Mathematical Modelling and Performance Evaluation of Grid Connected PV System with Hybrid Energy Storage

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Abstract— **In this project Energy storage will play an important role in the integration of renewable energy sources. Additionally, hybrid energy storage will be integrated into various systems to achieve different applications. Specifically, the combination of high energy and power ratings, increased life cycle, duration of discharge periods, and other features will not be satisfied by a single storage technology. There will be several storage technologies that can be used in a photovoltaic (PV) system. This will focus on the mathematical modelling of the hybrid battery supercapacitor storage system. The hybrid storage will combine the advantages of both battery and supercapacitor storage. Also, supercapacitors will reduce stresses on battery storage and thus extend their battery life. Furthermore, the proposed algorithm will supervise the battery state of charge (SOC) and satisfy the highest priority load demand under different situations. The next step will be to integrate the hybrid battery-supercapacitor storage into a grid connected PV system which increases clean energy generation. The proposed mathematical model will be implemented using MATLAB/Simulink.**

Keywords— *Hybrid energy storage, supercapacitors, lithium-ion, battery, photovoltaics, modeling, Simulink*

I. INTRODUCTION

The increasing demand for renewable energy sources has led to a significant expansion of photovoltaic (PV) systems worldwide. These systems harness solar energy and convert it into electricity, offering a sustainable alternative to conventional fossil fuels.

However, the intermittent nature of solar power generation poses challenges for grid stability and reliability. To address this issue, energy storage systems (ESS) have emerged as a promising solution, enabling the integration of renewable energy into the grid more effectively.[1]

Hybrid energy storage systems, combining different energy storage technologies such as batteries, supercapacitors, and flywheels, offer enhanced performance and reliability compared to standalone storage systems. By integrating hybrid ESS with grid-connected PV systems, it is possible to mitigate the intermittency of solar power generation, optimize energy utilization, and improve system efficiency. The mathematical modelling and performance evaluation of grid-connected PV systems with hybrid energy storage play a crucial role in understanding system behavior, optimizing system design, and assessing overall performance.[2]

Through rigorous mathematical analysis and simulation studies, researchers can investigate various aspects of system operation, including energy generation, storage, conversion, and distribution. This research aims to develop comprehensive mathematical models that accurately represent the dynamics of grid-connected PV systems with hybrid energy storage. A simple schematic block diagram for Mathematical Modelling and Performance Evaluation of Grid Connected PV System with Hybrid Energy Storage is shown in Fig 1.

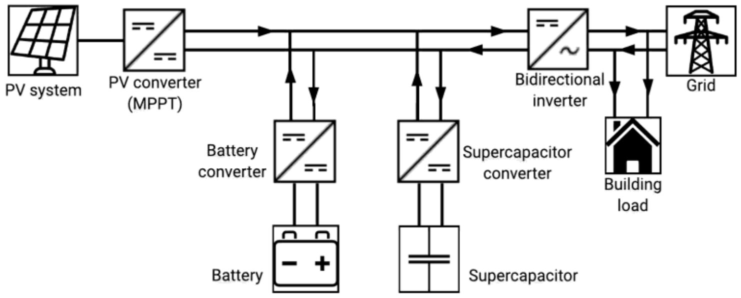


Fig. 1. Schematic Block Diagram of the Proposed System.

The research will develop models accounting for factors like solar irradiance variations, battery characteristics, converter efficiencies, grid interactions, and load demands. These models will enable simulation of diverse operating conditions to evaluate system performance. Evaluation metrics such as energy efficiency, system reliability, grid stability, and economic viability will be employed. Comparative studies will analyze advantages and limitations of different hybrid energy storage technologies and system architectures. The research aims to offer insights into design, optimization, and operation of grid-connected PV systems with hybrid energy storage to enhance efficiency, reliability, and sustainability. Without such systems, challenges like grid instability, voltage fluctuations, and energy wastage persist, hindering renewable energy integration. Hybrid energy storage aims to address solar power intermittency, optimizing energy utilization and grid stability. The research seeks to contribute to making solar power setups more efficient and reliable, utilizing energy storage to ensure continuous electricity production and enhance grid stability. Ultimately, findings will inform the design and implementation of more reliable and practical renewable energy solutions.

II. PROPOSED SYSTEM ARCHITECTURE

A. *Battery and Supercapacitor Model*

The battery and SC banks were modelled using MATLAB and SIMULINK. The implementation models is described in this chapter. Both models allow for bidirectional current flow, meaning that the components can either be discharged (positive currents) or charged (negative currents) at any time during the simulation.[3]

Battery Model :

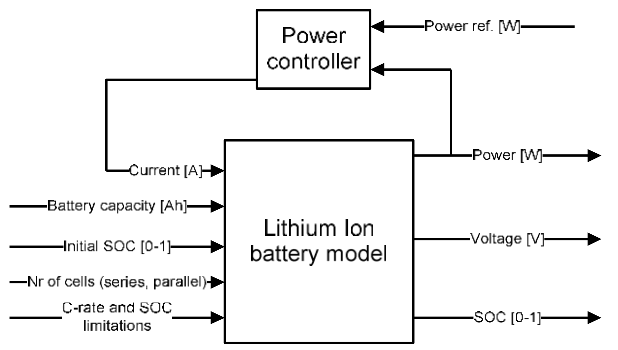


Fig 2. Block diagram of the battery system.

Power controller: The power controller regulates the battery current in order to obtain the required power. Charging/discharging current limits and maximum SOC limitations are also included in the model.

SOC: SOC is nothing but state of charge i.e., the difference between a fully charged battery and the same battery in use. It is associated with the remaining quantity of electricity available in the cell.

$$SOC = \frac{\text{current capacity}}{\text{nominal capacity}} \text{ - - - - - - - (1)}$$

Where, SOC =1 (fully charged;100%) and SOC =0 (discharge)

Number of cells: Battery packs include battery modules, with each battery module containing several battery cells in series, parallel, or series and parallel configuration. Battery cells are connected in series to achieve higher pack voltage, while parallel cells connection is used to achieve higher current and power capability and consequently higher pack capacity. In this paper, our focus is paid on the battery cell model.

<u>EQUIVALENT CIRCUIT BATTERY:</u>

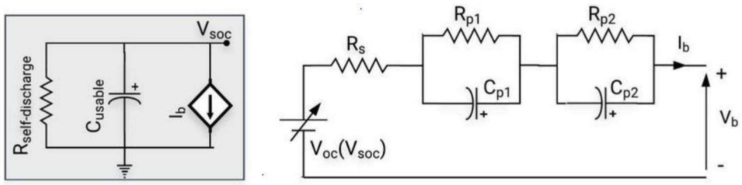


Fig 3. Equivalent circuit-based lithium-ion battery model.

Contains all the typical characteristic curves of the battery in which battery parameters can be calculated. The calculation of all battery parameters is presented and analyzed as follows.

Usable capacity calculation:

The usable capacity of the battery (C_{usable} in Coulombs) represents the charge that a battery can store. Specifically, it is the nominal battery capacity in Ah (C_{init}) multiplied by cycle number-dependent correction factor (f1(N), see Fig. 4(a)) and temperature-dependent correction factor (f2(T), see Fig. 4(b).[4]

$$C_{usable} = 3600.\ C_{init}.f_1(N).f_2(T) \qquad (2)$$

Regarding the capacity fading because of the battery cycle number, the cycle number-dependent correction factor f1(N) can be calculated as below:

$$f_1(N) = 1 - (k_1\sqrt{N})$$

where, N is the cycle number and k1 = 4.5×10^{-3} - - - - - - - - - - - - (3)

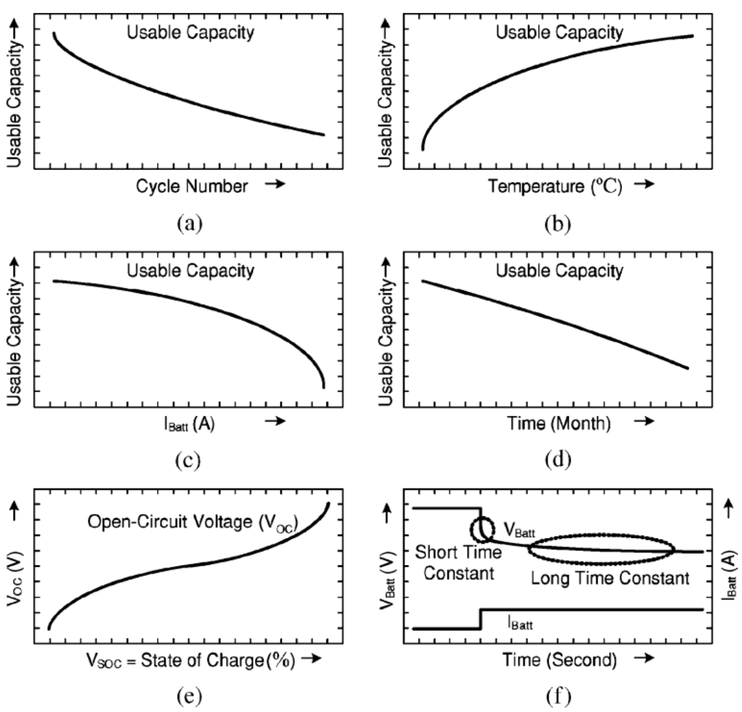


Fig. 4. Battery characteristic curves of usable capacity with respect to: (a) cycle number, (b) temperature, (c) battery current, (d) storage time, (e) open-circuit voltage V_{OC} versus SOC, and (f) transient response to a step load current event

V_{oc} and SOC Calculation :-

$$V_{oc}(SOC) = a_0 + a_1.SOC + a_2.SOC^2 + a_3.SOC^3 \text{ - - - - - - - - - (4)}$$

Where a_0, a_1 and a_3 are constant values.

$\alpha0 = 3.2416$, $\alpha1 = 1.3905$, $\alpha2 = -1.3781$ and $\alpha3 = 0.9206$.

$$SOC = SOC_0 - \int \frac{Ib}{Cusable}\,dt \text{ - - - - - - - - - - - - - - - (5)}$$

Where SOC_0 is the initial SOC of the battery ($0 \le SOC \le 1$).[5] [6]

RC Calculation:

The values of Rs, Rp1, Rp2, Cp1 and Cp2 depend on the battery current and SOC. The following general functions correspond to the RC parameters related to SOC

$$Rx = y0e\text{-}y1.SOC + y2$$
$$Cx = z0e\text{-}z1.SOC + z2$$

Where x = (s, p1, p2), y = (p1, p2) , $R_s = 0.0314\ \Omega$, $R_{p1} = 0.0181\ \Omega$ $R_{p2} = 0.0281\Omega$, $C_{p1} = 1712$ F, $C_{p1} = 1712$ F, $C_{p2} = 55257$ F

Supercapacitor Model :

A supercapacitor, also known as an ultracapacitor or electrochemical capacitor, is an energy storage device that bridges the gap between conventional capacitors and rechargeable batteries. Supercapacitors are valued for their high-power density, rapid charge and discharge rates, and long cycle life, making them useful in applications where quick bursts of energy are required, such as in hybrid vehicles, renewable energy systems, and consumer electronics. [7]

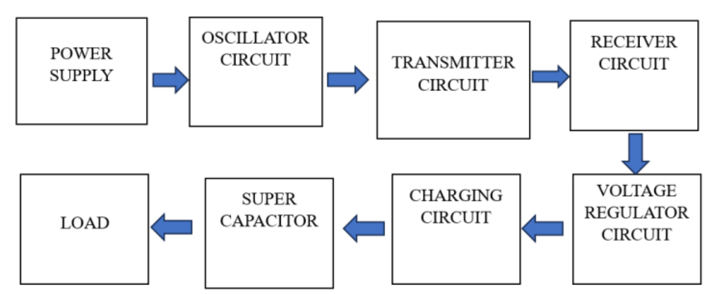


Fig 5. Block Diagram of Supercapacitor

Transmitter circuit:

A transmitter circuit is a fundamental component in communication systems, responsible for converting information into electromagnetic waves or signals that can be transmitted over a medium, such as air or cables.

Receiver circuit:

A receiver circuit is an essential component in communication systems that captures and processes electromagnetic signals transmitted over a medium, such as radio waves or electrical cables. Its primary function is to detect, amplify, and demodulate the received signals to extract the original information.

Voltage regulator circuit:

A voltage regulator circuit is used to maintain a constant output voltage regardless of changes in input voltage or load conditions. It is a fundamental component in electronic devices and power supplies, ensuring stable and reliable operation of sensitive components.

Oscillator circuit:

An oscillator circuit is an electronic circuit that generates periodic, repetitive waveforms, such as sine waves , square waves, or triangular waves, without the need for an external input signal. Oscillator circuits are widely used in various applications, including signal generation, clock generation, frequency synthesis, and modulation.

Equivalent Circuit of Supercapacitor :

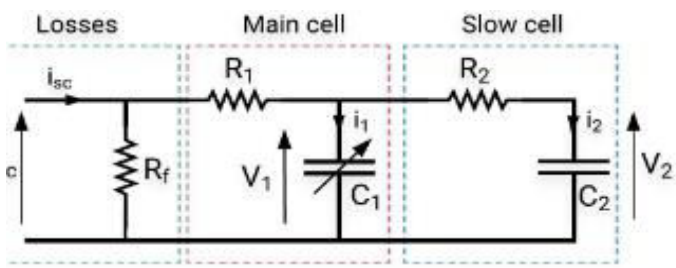


Fig 6. Two branches equivalent circuit of a supercapacitor cell

The calculation of all supercapacitor parameters as follows

Calculation :

In the main branch, R1 is the series resistance and represents the waste power for internal heating on charging and discharging (mΩ). The capacitor C1 depends on the voltage V1 as expressed in (1), where C0 is the constant capacitance in Farads (F) and Cv is the constant parameter.[8]

$$c_1 = C_0 + C_v v_1 \quad (1)$$

The parallel resistance R f describes the leakage current when the supercapacitor is in standby mode (kΩ× 10 2). This self-discharge property can be neglected for fast charge and discharge cycles . Equation (2) represents the voltage Vsc of the supercapacitor module.[9]

$$v_{sc} = N_S U_{SC} = N_S (V_1 + R_1 \frac{I_{SC}}{N_P}) \quad (2)$$

where N s and Np are the number of supercapacitor cells in series and parallel connection, respectively. Also, U_{SC} is the cell voltage and Isc is the current of the supercapacitor module.

Concerning the slow cell, the voltage V_2 can be expressed

$$v_2 = \frac{1}{c_2} \int \frac{1}{R_2} (V_1 - V_2) dt \quad (3)$$

The voltage V_1 across the capacitor C_1 on the main cell is given by:

$$V_1 = \frac{-c_0 + \sqrt{C_0^2 + 2C_V + Q_1}}{C_V} \quad (4)$$

Where Q1 is the instantaneous charge of C1 and can be calculated by:

$$Q_1 = C_0 V_1 + \frac{1}{2} C_V V_1^2 \quad (5)$$

Where $R_1 = 0.29\text{m}\,\Omega$, $R_2 = 1.92\,\Omega$, $c_0 = 2100\text{F}$, $c_v = 623\text{F/V}$ $C_2 = 172$ F

III . PROPOSED SYSTEM CONTROL ALGORITHM

Mathematical Modeling:

This step involves developing mathematical equations that describe the behavior of the grid-connected PV system with hybrid energy storage. This includes modeling the behavior of the PV panels, the power electronics (inverters, converters), the grid connection, and the hybrid energy storage system (which could include batteries, supercapacitors, etc.).

Control Algorithm Design:

Based on the mathematical model, control algorithms are designed to optimize the operation of the system. This includes algorithms for maximum power point tracking (MPPT) to extract the maximum power from the PV panels, algorithms for energy management to control the charging and discharging of the energy storage system, and algorithms for grid interaction to ensure stable and efficient operation while interacting with the grid.[10]

Simulation and Performance Evaluation:

Once the control algorithms are designed, they are usually tested using simulation software. Simulation allows researchers to evaluate the performance of the system under various operating conditions, including different levels of solar irradiance, load demand, and grid conditions. Performance metrics such as efficiency, response time, stability, and reliability are assessed to determine the effectiveness of the control algorithms.

Experimental Validation:

After successful simulation, experimental validation may be conducted using a real-world prototype of the grid-connected PV system with hybrid energy storage. This step helps to verify the performance of the control algorithms under actual operating conditions and identify any discrepancies between the simulation and reality.

Performance Optimization:

Based on the results of simulation and experimental validation, the control algorithms may be further optimized to improve the performance of the system. This iterative process may involve fine-tuning the control parameters or even redesigning the algorithms to address any shortcomings or inefficiencies.

IV. CONFIGURATION OF THE PROPOSED SYSTEM

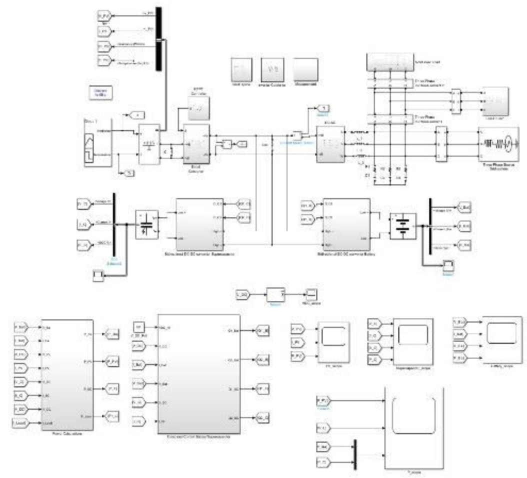
For modelling, simulating, and analyzing electrical systems. It supports linear and nonlinear systems, modelled in continuous time, Simulink is a simulation and model based design environment for dynamic and embedded systems, integrated with MATLAB. Simulink, also developed by Math Works, is a data flow graphical programming language tool for modelling, simulating and analyzing multi-domain dynamic systems. It is basically a graphical block diagramming tool with customizable set of block libraries.

It allows you to incorporate MATLAB algorithms into models as well as export the simulation results into MATLAB for further analysis.

Simulink supports −

- System- level design
- Simulation

Simulink is started from the MATLAB command prompt by



entering the following command: Simulink

Fig 7. Simulation Diagram of Proposed System

V. RESULTS AND DISCUSSION

The performance of PV cell, Supercapacitor, Battery and Grid connected hybrid energy storage voltage, current, state of charge are shown in Fig 8,9,10,11

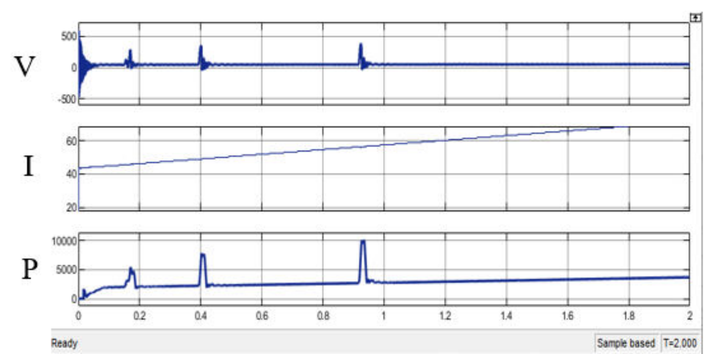
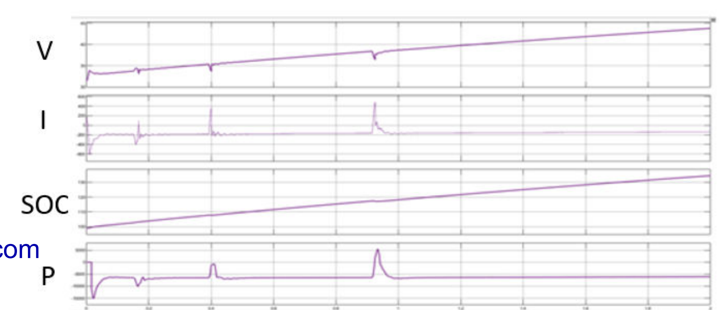


Fig 8. Performance of PV cell

Fig 9. Performance of Supercapacitor



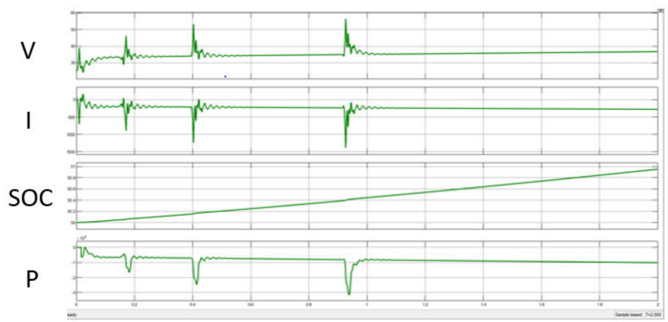


Fig 10. Performance of Battery

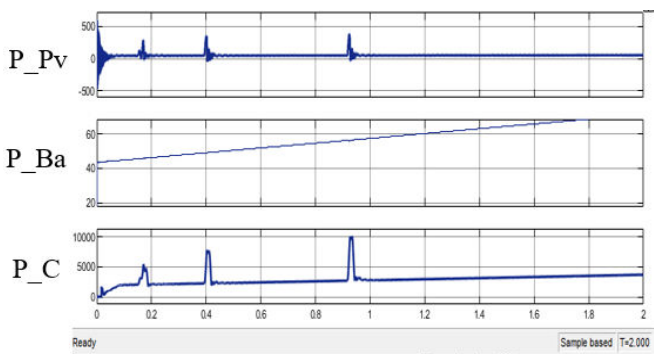


Fig 11. Performance of Grid connected hybrid energy storage

VI. CONCLUSION

Hybrid energy storage can be integrated into various systems to achieve different applications. Hybrid storage has significant features in some specific applications compared to single energy storage. In this paper, a mathematical modeling of the supercapacitor and battery call was examined. The supercapacitor cell was analyzed though the two branches equivalent circuit. Regarding the battery cell model, the dual polarization model of two RC networks was investigated.

The hybridization of battery-supercapacitor can be integrated into a system to achieve several solutions in transportation, renewable energy integration and grid support. The proposed system topology of a grid- connected photovoltaic system with hybrid energy storage system. The system must be adjusted to different situations of the weather and be synchronized with the utility grid. An active parallel configuration is used for the battery- supercapacitor model. The battery and supercapacitor modules are connected on the 400 V DC bus (output of PV converter) through two bidirectional DC-DC converters. The DC-DC converter allows the battery and supercapacitor module to have different voltage and controls their energy flow. Several energy managements exist in the literature. Our future goal is to integrate an energy storage control system into the grid- connected photovoltaic system to eliminate power fluctuations and provide energy management, power and voltage smoothing, peak shaving and standby generation in case of a fault on the grid side.

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