multiple datasets, the model achieves superior accuracy of 98.88% when test using percentage accuracy using prediction error , it demonstrates root-mean-square error (RMSE) value of 1% on the CALCE dataset. And achieves a mean absolute error of 1%.

Neuro – Fuzzy Approach.

The eq (3.11) can be separated into two terms parts if we apply Neuro– Fuzzy approach. If the external controllable variable = E_c, and the Internal controllable variable = I_c and the modified ($SOH_{modified}$) = SOH, then

$$E_c = \frac{1}{2_n Q_r} \int_0^t |i(t)\, dt| \qquad (3.10)$$

$$I_c = \frac{\int_0^t n\left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right) KTc\, dt}{C_{initial}} \qquad (3.11)$$

$$SOH_{modified} = [I_c - E_c]\ X\ 100\% \qquad (3.12)$$

The parameters such as temperature, current, voltage and internal resistance from equation (3.11) can simply be controlled by controlling the external source of power supply that charges the lithium-ion BESS, thus a good battery management system can control both internal and external factors.

BESS Coding Analysis

A Matlab coding was carried out to get some graphical information of different values with different variables. These variables include temperature, number of cycles, capacity degradation, state of charge, lithium-ion battery, and charging and discharging capacity. During the program battery of cycles was set at different values (1000,2000,3000,4000 and 5000 cycles). Degradation rate was set at 0.08 and a temperature range of 25°C to 50°C as operating temperature range [°C]. the program was ran and the was obtained.

Battery Number of Cycle

Battery life-span depends on the number of cycles the battery can delivered, whenever a battery is fully charged and fully discharged it losses one cycle. From eq (3.1) it is very clear the higher the number of cycles the higher the state of charge of the BESS. During our matlab coding program, different number of battery number of cycles to analyze the performance, the battery number of cycles was set at 2000, 3000, 4000, and 5000 number of cycles to analyze the BESS performance at each assigned number of cycles.

Lithium-Ion Bess Simulation

A simulation was run to ascertain the BESS performance with twelve lithium battery cells. Twelve battery energy storage cell blocks and some other Simulink blocks were used in the MATLAB Simulink environment to carry out the model simulation. Three group of four battery cells were connected in parallel to get more current and the three group were then connected in series to get more voltage. Voltage measurement block was connected between the node to get the output voltage this block saved as a voltmeter in Simulink environment, a current measurement blocks was also connected between the RLC load block and MOSFET block to measure the current from a cell, four display

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blocks were used to present the digital output values of some parameters. Below Figure 3.1 shows the simulated model.

State Of Health (SOH) of Lithium-Ion Battery

The most important aspect of battery performance is the State of Health (SOH) for a lithium-ion battery, is its maximum available capacity (capacity fades as cycles reduces). The simulation was conducted to improve the state of health of lithium-ion battery on matlab Simulink environment, the Simulink block display shows the output value of 99% of state of health when employing the charging and discharging process.

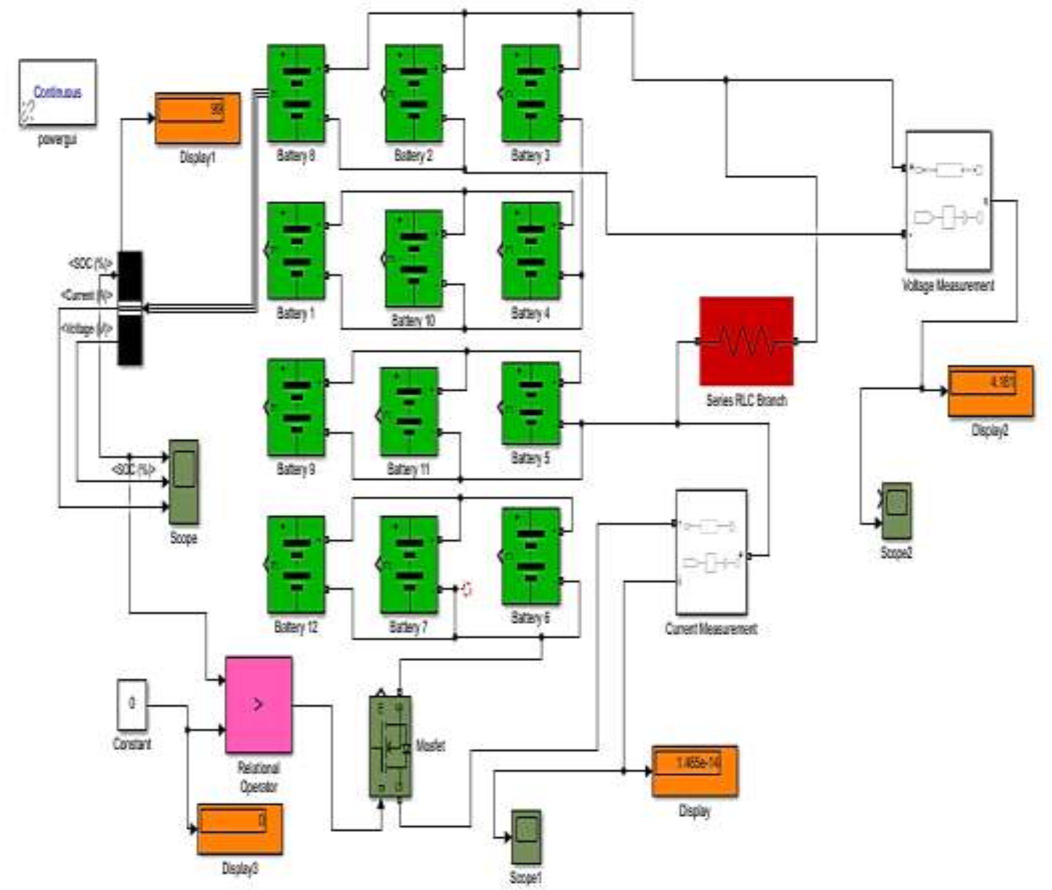

Figure 3.1: BESSS model simulated

RESULT AND DISCUSSION

Model Developed for Improving Bess Reliability Performance

$$SOH_{modified} = \left[\frac{\int_0^t n\left(\frac{V_{(t)}}{R_{an} + R_{ca}}\right)KTcdt}{C_{initial}} - \frac{1}{2_n\, Q_r}\int_0^t |i(t)\; dt|\right] X\; 100$$

the model developed in chapter three for improving the reliability performance of lithium-ion batteries was first checked and analyzed. Based on the parameters used to develop the model, which include current (i), voltage (v), coefficient temperature (Tc), charging multiplayer (k), state of health (SOH), rated capacity, battery number of cycles (n), internal resistance (Rint), initial capacity, and time (t).

Equations 3.1 and 3.2 were first considered, and the parameters were thoroughly

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analyzed, and their relationship was carefully identified. For example, from the modified model, it can be seen clearly that as the internal resistance of the battery increases, the battery voltage will decrease; thus, charging multiplayer and temperature coefficient were introduced to minimize the effect of internal resistance on battery voltage. A single lithium-ion battery cell was used as a sample to practically validate the model; the battery cell parameters were measured using a multimeter while estimated values of 0.5C and 0.08 as charging multiplier and temperature coefficient were considered. The measured values were used to mathematically calculate the percentage accuracy of the developed model, root mean square error, and mean absolute value as 98.88%, 1%, and 1%, respectively.

Temperature Impact on Battery Capacity

The Matlab program was conducted by varying some parameters such as temperature, state of charge, and number of battery life cycles to generate and display some visual signals in the form of graphs to analyze the effect of changing any parameter. For example, the BESS performance at a temperature above 50°C was poor; also, the performance tended to be poor when the temperature was very low. See fig. 4.1a and fig. 4.1b below:

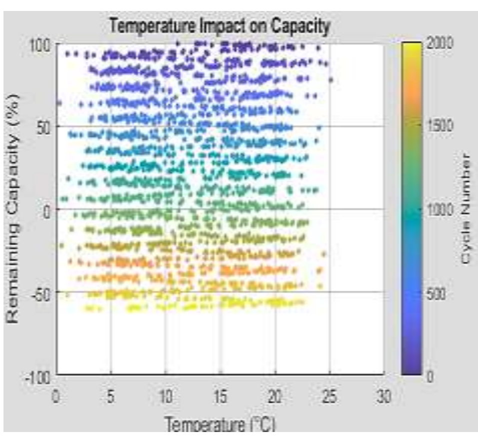

Fig.4.1a: Temperature impact on capacity

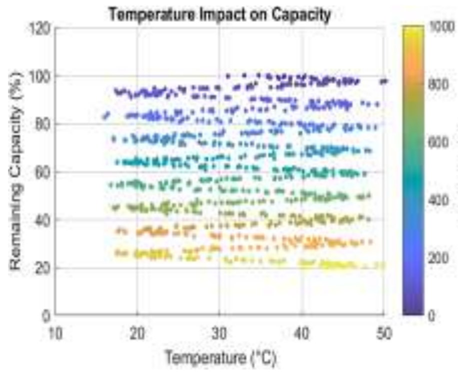

Fig.4.1b: temperature impact on capacity

It is clear at very low temperatures, for instance, 5°C, the battery electrons tend to have low degrees or freedom of movement due to high internal resistance, thereby lowering kinetic energy from the system, as we all know that electrons move from cathode to anode during charging and from anode to cathode during discharging; this movement reduces as the temperature reduces. From fig. 4.1a, electrons were relatively restricted to move fast due to the low temperature of 5°C to 20°C; this will lead to poor BESS performance, while from fig. 4.1b, electrons possess relatively high freedom of movement due to the relatively high temperature of 25°C to 50°C; this will lead to better BESS performance.

Battery Capacity Degradation Based on Cycles

Battery capacity reduces with cycle count; it is considered 100% at the initial stage, but this decreases linearly with the number of cycles. This is because whenever the battery is charged and discharged, the cycles create an irreversible change in the chemical and physical properties of the battery system. In this research work we carried out a performance analysis on battery capacity degradation in relation to the number of cycles; capacity degradation can occur as a result of many factors, such as overcharging, undercharging, high temperature, improper maintenance culture, and so on. In this work, a linear capacity degradation with random noise was used to simulate a real-world variation.

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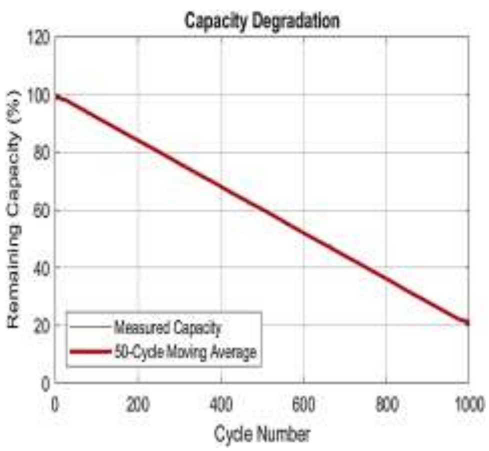
Fig. 4.2a indicates a visual signal display from the MATLAB environment where we put the degradation rate to be 0.08, or 80%, and the number of cycles to be 1000 with a normal operating temperature boundary of 25°C to 50°C. It can be observed from fig. 4.2a that when the battery completes 1000 cycles, the remaining capacity is 20%; that means it has lost 80% of its original capacity. This shows that the number of cycles plays an important role in battery performance analysis.



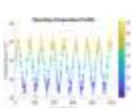
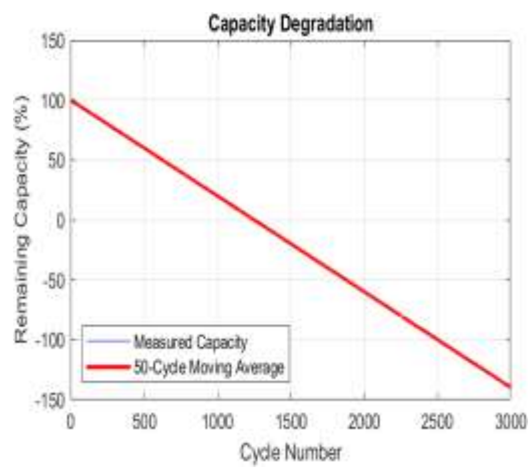


Figure 4.3a: Capacity Degradation with 3000 Cycles

Most of the installed BESS capacity decreases as the batteries' number of cycles reduces, thus affecting the entire performance efficiency of the installed system. When a battery is fully charged and fully discharged, it has made one complete cycle. Repeating the process 1000 times will render the battery system with 1000 cycles to a stage called "end of life." At this stage, the battery can no longer be operated as needed; hence, increasing the number of cycles to a high level as much as possible during the design process will surely improve the overall performance of the system. In view of this, another simulation was carried out to analyze the impact of increasing the battery number of cycles to 3000 times while maintaining the same temperature; the larger the number of cycles, the better the chance of getting high performance. Fig. 4.3a and Fig. 4.3b indicate the generated visual display when simulating with a high number of cycles.



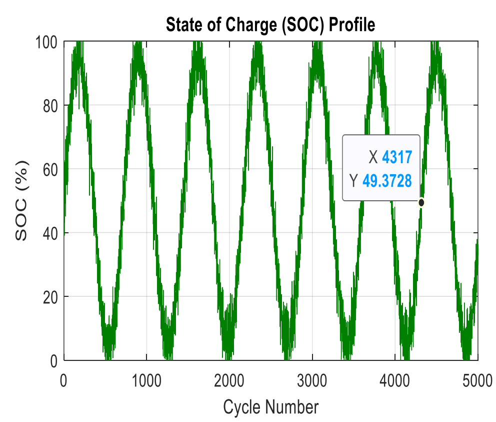


Fig 4.2b: Temperature Effect on Battery Cycles

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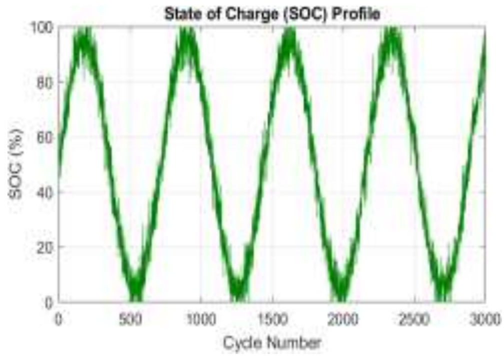

Fig.4.4: Impact of High Number of Cycles on Improving BESS Reliability Performance.

Fig.4.4 was obtained from Matlab program where we used 5000 number of cycles to verify the effect of increasing the number of cycles of battery's state of health, the result shows that the higher the number of cycles the better performance of BESS which clearly conformed with the mathematical model developed in chapter three.

Internal Resistance Effect

A mathematical model was developed in chapter three, the model developed relates or adds the anode and cathode resistances to get the internal resistance of the battery mathematically. During the Matlab program, the effect of temperature on BESS performance was analyzed and it was clearly observed that low or cold temperature increases the internal resistance and at a high or optimal temperature the internal resistance reduces thus affecting the overall performance of the system. Fig. 4.1a and Fig. 4.1b was generated from Matlab environment clearly shows how internal resistance of battery system affect BESS performance directly or indirectly.

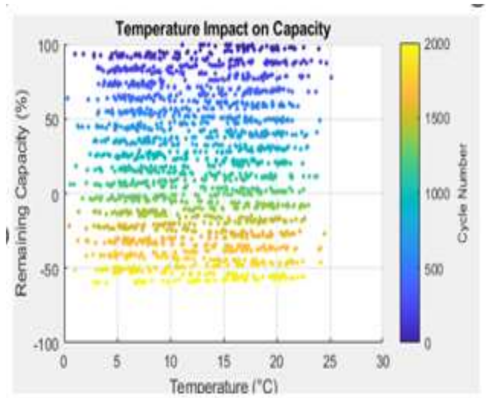

Fig.4.1a: Temperature impact on capacity

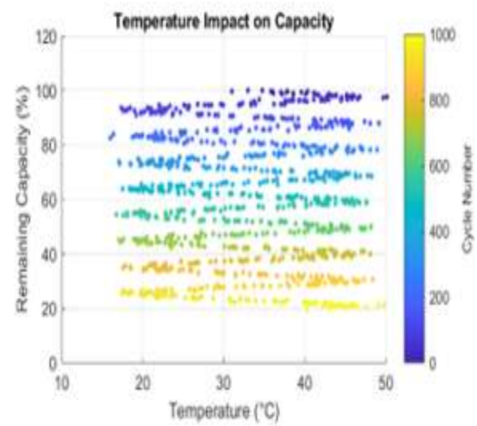

Fig.4.1b: temperature impact on capacity

WORK FLOW CHART

The figure below indicates the flow chart of the model developed.

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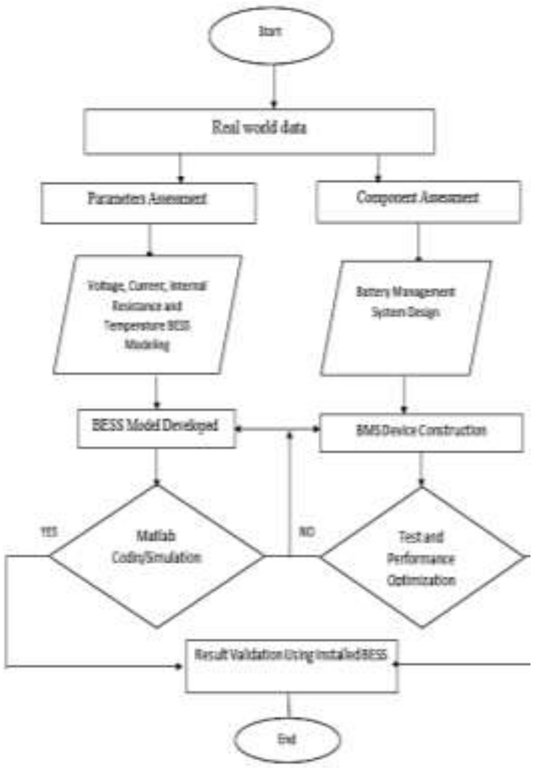

CONCLUSION

The modified model achieves percentage accuracy of 98.88% when tested using the percentage accuracy prediction error method; it demonstrates a root-mean-square error (RMSE) value of 1%, and it achieves a mean absolute error of 1%. Based the MATLAB program developed, the results clearly show that lithium-ion BESS performs effectively at a temperature range of 25°C - 45°C; it indicates that at this temperature range the internal resistance becomes low, thus permitting free flow of electrons within the BESS. This condition minimizes the rate of degradation of battery capacity, thereby improving the reliability performance of the system.

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