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EXTERNAL ENERGY MAXIMIZATION TECHNIQUE FOR OPTIMIZED ENERGY MANAGEMENT IN ELECTRIC VEHICLES WITH HYBRID ENERGY SYSTEM

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ABSTRACT
The Electric Vehicles (EVs) use Energy management System (EMS) for optimizing the performance of energy storage systems consequently improving their efficiency and extending their lifespan. EMS monitors the key parameters such as State of Charge (SOC) and temperature of the energy storage systems and ensures that the battery performance is improved thereby extending its remaining useful life (RUL). Moreover, it regulates the flow of power withing the vehicle power train and its other accessories, also controls the battery energy flow according to the driving conditions thereby maximizing the range of the EV. However, energy management in EVs with multiple energy pose serious challenges such as optimal power distribution, consumption and control of power and coordination amongst the energy systems in feeding the drive train and auxiliary needs. This work proposes a novel External Energy Maximization Strategy (EEMS) to overcome these challenges for efficient EMS. This paper examines the performance of a novel external energy maximization technique for energy management in a Hybrid Energy Systems (HES) involving photovoltaic (PV) systems, lithium-ion batteries, and supercapacitors (SCs) powering the drive train of EV. The results obtained from the study corroborates the effectivity of the proposed strategy in managing the power obtained from the different energy sources
Keyword: Electric Vehicle, Energy management, PV array, SOC.

1. INTORDUCTION
Modern transportation is moving away from the commercially prevalent IC engine-based smoke emitting vehicles to cleaner option such as EVs. Electrification of modern transport is becoming more prominent in the wake of increased environmental pollution globally. Different types of energy storage devices are being used for storing the electrical charge required for propelling the EV drive train. Most commonly used energy storage systems are the batteries; particularly the Lead acid batteries and the Li-ion batteries. Better technologies than batteries are required for obtaining enhanced reliability and better torque characteristics of the drive train in EVs. As a result, hybrid energy sources are being used as alternatives for supplying the power to the drive trains in EVs. The performance of hybrid energy systems involving PV panel, Li-ion battery and super-capacitors are being explored for being used in the modern EVs. These hybrid energy systems require effective EMS for optimal allocation of power amongst the different energy sources on the basis of drive train requirements and their operational limits with the objective of reducing the impact on the battery and other component’s life cycle. This paper mainly focusses on energy maximization (EEMS) approach for energy management of hybrid energy system for EVs [1]. An analysis of this strategy has been performed for a hybrid system involving a PV array a Li-ion battery and a super-capacitor for driving the EV motor. The analysis involves a comparison of the overall system efficiency for this EMS.

The paper's primary contribution lies in providing performance analysis EEMS strategy for EVs comprising a PV array, Li-ion battery and a Super-capacitor. This evaluation considers its impact on overall efficiency and system life-cycle. The paper is organized as follows: introduction is presented in section 1 followed by review of literature about different EMS used in EVs their critical assessment in section 2. Materials and method is presented in section 3 describing the mathematical modelling of each component used in this study. Result and discussions are presented in section 4. Conclusion of the research are presented in section and finally the references are presented.

2. Literature Review

The review of literature related to the various energy management approaches in the EVs containing hybrid energy sources is presented in this section. These reviews will provide a better insight about the key findings obtained from the research works.

(*Bambang et. al., 2014*) tackled the challenges associated with integrating a fuel cell as the primary power source in EVs due to its slow response to sudden load changes. To address this, the study proposed supplementing the fuel cell with a battery and/or supercapacitor to enhance the performance. The research emphasized the importance of current regulation to prolong the lifespan of the energy storage system by controlling current slopes for both the fuel cell and batteries and stabilizing the DC output voltage. To achieve this, a feedback control system was developed for a Hybrid Power Source (HPS) consisting of a fuel cell, batteries, and a super-capacitor.

(*Shen and Khaligh., 2016*) explored two real-time EMS for optimizing current distribution between batteries and ultracapacitors (UCs) in EVs. The first strategy involved solving an optimization problem using Karush-Kuhn-Tucker (KKT) conditions to determine real-time current split points for the Hybrid Energy Storage System (HESS). The second strategy employed a neural network-based intelligent controller. To evaluate performance, a metric based on battery SoH was developed, focusing on the way, instantaneous battery currents affect degradation, particularly from high peak currents and frequent charging/discharging cycles.

(Snoussi et. al., 2018) introduced a specific hybrid electric bus along with a new fuzzy rule-based EMS designed to optimize motor torque during acceleration and cruising phases. Through simulations using a validated EV model and the MLTB drive cycle, the proposed strategy achieved a 2.2% reduction in cumulative fuel consumption compared to the existing energy management system. These results highlighted the strategy's potential to lower fuel consumption and emissions in hybrid electric buses.

(Sankarkumar and Natarajan., 2021) emphasized the essential function of the EMS in EVs, which ensures efficient energy transfer from the power drive to the wheels. By integrating hybridization with optimized EMS, focused on maximizing the use of energy storage systems, improving overall performance and efficiency, extending driving range, and minimizing battery size.

3. Material and methods:

Figure 1 depicted below gives the block diagram of the simulated hybrid energy system driving a BLDC drive train in EVs. Mathematical modelling of each component involved in the system is also presented in the sections below:

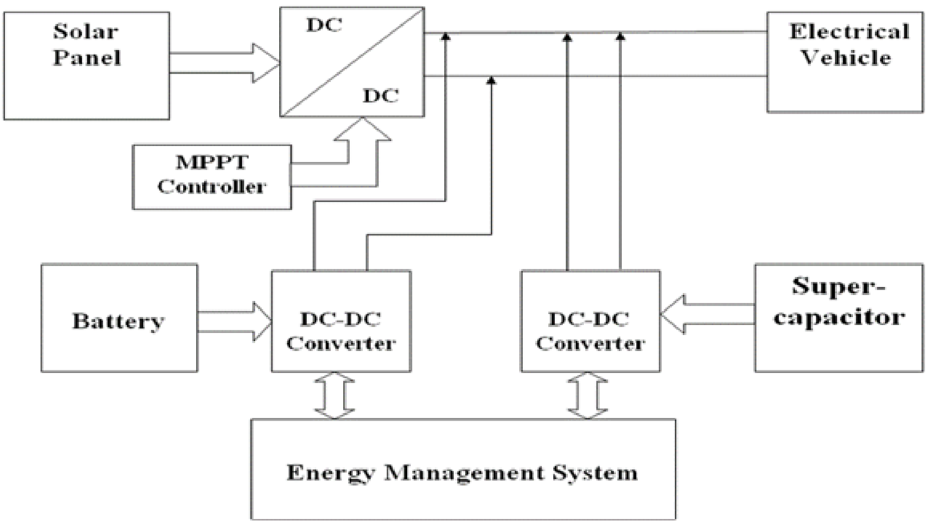

Fig. 1 Functioning block diagram of EMS

The important components of an energy management system are: PV array, super-capacitor, Li-ion battery, power electronic converters, and BLDC drive.

3.1 PV array

Fig. 2 depicts the equivalent circuit diagram of PV cell which is used for modelling the PV array. The mathematical model is represented by a series of equations (1)-(4) and the array design specifications are presented in Table 1.

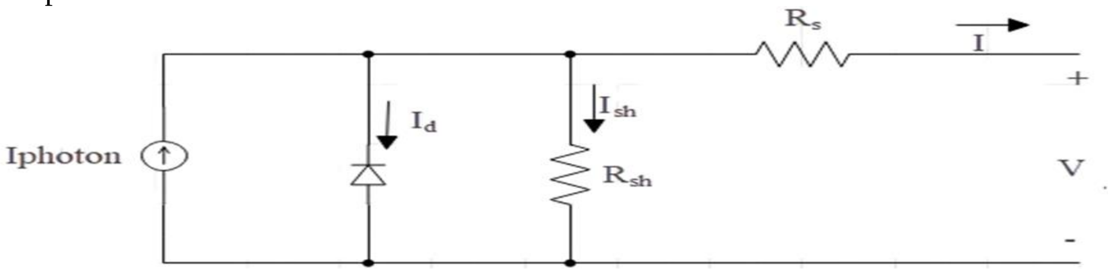

Fig. 2 Electrical equivalent circuit of PV cell

Equation 1 gives the module photo current in the PV array.

$$I_{photon} = [I_{SC} + k_I(T - 298)] \times \frac{I_r}{1000} \quad (1)$$

Where, I_{photon} is photo current (A); I_{SC} is short circuit current (A); k_I is short circuit current of cell at 25°C and 1000 W/m^2 and T is operating temperature (k); I_r is solar irradiation (W/m^2).

Module reverse saturation current I_{rs} is described by equation (2)

$$I_{rs} = \frac{I_{sc}}{[exp(\frac{qV_{OC}}{N_S K n T}) - 1]} \quad (2)$$

where, q is electron charge which is 1.6×10^{-19}C; V_{oc} is open circuit voltage (V); N_s is number of cell connected in series; n is ideality factor of the diode; k is Boltzmann's constant which is 1.38×10^{-23}J/k.

The diode I-V characteristic is defined by equation (3) and (4)

$$I_{diode} = I_o \left[exp\left(\frac{V_d}{V_T}\right) - 1\right] \quad (3)$$

Where, I_{diode} is diode current; I_o is diode saturation current; V_d is diode voltage (V); V_T is terminal voltage (V).

$$V_T = \frac{kT}{q} \times n \times N_{cell} \quad (4)$$

where, N_{cell} is number of cells connected in series in a module

The table 1 shows the design specification of PV array:

Table 1: Design specification of PV array.

Design specification	Values
Parallel string	2
Series connected modules per string	1
Cell per module (N_{cell})	72
Open circuit voltage (V)	44.7
Short circuit current (A)	8.78
Temperature coefficient of Voc (%/0c)	-0.4051
Temperature coefficient of Isc (%/0c)	0.075604
Voltage at maximum power point (V)	36.1
Current at maximum power point (A)	8.31

3.2 Supercapacitor Model

The supercapacitor is modelled on the basis of equivalent circuit depicted in fig. 3 below. The parameters used for modelling are given in Table 2. SC stores the electrical charge and offers high-power density, making it useful in specific applications such as EVs. Unlike batteries, SCs have a lower energy density but offer higher power density [2],[3].

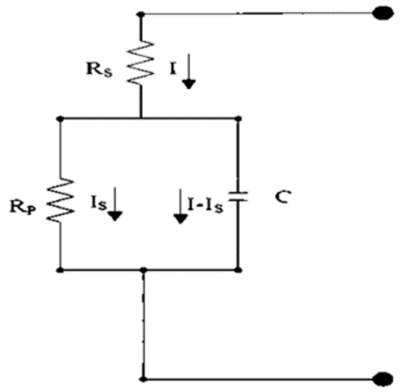

Fig. 3: Electrical equivalent circuit of SC

The SCs output voltage is expressed in equation (5)

$$V_{Supercap} = \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0} + \frac{2 N_e N_s RT}{F} \operatorname{Sinh}^{-1}\left(\frac{Q_T}{N_p N_e^{\,2} Ai \sqrt{8RT\varepsilon\varepsilon_0 C}} \right) \tag{5}$$

Where, A_i is interfacial area between electrodes and electrolyte (m^2), I_{sc} is SC current (A), V_{sc} = SC voltage (V), C_T is Total capacitance (F), R_{sc} is the total resistance (ohms), C is Molar concentration (mol/m^3), R is Molecular radius (m), F is Faraday's constant, N_e is number of layers of electrodes, N_A is Avogadro constant, N_p is number of SC connected in parallel, N_s is number of SC connected in series, Q_T is electric charge (C), R is the Ideal gas constant, d is the molecular radius, T is the operating temperature (ºK), E is the permittivity of material and ε_0 is the permittivity of free space[2],[3]. Table 2 given below presents the design specification of SC:

Table 2: Design specification of SC.

Design specification	**Values**
Rated capacitance (F)	15.6
Equivalent DC series resistance(ohm)	0.150
Rated voltage(V)	290.6
Number of series capacitance	2
Number of parallel capacitance	5

3.3 Battery Model

Li-ion battery is modelled on the basis of equivalent circuit depicted in fig. 4. The charging and discharging behavior of the battery are modelled as per equation (6) and (7) and the design parameters given in Table 3.

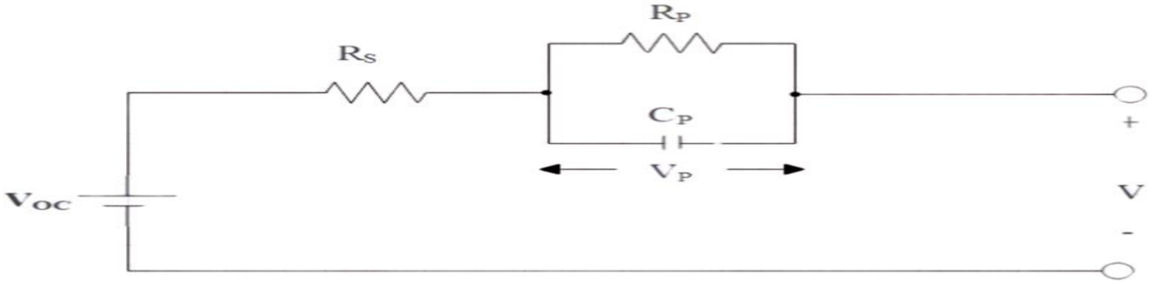

Fig. 4: Electrical circuit model of Li-ion battery.

For charge model (I^0>0)

$$F_1(it, I^0, I) = E_0 - K\frac{Q}{Q-it}I^0 - K\frac{Q}{Q-it}it + A.Exp(-B.it) \qquad (6)$$

For discharge model (I^0<0)

$$F_1(it, I^0, I) = E_0 - K\frac{Q}{0.1Q+it}I^0 - K\frac{Q}{Q-it}it + A.Exp(-B.it) \qquad (7)$$

Where, E_0 is constant voltage in V, Exp(s) is exponential zone dynamics in V, Sel(s) is battery mode, Sel(s) is 0 (during battery discharge), Sel(s) is 1 (during battery charging), K is polarization constant in V/Ah, I^0 is low-frequency current dynamics in A, I is battery current in A, it is extracted capacity in Ah, Q is maximum battery capacity in Ah, A is exponential voltage in V and B is exponential capacity in Ah^{-1}[4].

Table 3: Parameter specification of Li-ion battery.

Design specification	Values
Nominal voltage(V)	48
Rated capacity (Ah)	343.75
Initial SoC (%)	65
Battery response time(s)	1
Maximum capacity (Ah)	300
Cut off voltage(V)	36

3.4 Modeling of Converters

The equivalent circuits depicted in figs. 5 and 6 are used for modelling the buck-boost power converters in this work. The converters, in a drive system are used for controlling the flow of energy from battery and other energy sources in a hybrid energy system [3], [4].

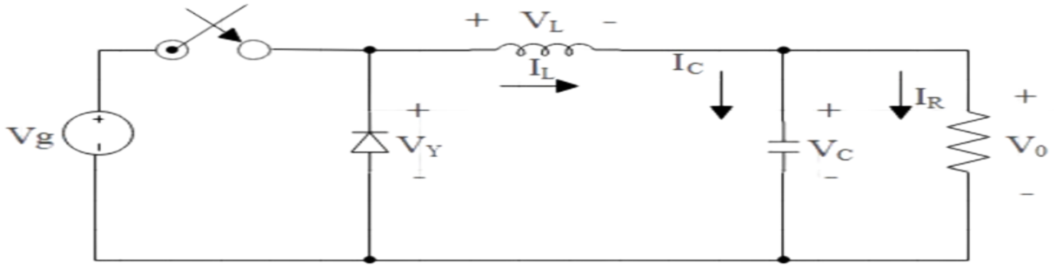

Fig. 5: Schematic diagram of buck converter

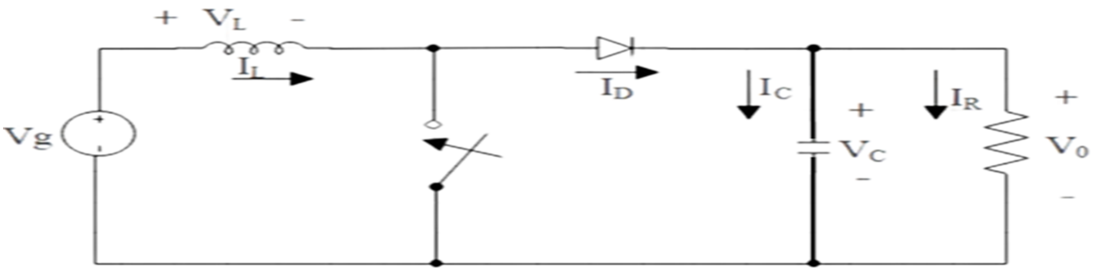

Fig. 6: Schematic diagram of boost converter

3.5 Modeling of Electric Drive

The EV drive train used in this work contains a brushless DC(BLDC) motor having trapezoidal shaped back emf. The trapezoidal shape is due the similar shape of the curve between the mutual inductance of the stator and the rotor for single rotation of the rotor [2],[3],[4]. Three phase variables namely a,b,c has been used for the modelling of the motor instead of using conventional two phase d-q variables. The assumptions such as neglecting magnetic circuit saturation, assuming equal and constant stator resistance, self-inductance, and mutual inductance for all phases, disregarding hysteresis and eddy current losses etc. has been used for creating this model. The Phase voltage equations representing BLDC motor is given in equation 8 to 14:

$$V_a = Ri_a + (L - M)\frac{di_a}{dt} + E_a \quad (8)$$

$$V_b = Ri_b + (L - M)\frac{di_b}{dt} + E_b \quad (9)$$

$$V_c = Ri_c + (L - M)\frac{di_c}{dt} + E_c \quad (10)$$

Torque equations are each phase of BLDC motor are given in equations (11)-(14):

$$T_a = K_t.i_a.f.(\phi_e) \quad (11)$$

$$T_b = K_t.i_b.f.\left(\phi_e - \frac{2\pi}{3}\right) \quad (12)$$

$$T_c = K_t.i_c.f.\left(\phi_e - \frac{4\pi}{3}\right) \quad (13)$$

The electromagnetic torque is

$$T = T_a + T_b + T_c \quad (14)$$

3.5 Equivalent Energy Maximization Strategy

The EEMS for EVs involving a hybrid energy system containing a solar PV array, a Li-ion battery and a Supercapacitor along with external source is presented in this section. This strategy involves the goal of maximizing the use of external energy sources like grid so that the dependence on internal storage systems and their overall efficiency is maximized [8]. The EEMS checks the parameters such as electricity cost, grid stability and the preference of users. It estimates the energy demand of EV on their driving pattern, routes and user requirements [5],[6],[7]. Optimization algorithms are used for calculating the best allocation amongst the different energy sources for calculating the amount of energy to be drawn from the PV array, battery, SC and external source for meeting the instantaneous energy demands while minimizing the costs for maximizing the use of external energy [8].

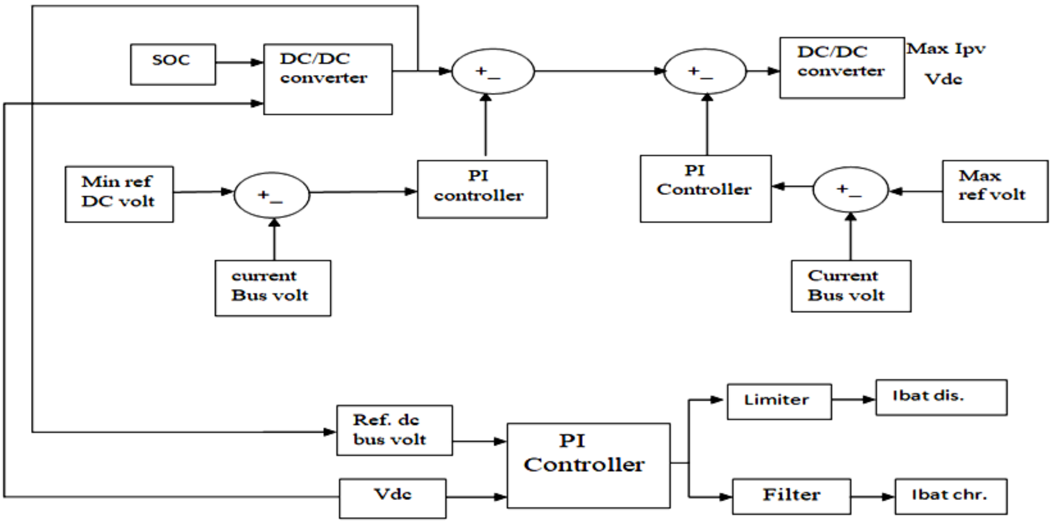

Fig. 7: Block diagram of EEMS

The basic objective of EEMS is to maximize the utilization of external energy while minimizing the costs. Hence, the optimization problem for this objective is defined by the objective function according to equation (15).

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$$F_{\max} = \sum_{t-1}^{T} E_{ext}(t) - \sum_{t-1}^{T} C_{\text{int}}(t) \quad (15)$$

Where,
F_{max} = objective function to maximize external energy usage.
$E_{ext}(t)$ = external energy consumed at time t.
$C_{int}(t)$ = cost or penalty associated with internal energy usage.
The energy balance equation is given by equation (16)

$$E_{load}(t) = E_{PV}(t) + E_{bat}(t) + E_{sc}(t) + E_{ext}(t) \quad (16)$$

Where,
$E_{load}(t)$ = Energy demand of the EV load at time t.
$E_{PV}(t)$ = Energy harvested from the PV array.
$E_{bat}(t)$ = Energy flow to/from the battery.
$E_{sc}(t)$ = Energy flow to/from the SC.
$E_{ext}(t)$ = Energy obtained from the external source.
The equivalent energy consumption is proportional to the battery and SC energy times an equivalence factor (α), where α varies with the battery/SC SOC. In this work, the equivalence factor is represented empirically by equation (17):

$$\alpha = 1 - 2\lambda \frac{(SOC - 0.5(SOC_{\max} + SOC_{\min}))}{SOC_{\max} + SOC_{\min}} \quad (17)$$

Where SOC_{min} and SOC_{max} are minimum and maximum SOC of the battery, λ is the SOC balance coefficient λ = 0.6, the value obtained to achieve a minimum SOC of 60% at the end of the EMS profile, with an initial SOC of 75%. The EMS algorithm is expressed as follows. Get an optimal solution Y= [P_{PV}, α, P_{bat}] which minimizes equation (18)

$$E = [P_{PV} + \alpha.P_{bat}].\Delta T \quad (18)$$

Under the limiting conditions
$P_{PVmin} \leq P_{PV} \leq P_{PVmax}$
$P_{PVmin} \leq PPV \leq P_{PVmax}$
$0 \leq \alpha \leq 2$
Where E is the equivalent energy consumed by the PV array and battery respectively during the sampling time ΔT.

4. Result and Discussion

Figure 9 illustrates the distribution of power among the load, PV array, battery, and SC. Initially, there is a stabilization phase following a sharp increase, likely due to the system activating to meet the demand. The PV array provides a steady contribution, with less fluctuation compared to the other sources, possibly due to the maximization strategy focusing on utilizing external energy sources. The power from the battery and SC exhibits some oscillations, indicating that they are balancing transient imbalances between the load demand and the PV supply.

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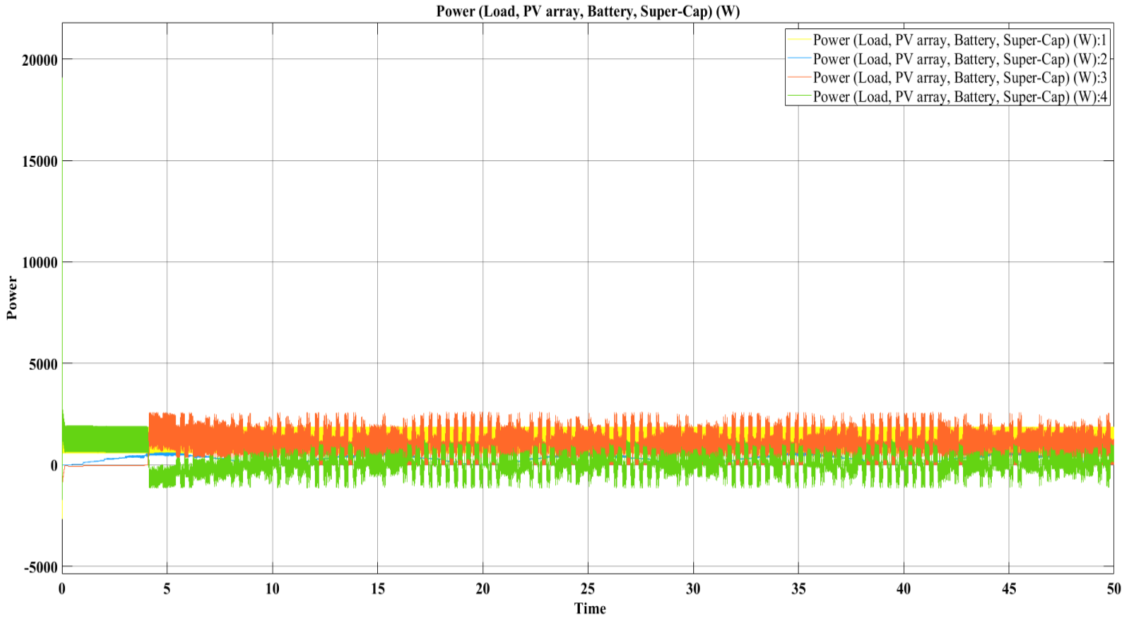

Fig. 9: Power curve of load, PV array, battery, SC in EEMS

Figure 10 illustrates the operating behaviour of the battery in the EMS. Initially, the battery current experiences a sharp spike before stabilizing into consistent oscillations, likely due to the battery alternately charging and discharging according to the control strategy. The battery voltage remains relatively stable with minor fluctuations, indicating a balanced charge-discharge process. Battery current fluctuates between 18 and 60 amperes, starting from zero and gradually increasing over a 50-second period. The SOC shows a steady, linear decline over the 50 seconds, suggesting a controlled discharge rate. This is likely done to optimize the use of external energy while safeguarding battery health. In the third part of the graph, the SOC begins at 65% between 0 and 4 seconds and decreases to 64.85% by the 50th second during the discharge cycle.

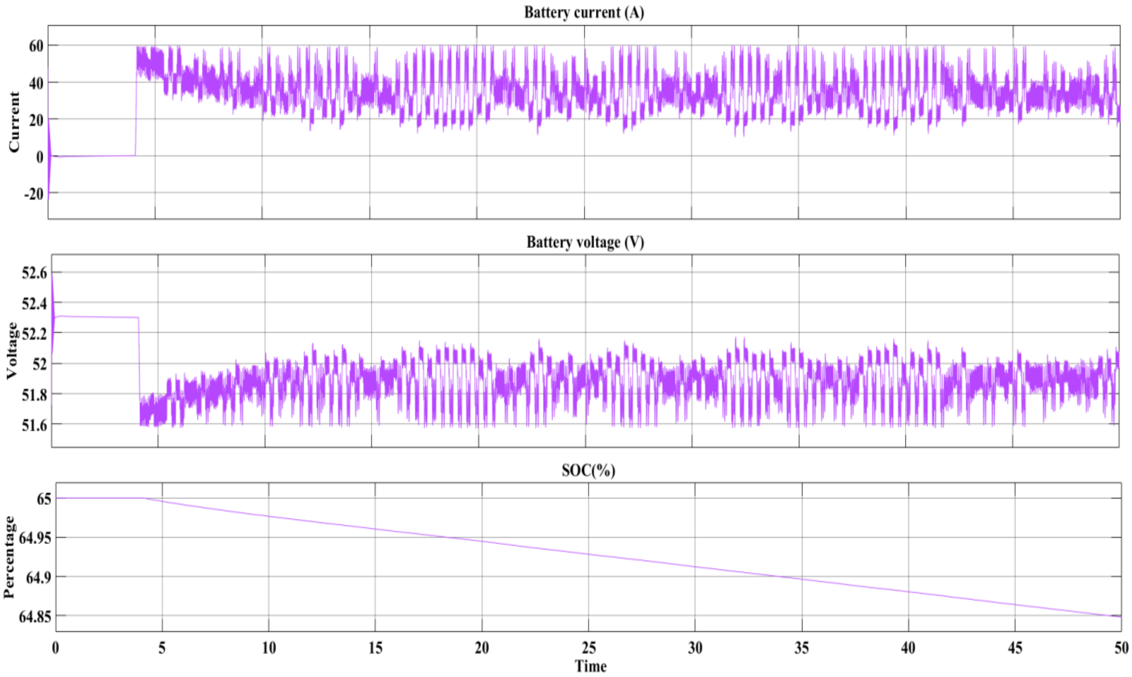

Fig. 10: Battery current, voltage, and SOC curve of EEMS

Figure 11 shows the voltage and current graphs of the converters. Initially, the SC current drops, but then it stabilizes with minor fluctuations for the remainder of the period, reflecting its function in shortterm energy storage and release. The SC voltage decreases slightly before leveling off, indicating that it is maintaining a balance between charging and discharging to help stabilize the system voltage.

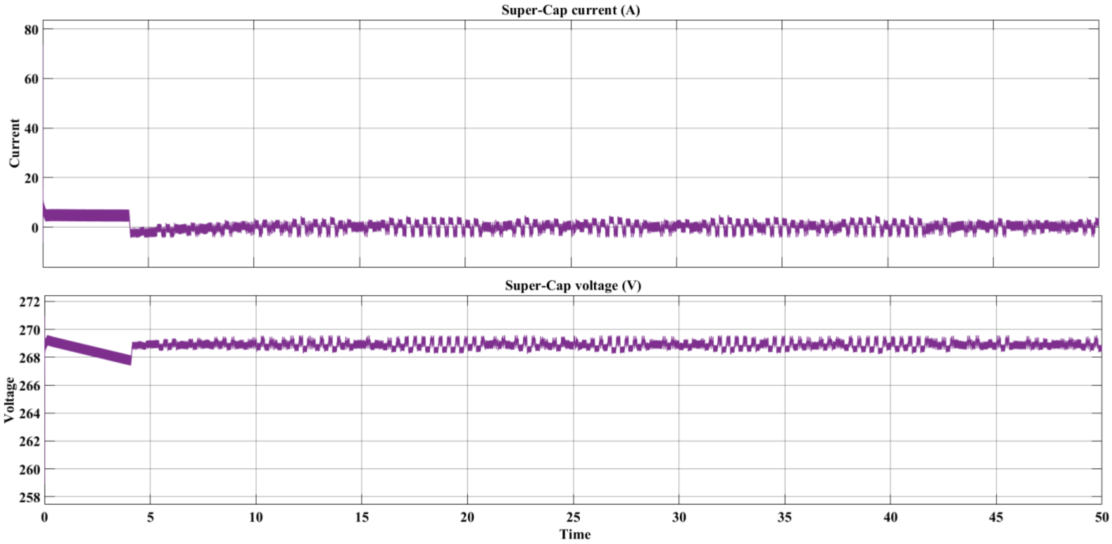

Fig. 11: SC current, voltage curve of EEMS

5. Conclusion:

The EEMS has been designed to maximize the utilization of externally available renewable energy, generated from the PV array, while ensuring that the battery and SC offer stability and backup power as and when required. This strategy effectively balances the use of externally available and stored energy, preserving system stability and managing the health of the components over time. The gradual decrease in SOC and the stable battery voltage indicate that the strategy is also focused on the long-term sustainability of the battery, preventing deep discharges or overcharging.

6. References

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