Prediction of Battery Lifetime using Hybrid Solar Power System

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Abstract

In recent years there has been a great concern to implement more renewable energy sources to supply energy around the world. Solar energy seems to be a good choice since it is accessible and does not cause pollution. The main problem with the solar system is that energy production only takes place when the sun is shining. Large storage systems need to be developed to provide a constant and reliable source of electricity when the sun is not shining at night or when a cloud goes overhead. The main objective of this study is to predict the lifetime of the battery in the solar hybrid system. This will involve investigating the stress factor that contributes to the battery. From the simulation done in Matlab Simulink, a graph of state of charge (SOC) versus time is gathered with the help of the Rainflow algorithm extracted from the fatigue cycle of the battery. Once the fatigue cycle is determined, the ageing rate will be calculated. The outcome of this study is battery lifetime can be predicted and the proper battery can be used to reduce for maintenance purposes.

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Introduction

This In this modern world energy plays an essential role in the economic growth of a country. According to Akikur et al. [1] statistics power consumption will increase at a rate of around 1.5% annually and 6% annually for the developing countries such as Malaysia and West Africa. Currently due to the Paris agreement, the target energy production for renewable energy has been set to 32% by 2020 [2]. Renewable energy is believed to be the best alternative solution compared to traditional energy types. Solar energy is one of the most significant form between all renewables energy because it is considered as clean, pollution-free and readily available [3]. Solar energy is considered as the next leading generating source of power because it is accessible, sustainable and has geological advantages concerning power generation. Solar energy system is a beneficial investment as it does not require a lot of maintenance, it is pollution free and does not deplete the resources. It is proved that for low load demand, hybrid system is economical through the life cycle cost analysis [4]. Nowadays, there is a will to change the current one source system for hybrid system for grid-connection applications.

The hybrid solar system is a system that generates power the same way as the original solar system which is generating an energy source from sunlight. This stored energy will provide a backup power supply if there is no energy can be generated at a point of time. Talking about the optimal sizing of hybrid system, the proper sizing of the battery is very important. So, it is essential to be able to predict the battery lifespan of the battery being used which in this case is lead-acid batteries. Multiple methods are being used to improve the factors that affect the lifetime of the battery such as depth of charge (DOD) and ambient temperature. A Simulink model was built in Matlab Simulink to simulate the ideal case of battery charging and discharging in hybrid system. Then a rain flow counting algorithm was written in Matlab to extract the fatigue cycle from the state of charge (SOC) graph. Actual data will also be imported into Matlab for fatigue extraction using the algorithm then a comparison can be made.

This paper presents the prediction of battery life using a hybrid solar system. The objective is to investigate the stress factor that contributes to battery degradation and predict battery lifespan using the rain flow counting algorithm in a solar hybrid power system. Besides that, the objective was to design MATLAB Simulink and simulation whereby a graph of (state of charge) SOC vs time shall be obtained. Another objective is to successfully compute the rain flow counting algorithm to extract the fatigue life of the battery to predict its lifetime.

Methodology

Project Framework

The proposed battery lifetime Prediction Model is described in Figure 1. A dynamic simulator design is done in MATLAB Simulink which will consider solar irradiance at a specific location, ambient temperature, and load profile to determine the battery state of charge. The simulation will be done for a whole year in the step of 30 minutes and a graph of battery SOC versus time shall be obtained. Then Rain Flow algorithm will be used to extract the number of cycles, amplitudes of these cycles, and their mean value. The end goal will be an estimation of the battery's expected time to failure.

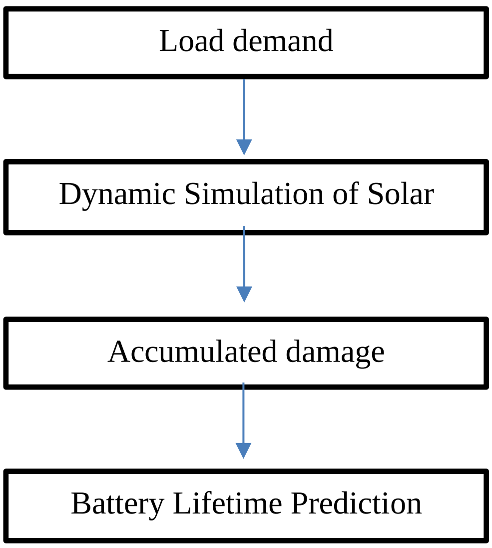

Fig. 1: Solar Hybrid flowchart

Material

Data Collection

To build a proper dynamic simulator for a solar hybrid system, long-term accurate analytic prediction is required. Several data are needed such as shown in the references from the chosen site as well as accurate information for both stochastic and deterministic components of solar irradiation, daily power generation, and load demand. Deterministic input of model properties that are well known whereas stochastic model input has random properties. For this required project, analysis at a selected location is done where there is already a solar hybrid system. In this way, the solar-based information carries on as a monthly normal consistent, in addition to or minus short arbitrary associated changes. In some situations, for specific sites especially at low latitudes, the minimum duration of inspection is more prominent than one month. One month is picked because it is very stable, and because that climatic information is normally accessible monthly.

The Rain Flow Algorithm was used to forecast the life of a lead-acid battery. As can be seen, the battery's anticipated life span ranges from 9 to 13 years, which is similar to the manufacturer's prediction. This could be because the battery type differs. Mostly because the battery undergoes undesirable physical and chemical reactions that cause the battery to decay. It's because there's a limit on how much data can be created in Matlab simulations, rather than the physical battery itself. Table 1 shows the number of days that were used for the simulation.

The total number of cycles is inversely proportional to the battery's expected lifetime, according to one relationship. The battery's anticipated life duration was discovered to be related to the amplitude of the cycles. The number of cycles in the system can be calculated using the Matlab simulation.

Table1: Load History

Simulation	Load History(days)
Simulation 1	94
Simulation 2	88
Simulation 3	59
Simulation 4	88
Simulation 5	109
Simulation 6	95
Simulation 7	83
Simulated data	120

Software and Tools

The version of Matlab Simulink that is used to model the hybrid solar system is Matlab (R2020a) 64-bit. This is because it can combine graphical and textual programming thus making it suitable for dynamic simulation. In Matlab Simulink, building the Simulink model based on real-life implementation can be done and it can also use hardware in-loop testing to validate the design. Matlab Simulink also supports non-linear and linear systems which are adequate in its own case. Besides in the Simulink library, power system components such as FACTS, transformers, and the battery can be found which are essential to construct the Simulink model. And in the case that a component is not available in the software Matlab provides ways to build the block using other components and necessary equations if required. In Simulink results can also be analyzed easily as Matlab has a proper toolbox and a function that allows extracting hidden info from some graph using an adequate algorithm. Besides that, Matlab will be used to write the code for the rain flow counting algorithm.

Method

Weighted Ah ageing model

In this method, the battery throughput is assumed to be a constant value from its manufacturing till the time it is thrown away. Here the different factors that contribute to the depletion of the battery such as temperature are considered and given weighted coefficients. Once the total throughput goes beyond the threshold value, then the battery is changed. The general Ah throughput is obtained by averaging the changing throughput under various DOD, and as a similar throughput at various SOC levels variously affects the battery life, the weighted aging model is set up dependent on the building knowledge [5]. By building knowledge, it means observation already made through experiments in a laboratory for the specific battery which is in this case is lead-acid batteries. Usually, these experiments are done under a constant temperature close to room temperature (25°C) [6]. Figure 2 illustrates the total throughput and cycles to failure for lead acid batteries based on manufacturer data.

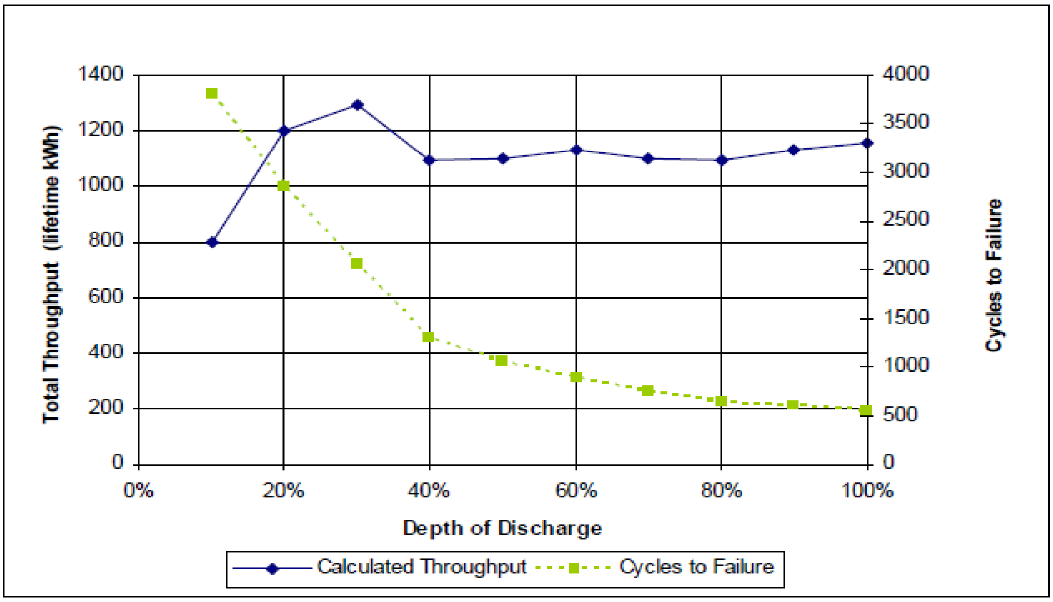

Fig. 2: Total throughput and Cycles to failure for lead acid batteries based on manufacturer data [6]

$$Throughput = Average\{(E_{NOM}\mathrm{DOD}) * C_F\} \quad (1)$$

Wherefrom Equation (1), DOD is the depth of charge, ENOM is the battery nominal capacity and CF is the cycles to failure to the specific DOD [7]. For example, battery discharge has fixed energy at a rated depth of charge which is defined as effective discharge, and that when the aggregate effective discharge value is equivalent to its maximum total effective discharge value, the battery must be changed.

Physic-Chemical Ageing Model

In this Ageing model, the depletion parameter responsible for battery performance continuously increases for the battery operation and life cycle. The battery end-of-life happens when the breakdown threshold is attained. Stress factors such as depth of charge and temperature will affect the deterioration rate of the battery as they have an impact on the internal chemical reaction in the electrolyte. In Hadwan et al. [8] states that another method was proposed to assess the battery lifetime at different conditions such as changing state of charge, arbitrary depth of charge, and operating temperature. They set forward a deterioration hypothesis measuring the major factors impact on the battery cycle, for example, DOD and temperature, and so on. Experiments was done and the results obtained proved that the model was accurate and achievable. If battery lifetime method is associated with real data, the whole model accuracy is increased.

Event-Oriented Ageing Model

Here each event that results in a reduction of the battery life is described and a value is assigned to the events determining the deterioration scale. So, while the battery is in use, each specific event will be tracked, and damage done to the battery by each event is recorded. Then relevant calculations are done to obtain the approximate battery life remaining. For this model to be accurate and efficient, each event must be independent of each other and the damage resulting from similar events at various intervals must be the same. One major advantage of this model is that it does not require complex calculation and that repetitive measurement is prevented when finding battery internal performance. One disadvantage is that stress factors such as temperature charge and discharge rate are not considered which may lead to inaccurate results. In addition to that this model cannot be used for real-time monitoring.

Equivalent Circuit Model

Another popular method but yet simple that is used to predict battery lifetime is using the equivalent circuit model (ECM) as illustrated in Figure 3. The ECM usually represents an approximation of the battery terminal behavior instead of the complete modeling of the battery internal chemistry. The battery equivalent circuit consists of two major part which is a parasitic branch that represents the end of charge battery behavior and the main branch that estimate the battery dynamics for every condition [9]. The ECM of the battery represents only one cell of the battery so the required calculation should be made to the model battery of interest. For example, if the output voltage of ECM must be multiplied by six to model a typical 12 V lead-acid battery used in a car.

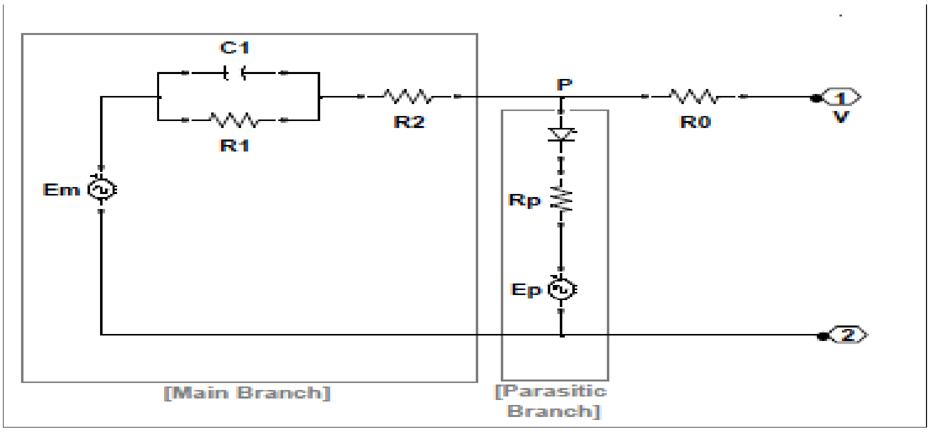

Fig. 3 Battery Equivalent Circuit [9]

To build an accurate equivalent circuit, must have a state of charge-open circuit voltage (OCV) together with resistance values of R1 and R2 integrated in the circuit model as illustrated in Figure 4.

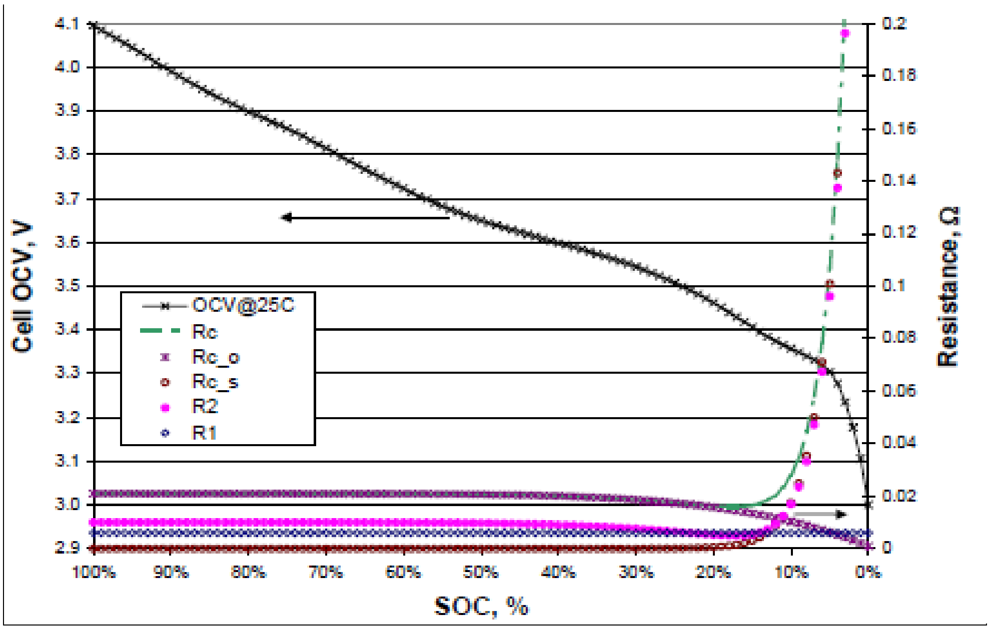

Figure 4: OCV and resistance versus SOC graph required for building an accurate ECM for specific battery [10]

When referring to the energy storage system, two important modes of operation are important which are the duty/mission and storage/standby mode thus they should be included in the model to predict battery lifetime accurately [10]. With enough collected data and comprehension of the lead-acid battery deterioration process, an accurate battery lifetime prediction model can be designed. One of the most common reasons for cell deterioration concerning the battery life cycle is thermal aging and continuous deep discharging and overcharging. In this way, life expectation can be accomplished and approved for both duty/mission and storage/standby periods [11]. Whenever accessible, this subset of information would then be able to be utilized in the ANN display advancement for versatile battery life prediction.

Dynamic Simulator

Based on K. C. Divya et al. [12] states that a dynamic simulator is used which are taken into considerations for the wind speed, solar irradiation, load profile, and operating temperature to predict the battery lifetime of a wind/solar/diesel and battery hybrid power system. The dynamic simulator was designed in Matlab Simulink environment and simulations were done for a whole with steps of 30 minutes.

Figure 5 shows the block diagram used for their dynamic simulator. The dynamic simulator made in the Simulink rain flow counting algorithm is used on the battery SOC to find the depth of charge (DOD) and the duration D K of every operation cycle. At the end of the process, the rate at which the battery degrade per year is calculated. Dimensioning was done based on the site's meteorological data and fuel consumption was also taken into considerations. Several aspects were fixed to reduce the complexity of the model such as load Profile for a year, efficiency of diesel generator, battery, and power electronics components.

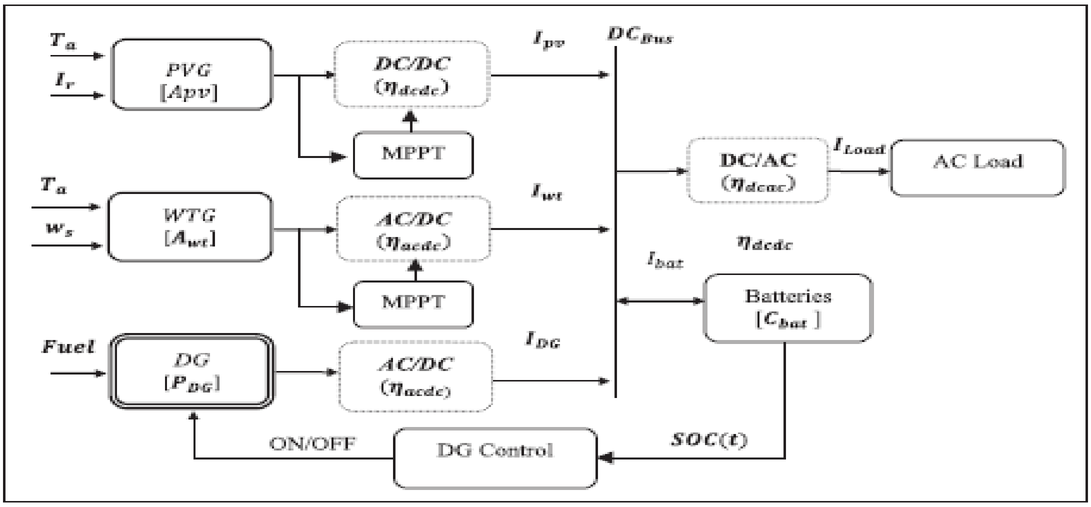

Fig. 5 Block diagram of dynamic Simulator [13]

Figure 6 shows the state of charge (SOC) versus the time graph of the battery obtained from the dynamic simulator. Figures shows also a zoomed part of the graph where the Rainflow algorithm is being applied. Every cycle is represented by the duration and amplitude of the graph. From the results obtained in the dynamic simulator, it was acclaimed that the maximum depth of charge is in winter when the energy produced by solar, and wind is less. In that instant, the diesel generator is turned on.

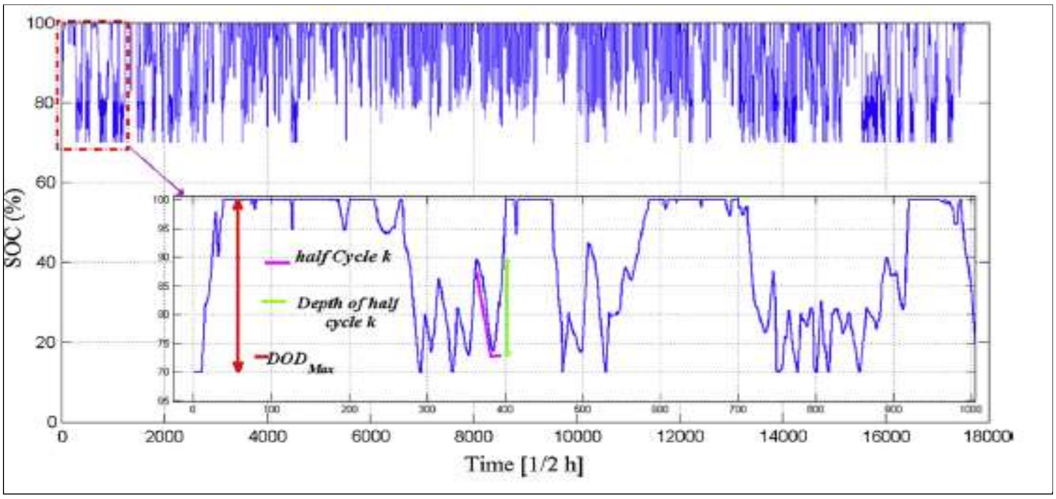

Fig. 6 State of charge of battery versus time [14]

Once the fatigue cycle is obtained from the rain flow counting algorithm, the ageing rate of every cycle is determined using the following equations

First, an expression for the number of cycles based on temperature and depth of charge was developed as shown in Equation (2).

$$N_{c(DOD)T} = \{12850e^{-(9.738+DOD)} + 3210e^{-(1.429+DOD)}.(37.68T^{-1.101} - 0.3897)\} if\ T > 20\,°C \quad (2)$$

After number of cycles were obtain from the Equation (3), its inverse was taken, and the following equation was obtained for aging rate of every cycle (k).

$$Ra_{/C(DOD_k)T_k} = \frac{1}{N_{(DOD_k)T_k}} \quad (3)$$

The cumulated ageing rate is the given by the Equation (4):

$$R_a = \sum_{k-1}^{N_c} {}^{R_a}/_{C(DOD_k)T_k} \tag{4}$$

Where N_c is the number of cycles, T is the temperature, T_k is the absolute temperature, k is the index of cycle and R_a is the ageing rate [15].

Solar Power System

The main power generation source will be from the photovoltaic array which will be modeled in Matlab Simulink. Equation (5) below was used to calculate the number of arrays:

$$number\ of\ array = \frac{maximum\ power\ output\ (kW)}{maximum\ power\ output\ for\ an\ array\ (kW)} \tag{5}$$

For array data as illustrated in Figure 7, the model for the PV array is the Trina Solar TSM-250PA05.08, and as per calculation 1080 PV arrays are required. All the initial data is being assumed according to trusted research material. The maximum power is being recorded at approximately 249W while an open circuit voltage and the maximum power point are stated as approximately 37V and 31V respectively. For cells per module, 60 Ncell is stated while for the short-circuit current and maximum current is being assumed approximately 8A for both currents [16].

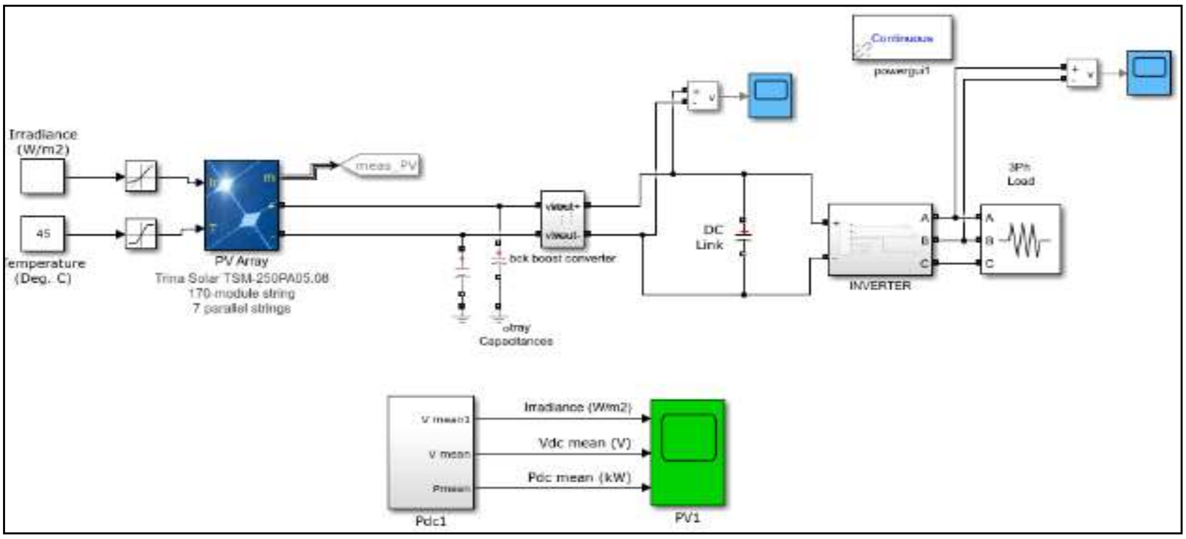

Fig. 7 Solar Power Subsystem [16]

The PV array was connected to a buck-boost converter as the power generated is intermittent. So, the buck-boost convert will step the voltage up or down to meet the required reference voltage of the bus bar. The buck-boost is then connected to an AC to DC converter to provide 3-phase power to the load. Variable values of solar irradiance and a fixed temperature of 45 °C are input parameters to the PV array.

Desired output from the PV is obtained from the 'm' port which is connected to the scope. A dc link is also connected to the bus bar to maintain a stable DC voltage throughout for cases when there is a sudden change from load and high current needs to be supplied to the inverter. It is to be noted that in the hybrid solar system, more array is used to meet low demand as in the model there is no

MPPT, so the solar array will not produce maximum power at all times. Here, 1190 arrays are used whereby there are 7 parallel strings which each contain 170 arrays connected in series.

3.7 Inverter

An inverter was designed as well in Simulink to convert the DC voltage to AC voltage. The inverter was designed referring to requirement specification and its parameters were set accordingly. Figure 8 illustrates the inverter built-in Simulink:

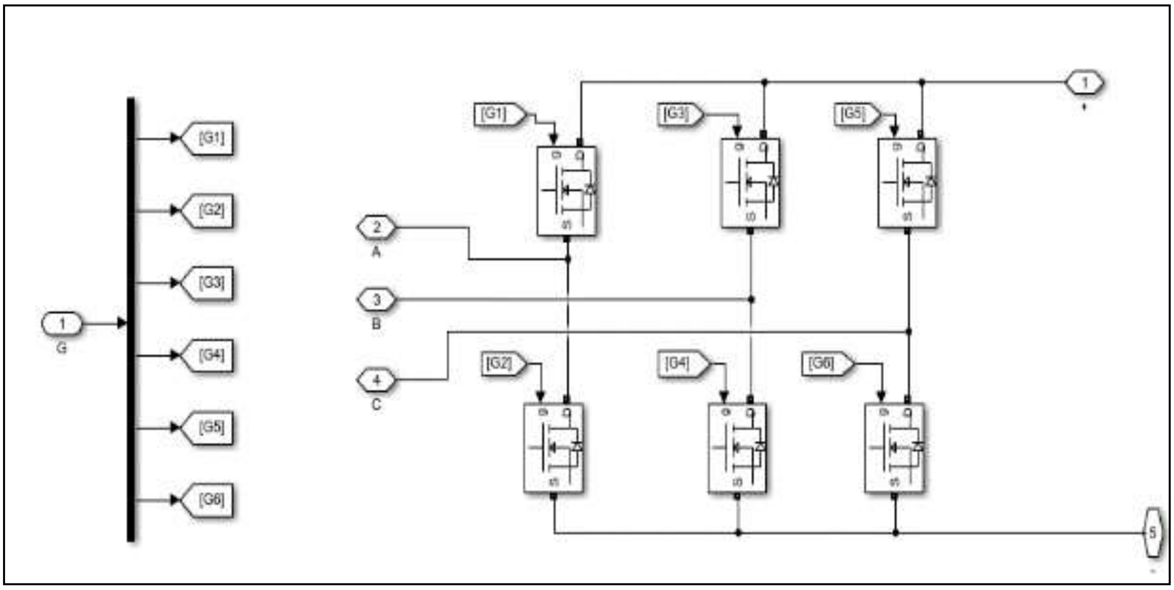

Fig. 8 Inverter block [13]

Figure 9 shows the inverter used for the model which consists of six MOSFET connected. The gate of each MOSFET is connected to a GOTO block from Matlab which is connected to a pulse width modulator. The inverter is connected to an LC filter which will limit the maximum output voltage.

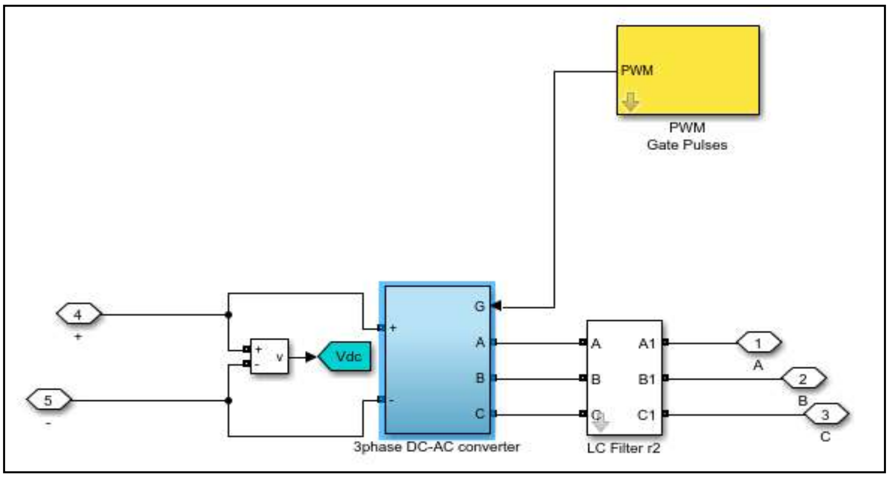

Fig. 9 Inverter and LC filter connection [15]

Overall Connection

Figure 10 illustrates the proposed connection for the solar hybrid power system in Matlab Simulink. It consists of the solar PV subsystem and the battery subsystem which each was built and simulated individually before to verify proper functionality. The PV panel block is connected to the buck-boost converter to step up or step down the voltage to match the reference voltage of the DC bus bar as the solar power is irregular.

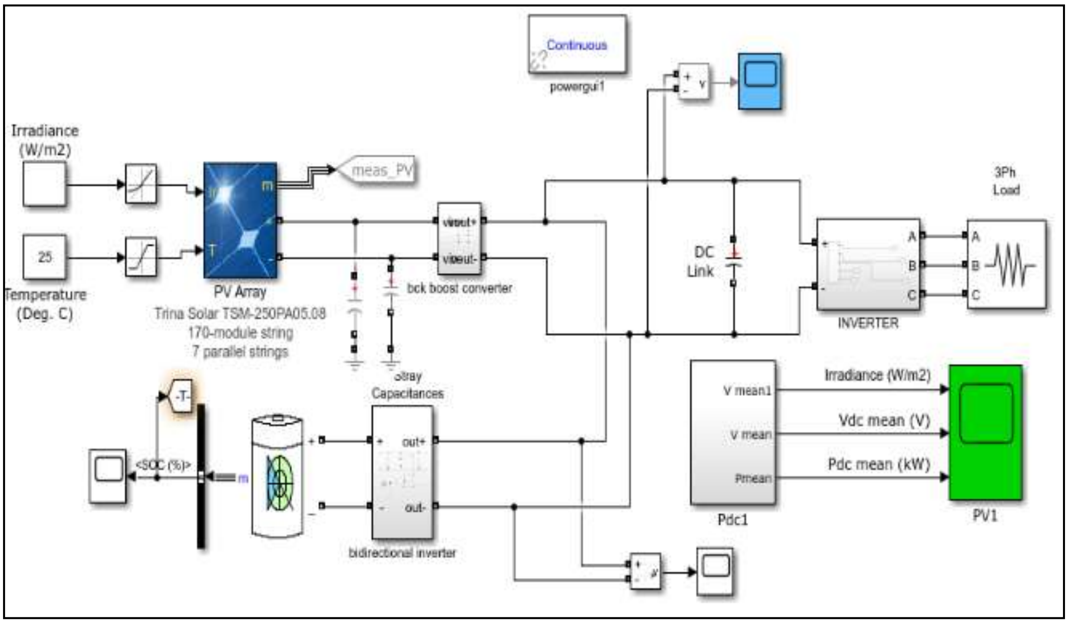

Fig. 10 Overall connection of the system

The battery subsystem is connected to a bidirectional converter which will have a control mechanism that will monitor the charging and discharging of the battery based on the battery SOC, power generation, and load demand. The DC voltage from the bus bar is supplied to the AC load with the help of an inverter. Finally, a power GUI is added as it is required to perform simulation in Simulink.

Rainflow Counting Algorithm

After the model is successfully built-in Matlab Simulink that is the SOC against time graph has been generated, the rain flow counting algorithm will be used to extract the fatigue cycle from the graph. A code will have to be written in Matlab itself in which SOC site data can be imported as well to extract the fatigue life cycle.

Figure 11 show that how the rain flow counting algorithm is used to extract the fatigue cycle [17]. According to Yang et al. [18] states that rainflow counting estimates the number of load change cycles as a function of cycle amplitude. The graph every cycle in the graph contribute to the overall deterioration of the battery thus the ageing of the battery as well. The way fatigue analysis works is by examining the total damage for a particular object which stress changes cyclically. The breakdown point of the object will depend on the amplitude of the cycle.

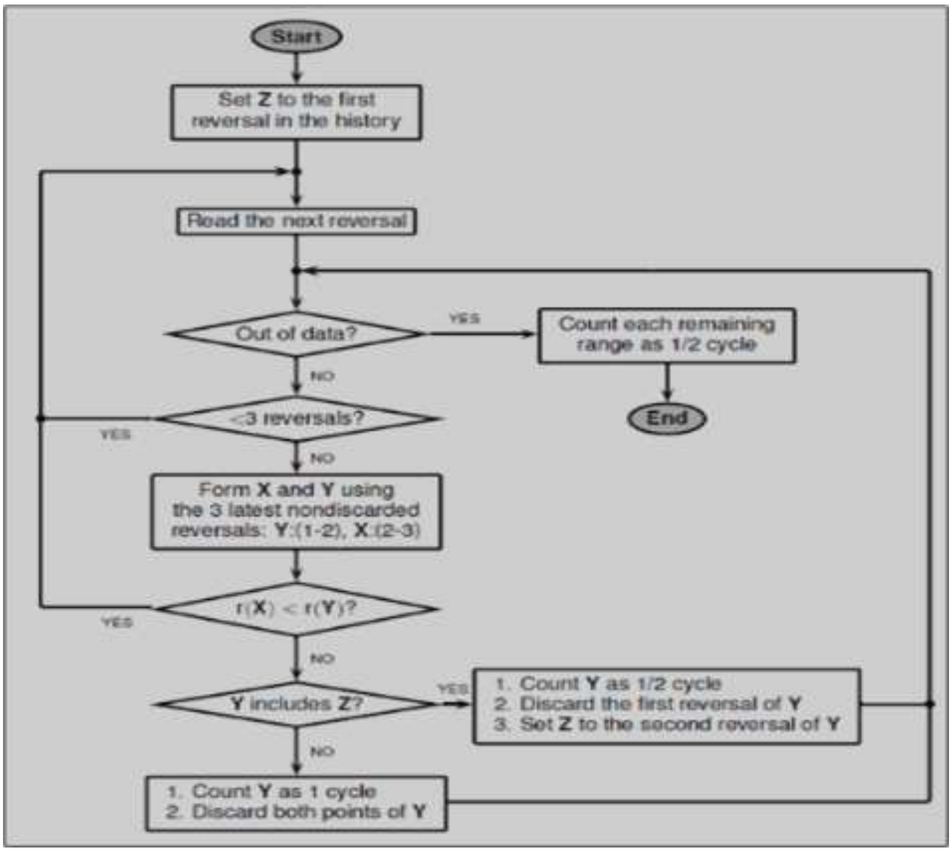

Fig. 11 Rainflow counting algorithm flowchart [17]

Result and Discussion

Meteorological Data

Solar irradiance data is essential as it is a main input to the dynamic system as it is directly proportional to the amount of power produced by the solar panels. The monthly solar irradiance from NASA database obtain using the Metronome of the selected site location to calculate the daily monthly average solar irradiance.

Dynamic Simulator

The load was represented using a dynamic load which would vary around the real site values for load demand. In the daytime when the irradiance is high, the power generation is higher compared to night time when irradiance is zero due to no sunlight whereby the power generation is low. When power generation is high during the day the battery will charge and at night when there is no sunlight the battery will discharge.

Figure 12 shows the graph of SOC vs time which is the main result from the Simulink design. This SOC graph represents the battery state of charge throughout the whole simulation which was done for three months. As it can be seen the battery is discharging and charging according to the logic and conditions set. The SOC as observed varies between 92% and 81%. The SOC data obtain from this graph will be the input to the rain flow counting algorithm which will damage the fatigue life form the cycle of this graph which will then help us to determine the predicted life for the battery.

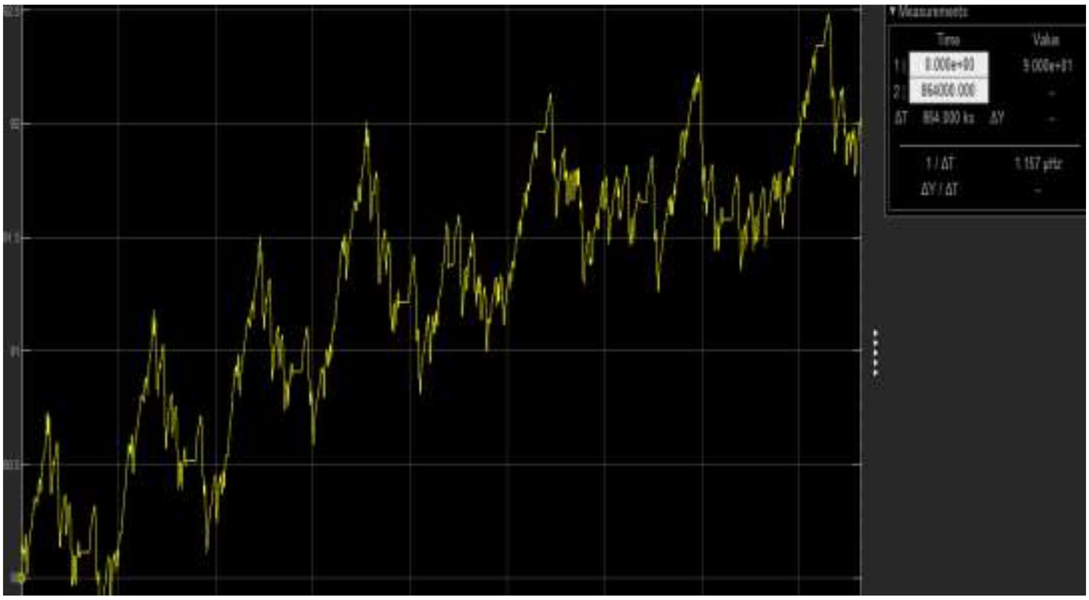

Fig. 12 Simulated SOC Graph

Figure 13 shows the SOC vs time graph. The time history for this graph is around 3 months as well. It can be observed that the battery state of charge varies between 94% and 80%. This graph was plotted using a GUI compiler that extract SOC data from the site log file which was then imported to MATLAB for the Rain Flow algorithm.

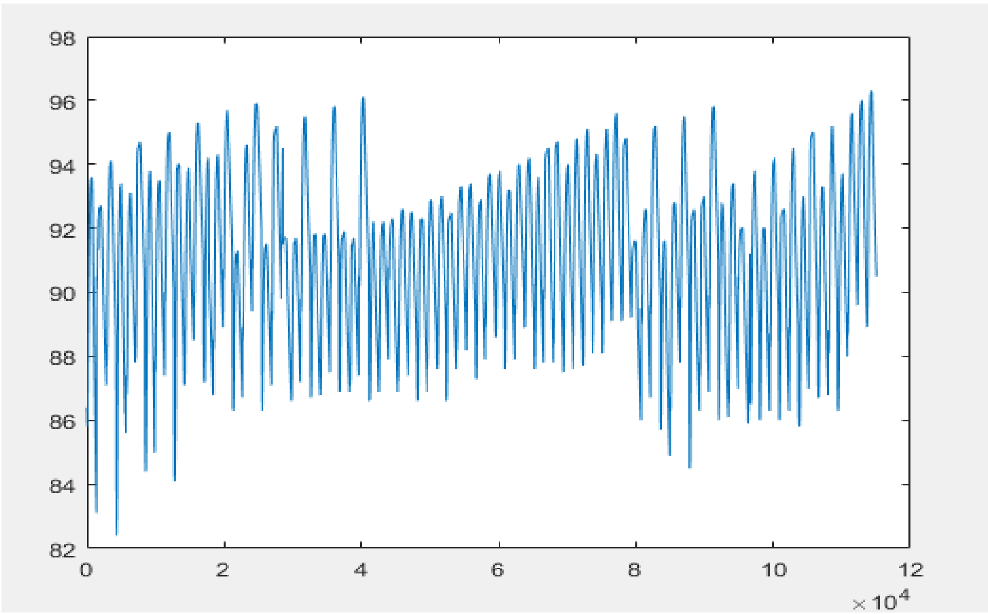

Fig. 13 SOC Graph vs Time

Rainflow Algorithm

Figure 14 shows the same graph as Figure 12. In this graph, the extrema of the graph of SOC vs. Time is found which will also illustrate the turning points of the graph. Once each turning point of the graph is determined, the Rain Flow matrix of amplitudes, mean, and the number of cycles of the graph can be obtained.

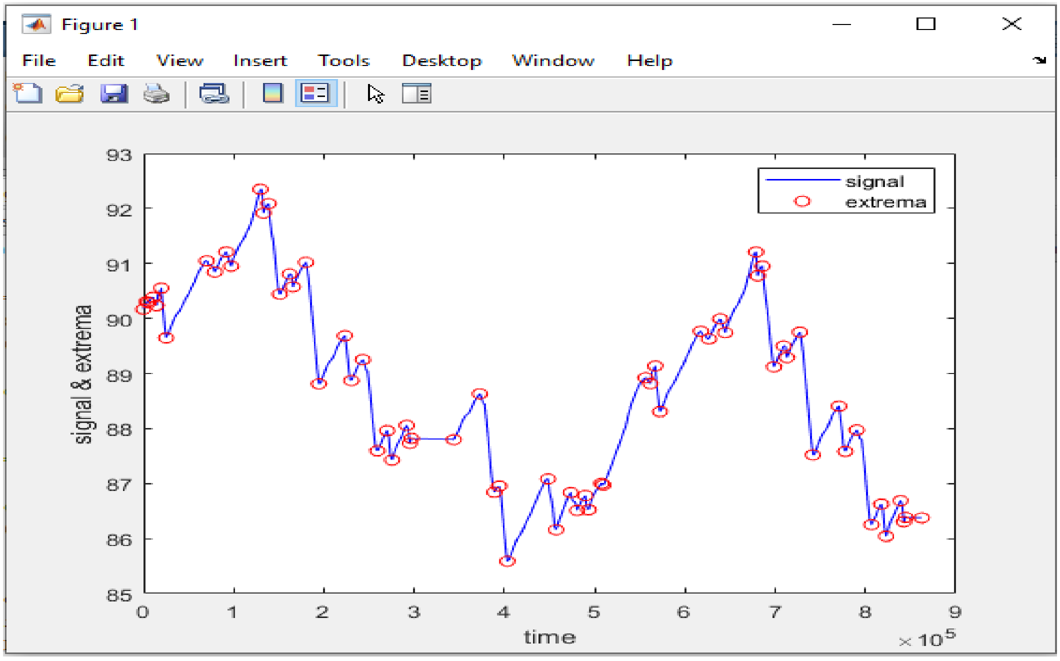

Fig. 14 Simulated Signal and Extrema Graph

Figure 15 is a graph of the Rain Flow matrix. As it can be seen the axes of the graph is the same as the row of the matrix described above which are the mean, amplitude, and the number of cycles. Let's take for example SOC of mean value 88, for this value most of the cycles have an amplitude of 0.1 and the total number of cycles for this value is about 20.

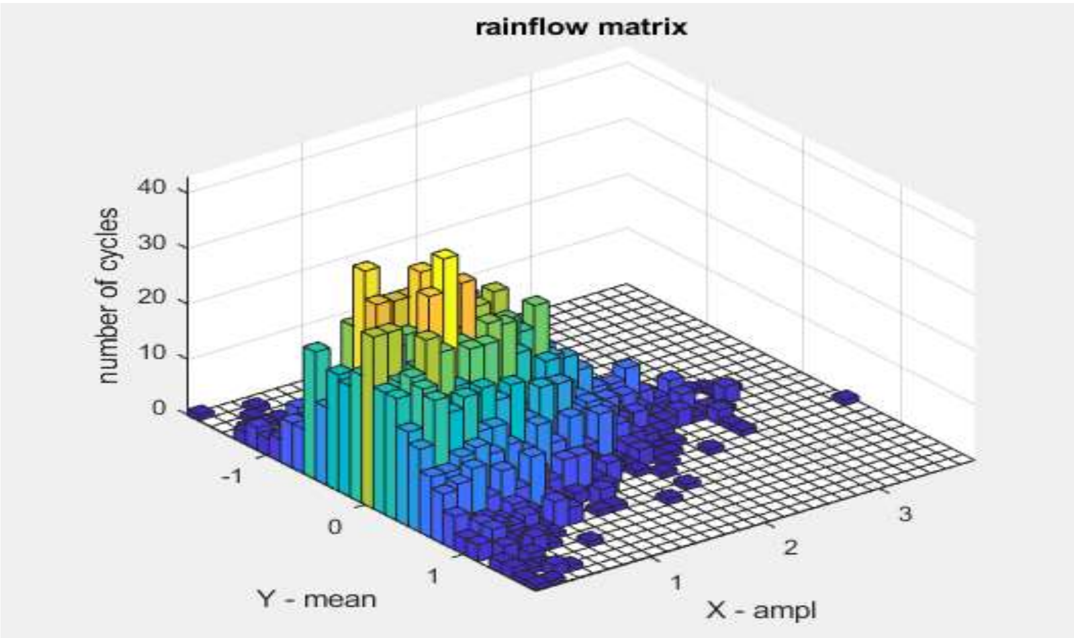

Fig. 15 Simulated SOC Rain Flow matrix Graph

Figure 16 shows the histogram of rain flow data which is a plot of number of cycles vs amplitudes of the cycles. A total of 349 cycles was recorded within which 3.5 are from half cycles. It can be observed that the amplitudes of the rain flow are small for the simulated data.

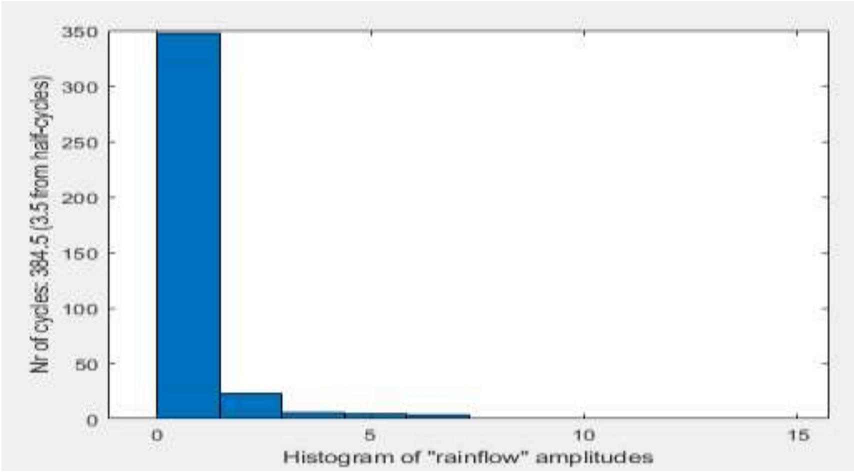

Fig.16 Simulated SOC histogram of rain flow amplitude

Figure 17 is a cross-section of the simulated SOC and Time graph whereby how the cycles are extracted. Once each cycle is extracted, the program determines whether the cycle has a value 0.5 or 1. Then the total number of cycles for the graph is counted.

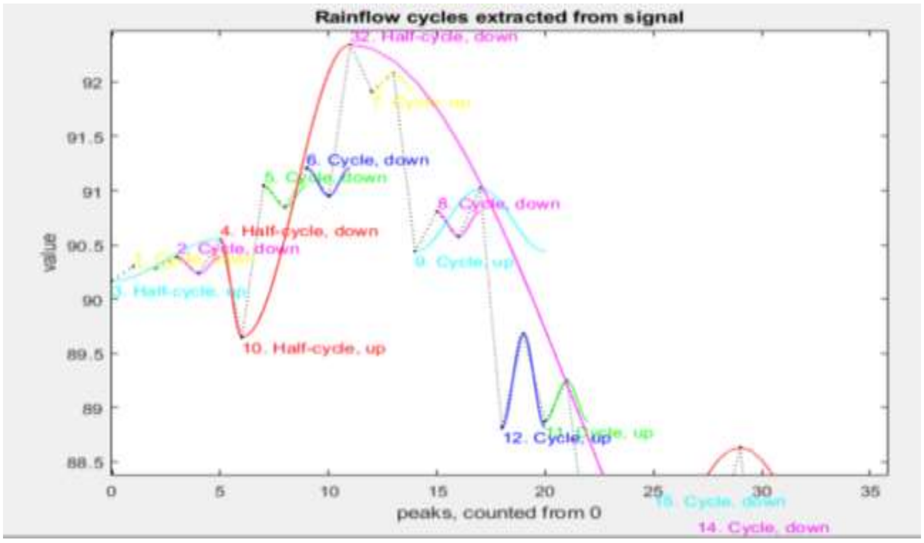

Fig. 17 Simulated SOC cycle extraction Graph

Figure 18 presents the result of the outcome of this whole project which is the battery predicted lifetime. as it can be seen the predicted lifetime of the lead-acid battery is 12.9911 years for the simulated SOC data it as expected and close to the manufacturer prediction which is 12 years.

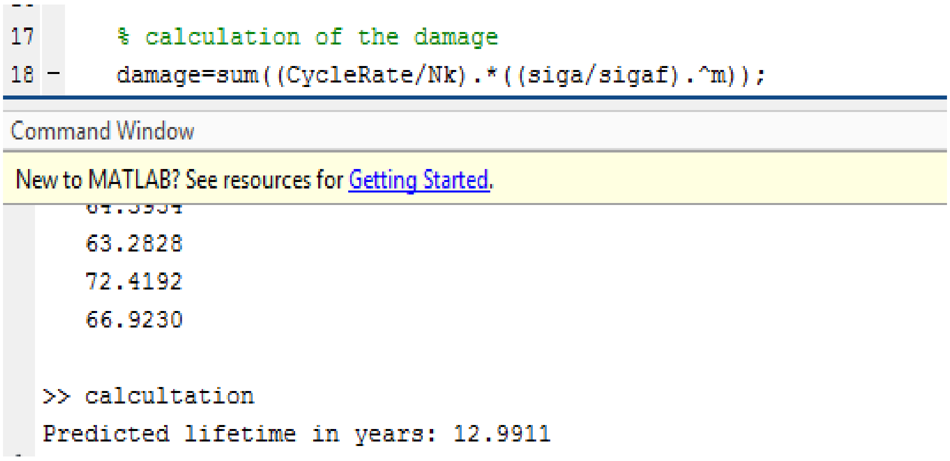

Fig. 18 Simulated Battery Expected Time to Failure Result

Table 2 tabulates the results for lead-acid battery predicted lifetime obtain from the Rain Flow Algorithm. The load history data are also shown as it is essential as it affects the results of the predicted lifetime. As it can be observed the value of battery predicted lifetime varies between 9-13 years which is somehow similar to the manufacturer prediction. This could be due to the limited amount of data obtain from the simulation which is less than four months.

Table 2: Predicted lifetime

Number of days	**Load History(days)**	**Battery Predicted life time (years)**
Simu1ation 1	94	11.7851
Simulation 2	88	13.6184
Simulation 3	59	11.3349
Simulation 4	88	10.7747
Simulation 5	109	9.7801
Simulation 6	95	14.5296
Simulation 7	83	11.735
Simulated data	120	12.9911

Table 3 tabulates the total number of cycles for the different sites analyzed and the simulated data. It is also observed that the number of half-cycles for each simulation is quite low. A relationship that can be pointed out is that the total number of cycles is inversely proportional to the battery's expected lifetime. As an example, it is seen that different simulation has different even though they have similar load histories. Also, from the analysis done from all the results obtained for the Rain Flow algorithm, a relationship was found between the amplitude of the cycles and the Predicted lifetime of the battery.

Table 3: Number of cycles

Number of days	Number of cycles	Number of half cycles
Simulation1	169	3
Simulation2	133.5	3.5
Simulation3	125.5	5.5
Simulation4	268	6
Simulation5	414.5	5.5
Simulation6	156.5	5.5
Simulation7	317.5	7.5
Simulated data	239.5	12.5

Conclusion

In conclusion, this project presents a technique to predict the lifetime of lead-acid batteries installed in solar power systems. A dynamic simulator Simulink was designed in MATLAB Simulink to model the system whereby the SOC graph of the battery was extracted. The design helps us to investigate the aging of lead-acid batteries in the system. Battery management and proper sizing can also be investigated. Thereafter the SOC data was imported into the Rain Flow counting algorithm whereby interesting results. It was found that the deeper the cycle of the charging and discharging of the battery the better the expected time to failure. A predicted lifetime of 8.2795 years was obtained. A proper oversizing of the battery also contributes to a better life.

To improve the battery lifetime, the following objective is taken into consideration component lifetime as a model for the optimization and sizing of renewable systems. The load profile representation in the Simulink design needs to be more accurate as it affects the SOC graph of the battery. More site data load profiles would be required and a way of integrating the changing weather in the system. The logic for the bidirectional DC/DC converter can also be improved for a smoother SOC graph. Regarding the rain flow algorithm, it will work according to IEEE standard, and that not much improvement is required as compared to the dynamic simulator. Once this improvement is done, the model could be set in the industry to investigate battery aging for different power systems thereby predicting the battery lifetime.

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