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Energy management strategy for photovoltaic powered hybrid energy storage systems in electric vehicles

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ABSTRACT

Nowadays, electric vehicles (EVs) using additional energy sources frequently deliver a safe ride without concern about the distance. The energy sources including a battery, an ultra-capacitor (UC), and a photovoltaic (PV) are considered in this research for driving the EV. Vehicles that only use battery-oriented technologies experience problems with charging and quick battery discharge. EVs are used with an ultracapacitor to decrease the quick discharge effects and increase the lifetime of the battery. Furthermore, bidirectional DC-DC converters are a type of power electronics device used to verify the smooth transfer of generated power from energy sources to the motor throughout various stages of the driving cycle. Therefore, this study proposes a perturb and observe (P&O) energy management control technique based on tuna swarm optimization (TSO). The suggested TSO-P&O completely uses UC while regulating the battery because it lowers dynamic battery charging and discharging currents. Due to the aforementioned aspect, the suggested TSO-P&O increases battery life and demonstrates a very dependable, long range power source for an electric car. The TSO-P&O technique achieves the EVs by obtaining the maximum speed of 91.93 km/hr. with a quicker settling time of 4,930 ms when compared with the existing zero-fuel zero-emission (ZFZE) method.

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1. INTRODUCTION

In electric vehicle (EV), the battery has been deliberated as the most important component which has grown significantly in recent years as a result of power electronic converters [1], [2]. These difficulties present in EVs was lessened by combining high energy density sources like battery, ultra-capacitor (UC), superconducting magnetic energy storage (SMES) and flywheels storage devices [3]. The most attractive design for EVs is the battery-UC hybrid energy storage systems (battery-UC HESSs) [4]. An efficient controller achieves effective battery utilization and current stress protection by estimating the power balance between battery-UC because the large variations accelerate the discharging current in the battery [5]. An optimal energy management strategy (EMS) should provide control of battery life, power loss, and other necessary factors [6]. The traditional optimization-based method generates the ideal strategy with more factors and processing effort [7], but the rule-based and real-time strategy is a straightforward one that requires empirical knowledge that does not deliver an optimal solution to EV. Frequency-based techniques are used to filter demand current at high frequencies [8]. Till now, there are several difficulties have existed while working on EVs which include the improper selection of battery size/capacity, vehicle speed limit, distance, and efficiency [9]. Controllers, batteries, and power electronic converters are crucial EV components [10]. When upgrading the grid is expensive, autonomous photovoltaic (PV) is frequently used in off-grid locations [11]. These systems support a variety of isolated uses, such as home use, irrigation of water, and repeater stations for telecommunications, each requiring a different amount of electricity [12]. Although solar systems that primarily rely on battery storage face a problem when exposed to abrupt voltage swings, including motor as the resultant high discharge currents significantly reduce battery longevity [13]. For PV systems to handle the brief surge in current needed at specified times, enough battery capacity becomes essential [14]. To regulate the power generated by renewable sources, a flexible power conversion technique is necessary [15]. At the current stage, energy crisis is a serious issue that cannot be solved. Fossil fuels like petrol and diesel have substantial extraction and use costs. The primary cause of the overuse of these fossil fuel-powered vehicles is that they have made it more efficient to mine these traditional resources in an unsustainable manner.

Environmental issues like air pollution and global warming have a negative impact on people and their way of life. Due to the scarcity of traditional resources and rising costs, energy crises are starting to emerge as a problem. Due to all of these factors, emerging nations are concentrating primarily on EV implementation and switching internal combustion engine vehicles (ICEVs) to hybrid electric vehicles (HEVs) in order to fight the pollution problem. Due to its low emissions, reduced fuel consumption, low clangour levels, and low running costs, HEV is becoming more common in the automotive industry today. Numerous power conversion and management approaches have been examined so far, and both their advantages and disadvantages have been made plain. The future load demand for the cars is predicted by mathematical models that make use of state-of-the-art based techniques motivated by power system optimized performance [16]. A four-port bidirectional buck-boost converter (FPB3C) designed for EV was proposed by Katuri and Gorantla [17]. This converter demonstrated the amazing capacity to combine several energy sources, such as solar panels, batteries, and ultracapacitors, into a single module. The FPB3C's results were evaluated under different situations, proving the greater accuracy of the suggested design.

A multi-input bidirectional buck-boost converter (MIB 3C) for HEV systems was presented by Suresh *et al.* [18]. Particularly, this converter has a low component count, which results with decreased difficulty, and it may provide a positive output voltage despite the need for a transformer. It also supports bidirectional power flow whereas switching among a variety of modes, involving buck, boost, and buck-boost. To guarantee the permanent magnet synchronous motor's (PMSM) motor's continuous power supply, Babu *et al.* [19] suggested hybrid energy storage system (HESS). The structure included a battery and uninterruptible power supply, that was charged whenever consumption was greater than the amount of power produced through the PV. The three-phase output line currents from the inverter were transmitted to the PMSM motor using an efficient inductor–capacitor–inductor (LCL) filtering approach, which produced enhanced motor operation. Therefore, relative to a traditional HESS, the total effectiveness of the recommended HESS was much better. An artificial neural networks (ANN) based EMS was proposed by Surti and Modi [20] for a HESS that includes of PV, battery, and UC. An EMS approach was developed utilizing neural networks to guarantee constant DC bus voltage stability regardless of motor speed or sun irradiation. According to the findings, adding UC to a battery in electric cars significantly increased the restricted driving radius and accelerated vehicle velocity. In contrast, depending upon various parameter values, the efficiency of employing ANNs for EMS in EVs was altering. In addition, real-time applications may face difficulties due to the deployment of ANNs onboard, that necessitates significant processing resources.

Comprehensive analysis of on-board vehicle combined novel hybrid renewable energy sources (RES) with storage for EV has been demonstrated by Bourenane *et al.* [21]. The zero-fuel zero-emission (ZFZE) vehicle's design combines (PV+WE+FC+SC). The proposed HEV architecture uses a proton exchange membrane (PEM) and a supercapacitor (SC) to produce electrical energy to meet the high torque demands. In-wheel motors are used instead of mechanical transmissions in the design, which aims to ensure zero carbon emissions and enhanced energy efficiency. Meanwhile, the primary causes of carbon emissions and environmental damage were all these technologies' direct or indirect reliance on fossil fuels. For organic structure sun capacitors (OSSCs) in EVs, Mamun *et al.* [22] proposed an intelligent control system that was effectively built to satisfy load requirements by using PV. ESS were protected from potential harm owing to elevated temperature production from high-power output by the adaptive neuro-fuzzy inference system (ANFIS) controller's excellent regulation of power management. Guentri *et al.* [23] shown using hybrid battery-SC to manage and regulate the energy from PV. This study aimed to adapt the voltage regulation architecture of the HES to these robust control principles. These methods' dependability and performance measures were also assessed. The genetic algorithm (GA) optimization technique considerably decreased peak overshoot and settling time, improving efficiency. The machine only experienced issues with the GA-based proportional integral derivative (PID) controller architecture after the threshold of 67%. Al-Dhaifallah *et al.* [24] developed a successful an EMS for grid-EV and renewable power. In order to assess how EVs behave, three alternative charging procedures were considered: unsupervised, supervised, and smart charging methods. To deal with the optimization planning of micro grids, modified harmony search (MHS) method was used. The MG's Day-ahead preparation was a critical issue, but it warrants extended consideration. However, a number of issues, including the limited driving range, poor start-up performance, and short battery life, are impeding their development. A hybrid power system made up of PV cells, supercapacitors, and batteries is suggested as a solution to these issues. Numerous studies have been conducted recently that promise higher energy and power densities. The following properties cannot be found in any energy storage device alone: high power densities, low production costs, and lengthy life cycles. In order to achieve greater performance, the idea of combining ESS has evolved. EMS is used to manage the ideal flow between the ESS, converters, and additional components in EVs. The main contribution is listed as:

a. The tuna swarm optimization (TSO) and perturb and observe (P&O) energy management control technique is recommended for distributing energy across the PV system, batteries, and UC.
b. A proposed HESS architecture uses batteries and UCs to store PV energy.
c. The current from the buck-boost converter and voltage from DC bus are managed by the TSO-P&O controller.

The following is the organization of the paper: power source modeling in an energy system is explained in section 2. The proposed strategy is presented in section 3. The findings and explanations of the results are demonstrated in section 4. And the conclusion is stated in section 5.

2. HESS DESIGN CONSIDERATIONS

The aim of a hybrid energy storage system (HESS) is to use the advantages of varied energy storage methods while ignoring their individual limitations. This integration improves overall performance, extends the lifespan of the energy storage system, and optimizes energy use in EVs. In this study, three alternative energy systems such as PV modules, UC, and battery banks-are utilized [25]. The mathematical modeling of these three energy systems is briefly and clearly discussed in the following sections respectively:

2.1. Photovoltaic model

PV modules are sized optimally to satisfy load demand and save energy expenditures. The operating weather conditions, the production procedures, and the position of the PV module are the main determinants of output power [26]. The PV system's voltage and capacity are set by connecting the PV panels in parallel/series. To increase the output power of the PV system, maximum power point tracking (MPPT) technique is utilized. The output power that relies on I_M and V_M is identified using (1).

$$P_{MPPT}(t) = I_{MPPT}(t) \times V_{MPPT}(t) \tag{1}$$

2.2. Ultra-capacitor

UC is used as a secondary energy source and runs in active mode when a motor's load requirement is high or when a HEV's load requirement needs to be compensated. The recommended controller assists in controlling the conditions for UC charging and discharging. Other names for UCs include electrochemical capacitors and UCs, and these UCs have a high energy density. This UC has a long lifespan and charges and discharges efficiently. The capacitance values of UC are of a larger order of magnitude in comparison to regular capacitors. The voltage applied across the capacitor V_c determines its capacitance. Equation (2) calculates the voltage through each fixed capacitor individually.

$$V_c = \frac{V}{N_{series}} - i_n R_n \tag{2}$$

where, V refers voltage across the block, N_{series} refers number of cells in series, branch number is referred as $n = [1,2,3]$. The current via n^{th} branch refers i_n and resistance in n^{th} branch refers R_n.

2.3. Battery model

The altering environmental elements have an impact on how much power the RES can produce. The battery's charging and draining portions of state of charge (SoC) are given by (3) and (4), respectively. The battery is charged when the combined power of PV and UC is more than the load. When the load is larger than the RES powers, discharge happens.

$$SOC = SOC(t-1) \times (1-\sigma) + [P_{RES}(t) - P_L(t)/\eta_{inv}] \times \eta_{ch} \tag{3}$$

$$SOC = SOC(t-1) \times (1-\sigma) + [P_L(t)/\eta_{inv} - P_{RES}(t)] \times \eta_{disch} \quad (4)$$

SOC and $SOC(t-1)$ are denoted as charging and discharging conditions of the battery. The discharge rate for 1 hour is denoted as σ. RES and load power are characterized as P_{RES} and P_L respectively. Inverter efficiency, charging and discharging conditions are symbolized as η_{inv}, η_{ch} and η_{disch} respectively.

3. PROPOSED METHOD

In this work, an effective EMS is developed using PV and two storage devices. Additionally, surplus electricity produced by UC and PV modules is stored using battery-based storage. PV modules and UC are used as the primary and backup sources, respectively, to balance load demand. Additionally, the battery is used as a fallback option when neither the UC nor the PV module has enough energy to meet the load need. TSO-P&O is used to turn on the PV module's DC-DC converter and generate the best peak power under a range of irradiance and temperature conditions. Figure 1 depicts the system's proposed block diagram.

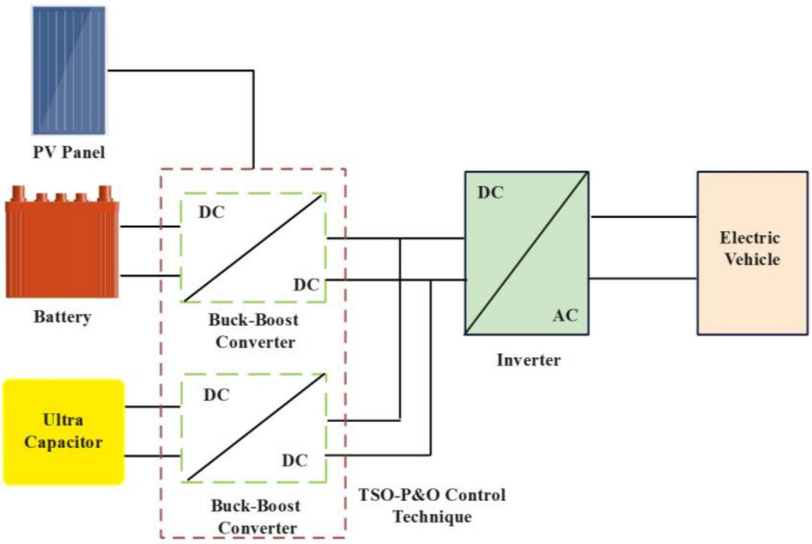

Figure 1. Overall process of the proposed model

3.1. Tuna swarm optimization

To optimize the parameters and functions of EV, this study proposed a swarm-based optimization technique name called tuna swarm optimization (TSO) [27]. This TSO algorithm has a greater exploration efficiency and a global-level search capability, which effectively fine-tunes the hyper-parameters. The advantages of this approach include not depending on the issue model, does not requiring gradient information, powerful search capabilities, broad applicability, and ability to strike a reasonable balance among quality and computing cost. Thus, these techniques have been suggested to address optimization issues. The following is a description of the iterative process used in TSO: A carnivorous fish called the tuna inhabits the ocean's surface. Even if a single tuna swims more quickly, it cannot move as quickly as nimble fish. Therefore, tunas use the tactic of group movement for predation. These animals are renowned for using cunning and successful foraging techniques to locate and catch their prey.

Initialization: It is the initial phase of the majority of optimization approaches. Tuna uses two different foraging techniques, including spiral foraging and parabolic foraging. In TSO, the uniform search space in which the initial populations are produced is expressed mathematically as (5).

$$X_i^{int} = rand \times (u_b - l_b) + lb, \quad i = 1,2,\ldots,NP \quad (5)$$

where X_i^{int} refers individual at the initial stage, the upper and lower bounds are represented as u_b and l_b respectively. The total population of tuna is represented as NP. The randomized vector, which is distributed in a uniform space, is denoted as $rand$ and it lies in the range of 0 to 1.

Spiral foraging: In some cases, it is difficult for predators to lock their victims when a little fish changes their direction to protect them. Therefore, tuna chase their prey by forming a spiral. Tuna transmits information to their neighbors after reaching their goal. Equation (6) presents this tuna technique numerically as (6).

$$X_i^{t+1} = \begin{cases} \alpha_1.(X_{best}^t + \beta.|X_{best}^t - X_i^t| + \alpha_2.X_i^t, \ i = 1 \\ \alpha_1.(X_{best}^t + \beta.|X_{best}^t - X_i^t| + \alpha_2.X_{i-1}^t, \ i = 2,3,\dots,NP \end{cases} \quad (6)$$

where the value of α_1, α_2, β and l are computed using (7)-(10).

$$\alpha_1 = a + (1-a).\frac{t}{t_{max}} \quad (7)$$

$$\alpha_2 = (1-a) - (1-a).\frac{t}{t_{max}} \quad (8)$$

$$\beta = e^{bl}.cos(2\pi b) \quad (9)$$

$$l = e^{3cos}\left(\left((t_{max} + 1/t) - 1\right)\pi\right) \quad (10)$$

where the optimistic individual in the current position is represented as X_{best}^t. The weighted co-efficient that regulates the individual at the optimal state and the previous state is represented as α_1 and α_2. The constant that is utilized to distinguish the operation of tuna which tracks the optimistic individual is represented as a. The iteration at the current state and maximum iterations are represented as t and t_{max} respectively. The random number which is distributed among the range of 0 and 1 is represented as b.

The tuna's capacity for exploitation increases as they spiral for food. However, it is unlikely that every fish in the school could be fed. Therefore, a randomized coordinate point is produced in a spiral search to aid individuals in doing a wider search, as shown in (11).

$$X_i^{t+1} = \begin{cases} \alpha_1.(X_{rand}^t + \beta.|X_{rand}^t - X_i^t| + \alpha_2.X_i^t, \ i = 1 \\ \alpha_1.(X_{rand}^t + \beta.|X_{rand}^t - X_i^t| + \alpha_2.X_{i-1}^t, \ i = 2,3,.NP \end{cases} \quad (11)$$

The randomly produced reference point is represented as X_{rand}^t. As a result, as the number of iterations increases, TSO modifies the reference points from random to ideal values. Equation (12) is the finalized formulation for spiral foraging process as (12).

$$X_i^{t+1} = \begin{cases} \alpha_1.(X_{best}^t + \beta.|X_{best}^t - X_i^t| + \alpha_2.X_i^t, \ i = 1 \\ \alpha_1.(X_{best}^t + \beta.|X_{best}^t - X_i^t| + \alpha_2.X_{i-1}^t, \ i = 2,3,\dots,NP, \ if\ rand < \frac{t}{t_{max}} \\ \alpha_1.(X_{rand}^t + \beta.|X_{rand}^t - X_i^t| + \alpha_2.X_i^t, \ i = 1 \\ \alpha_1.(X_{rand}^t + \beta.|X_{rand}^t - X_i^t| + \alpha_2.X_{i-1}^t, \ i = 2,3,.NP, \quad if\ rand \geq \frac{t}{t_{max}} \end{cases} \quad (12)$$

Parabolic foraging: Tuna has a parabolic growth pattern that uses mutual searching to find food sources. Generally, tuna consists of two processes, which have a 50% chance of proper food selection. Equation (13) represents those actions mathematically as (13):

$$X_i^{t+1} = \begin{cases} X_{best}^t + rand \times (X_{best}^t - X_i^t) + TF \times p^2 \times (X_{best}^t - X_i^t), \ if\ rand < 0.5 \\ TF \times p^2 \times X_i^t, \ if\ rand \geq 0.5 \end{cases} \quad (13)$$

where the value of $\rho = \left(1 - \frac{t}{t_{max}}\right)^{(t/t_{max})}$ and the random number which lies in the range of 1 or -1 is denoted as TF. Every candidate chooses two foraging techniques to recreate a position in search space due to probability z. At the time of optimization, the candidates are updated and evaluated till the optimal value is obtained. Further, the flowchart model of TSO is revealed in Figure 2.

3.2. Perturb and observe

By including data on current and voltage change (I and V), P&O is projected to address the drift issue. An I and V circuit is provided to P&O to address the drift problem. By altering the step value, P&O gets over the limitations of a few peaks and makes it possible for the MPPT to find the MPP even when it is completely in the shade. In the partial shading condition, power loss and instability start to decrease when P&O approach reaches its maximum value. As a result, the process of obtaining the ideal working situation moves along more quickly and with fewer oscillations [28]. If the irradiance is higher, P&O observed, dV and dI as null and hence, the duty cycle is developed through ΔDn that is stated as variable step size which is represented in (14).

$$\Delta Dn = \pm M|\Delta G| \quad (14)$$

where a shift in incidence is defined as ΔG and a fixed restriction is specified as M. Numerous financially feasible and scientifically sound solutions already exist for creating a hybrid energy system. Overall, this hybrid model includes PV, battery, and UC a control mechanism known as TSO-P&O based on an EMS which is taken into account for peak load changes and batteries SoC during dynamic weather conditions.

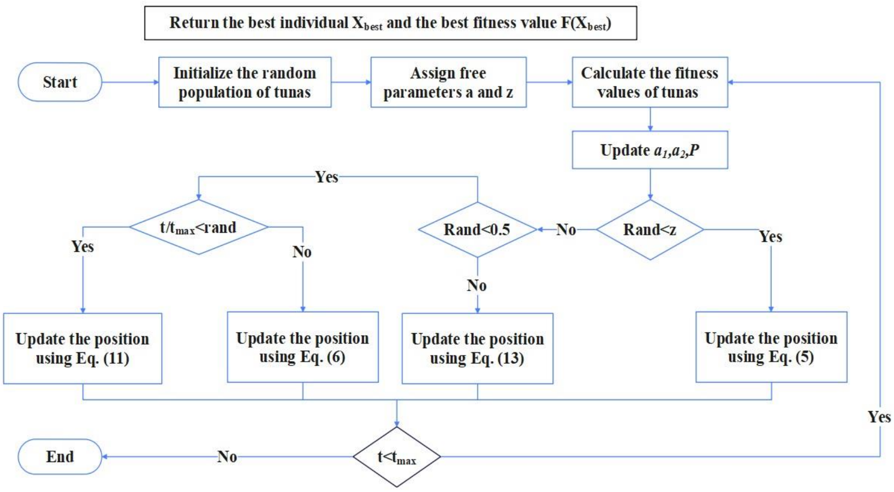

Figure 2. Flowchart of TSO

4. RESULTS AND DISCUSSION

Utilizing MATLAB/Simulink R2020a, the proposed methodology is simulated. Utilizing two distinct energy sources including a battery, UC in HEV is studied. Based on battery's SoC, UC is charged or discharged using the TSO-P&O controller. Here in this research, the PV cells contains 96 (N/cell), battery has the energy capacity of 7.7885 (Ah), UC contains the maximum voltage of 270 V, and motor has the speed of 3,500 rpm, respectively. For a fixed load (a PMSM motor) and a simulation time of 200 seconds, HESS is used.

There are many different types of energy sources, including generation techniques and electrical, chemical, hydrogen, and mechanical energy storage systems. However, due to their distinct features, sizes, and levels of efficiency, each energy source is task-specific for various EVs. The entire changeover of automobiles has been difficult because most of them are linked to charging station and ESS networks. The Simulink diagram of proposed technique is exposed in Figure 3. The battery, UC, HEV, and TSO are the main elements of this model. Since the NiMH battery is the primary source in this suggested manner, the HEV initially drew its power from it. Then, when the battery's SoC is <60%, UC is utilized which was done with the help of a TSO controller.

4.1. Performance analysis of PV

Due to the proposed controller, the voltage is fixed in MPP voltage with little variations. Only a little variation in the output voltage can be seen over the time intervals. As expected for a boost converter topology, the duty ratio of the converter switching signal is also detected. According to the randomly produced PV radiation between 0.1 and 1 kW/m2, PV voltage varies between a few Volts which is shown in first chart. According to the radiance, current from the PV array are produced which is shown in the second chart. If the PV output voltage is less than the peak reference, the UC switching signal will be ON and the battery switching signal will be in OFF condition. The performance analysis of voltage, current and overall PV power generation is illustrated in third chart Figure 4.

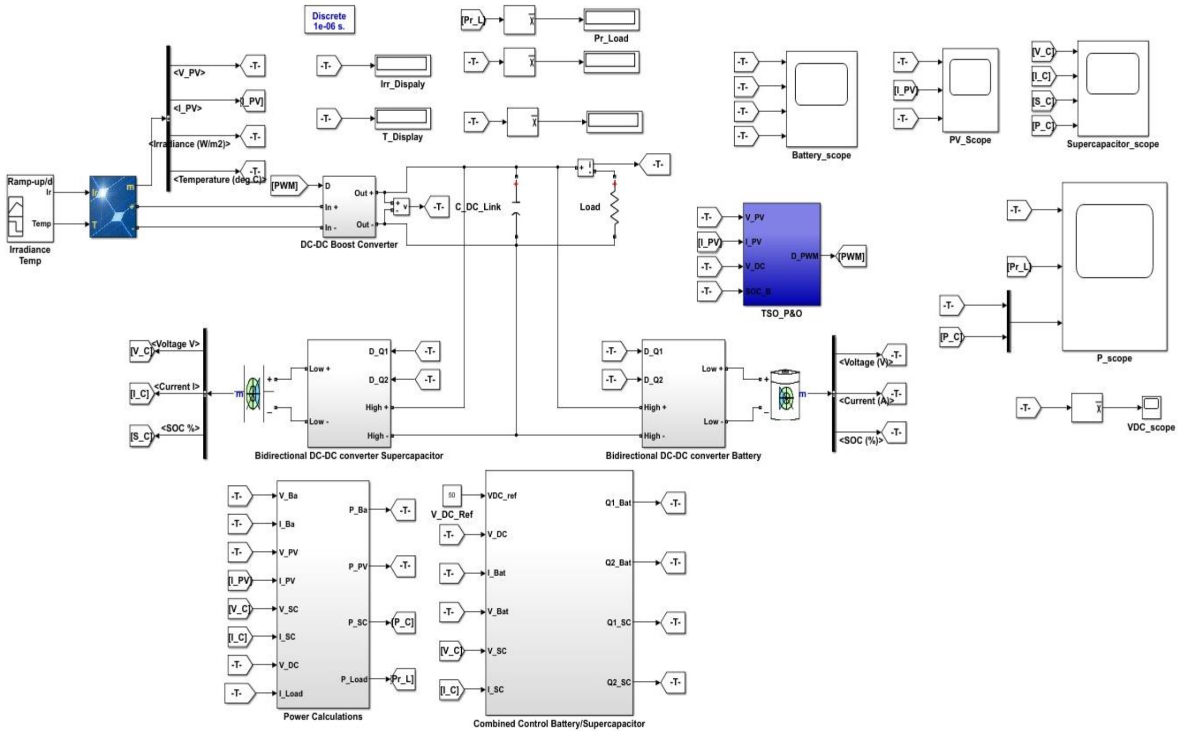

Figure 3. Simulink model for the proposed methodology

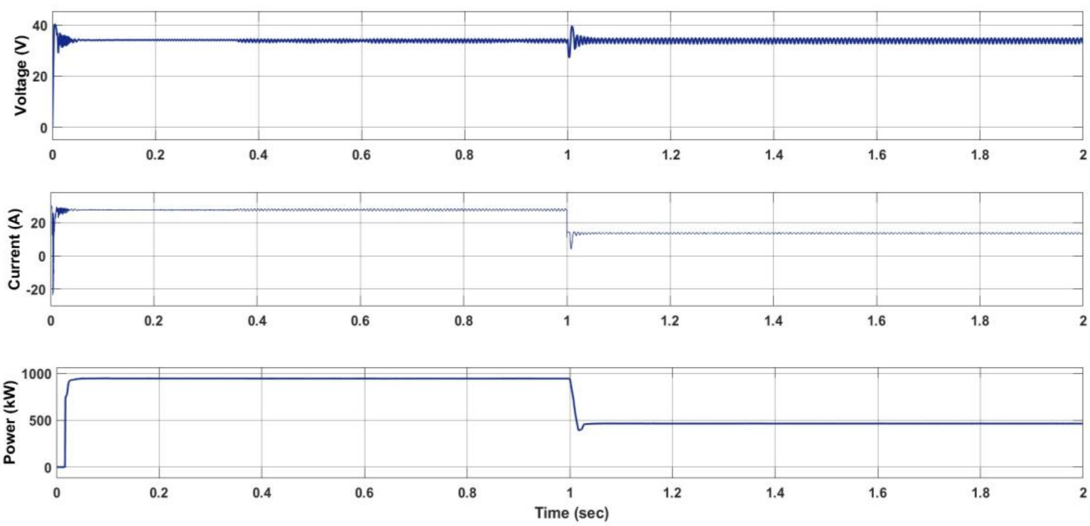

Figure 4. Performance of PV

4.2. Performance analysis of ultra-capacitor

In these simulations, Figure 5 displays the simulation outcomes for the UC in charge time from PV for varied irradiation. According to the suggested approach for each module, the voltage is gradually increased and remains steady over time and charging the UC in a dashed mode which is shown in first chart. In a given number of seconds, the charge current falls from its highest value to zero. Depending on the weather, the charge current can be varied which is illustrated in second chart. The charged power in UC is created by multiplying this voltage by this current; the area under the curve represents the energy that is stored in the UC module and its state of the charge is represented in third chart. The fourth chart represents the UC power calculation with respect to the voltage and current. For overall UC power, these figures need to be adjusted for series UC stacks. As anticipated, the DC bus voltage remains constant throughout time at 400 V.

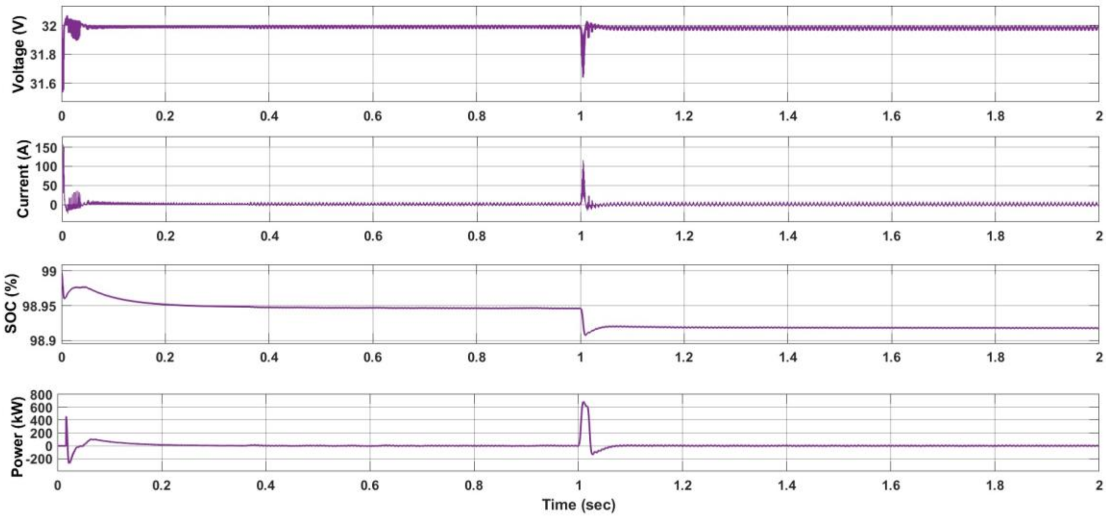

Figure 5. Performance of UC

4.3. Performance analysis of battery

Depending on the energy storage capability of the capacitor and the outside temperature, the peak shaving reference voltage can be changed. This study merely serves as a case study to demonstrate how much more effectively instantaneous voltage can be held by battery when used as active power control is shown in first chart. The current produced the battery storage is shown in second chart. Higher SoC can be maintained while reducing storage size and overall battery stress by using hybrid energy storage devices that combine batteries and UC is shown in third chart. It has been demonstrated that the use of UC can boost capacity by 25% in sunny conditions and by 10% in gloomy conditions. The fourth chart represents the battery power calculation with respect to the voltage and current. During times of low solar radiation, the energy held in UC is then released to charge the battery, as shown in Figure 6.

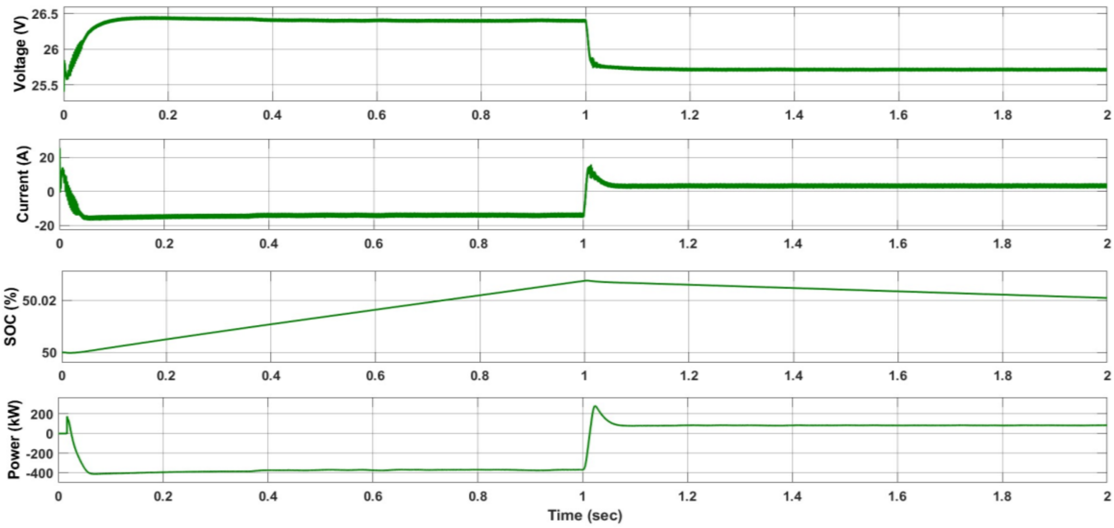

Figure 6. Performance of battery

The power-sharing between PV, battery, and UC is proposed to be controlled by a chosen combination topology and a new control strategy. Additionally, a technique for sizing the hybrid distribution and energy storage system based on photovoltaic power curves is introduced. This combination (PV/Battery/UC) not only extends the battery's lifetime by decreasing the amount of stress placed on it but also continuously supplies electricity to the EV for predetermined periods.

4.4. Performance analysis of converter

To have additional functioning points and produce a smoother curve, the circuit may have a few extra load resistors added. A software interface will be added to improve the upgrading. The region's various seasons' PV performance will then be regularly monitored using the upgraded designs. Resistive loads use less energy when connected to a hybrid system, and their waveforms are shown in Figure 7.

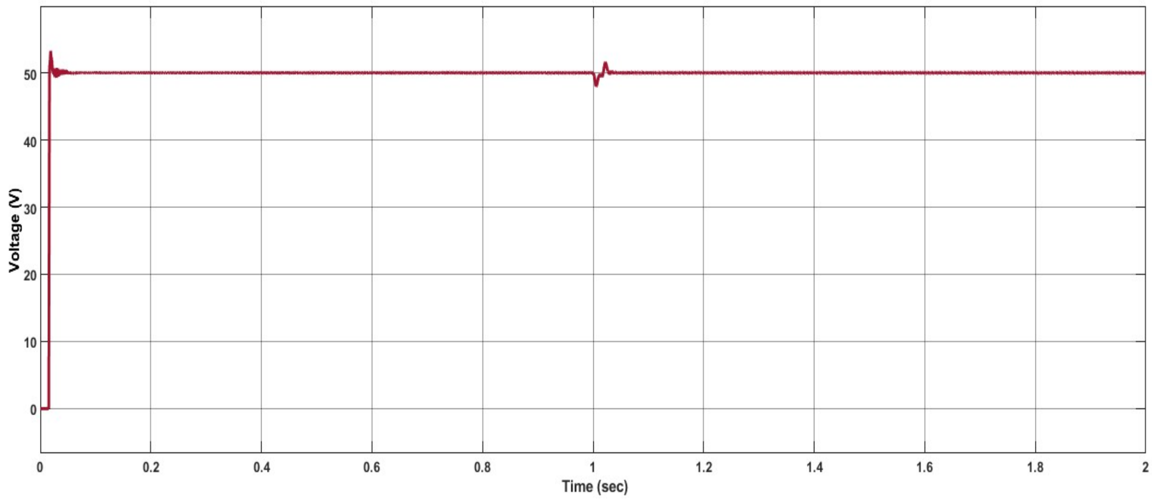

Figure 7. Performance of converter voltage

4.5. Performance analysis of overall power

A capacitor is installed between the PV modules and the inverter to maintain the current of the modules at a practically constant value. Although the inverter's power consumption varies, it consistently matches the power output of the PV modules, which are capable of generating electricity at or near their maximum capacity. First, the motor requires additional torque to overcome its inertia. This is because instantaneous power experiences greater fluctuations over time, leading to a simultaneous increase in peak power. To boost the motor's speed, more torque is required. The MPPT algorithm is used to transfer the maximum amount of power from the solar system to the motor, which is shown in first chart, as shown in Figure 8, where the simulation model's motor is utilized to drive a particular load which is shown in second chart of the figure.

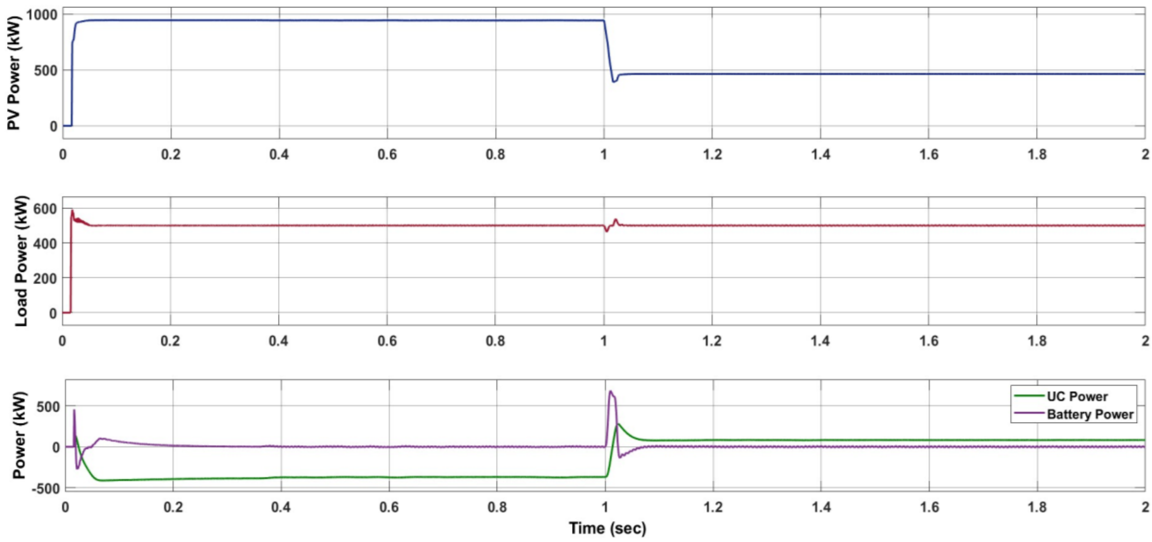

Figure 8. Performance of overall analysis

4.6. Comparative analysis

Here, in this section, the comparative analysis of proposed TSO-P&O and existing ZFZE [21], GA-PID [23] and MHS [24] are analyzed in terms of speed performance. Table 1 shows the comparative analysis of speed. From the Table 1, it clearly shows that the existing ZFZE [21], GA-PID [23] and MHS [24] has attained a speed range of 56.55 km/hr, 84 km/hr, 87 km/hr respectively while the proposed TSO-P&O has accomplished a better speed range of 91.93 km/hr which is better than the existing method.

Table 1. Comparative analysis

Methods	Maximum speed (km/hr)
ZFZE [21]	56.55
GA-PID [23]	84
MHS [24]	87
Proposed TSO-P&O	91.93

4.7. Discussion

The energy management approach between the PV, battery, and UC is carried out in this study using the least amount of electronic converters. This paper presents a P&O energy management control technique to regulate the EV based on TSO. The speed comparison between the existing ZFZE [21], GA-PID [23], MHS [24] and the proposed TSO-P&O is analyzed. The analysis clearly demonstrates that the suggested TSO-P&O has achieved a better speed range of 91.93 km/hr, which is better than the present approach, whereas the existing ZFZE [21], GA-PID [23] and MHS [24] which has only acquired a speed range of 56.55 km/hr 84 km/hr and 87 km/hr respectively.

5. CONCLUSION

Here, the EMS is conducted among PV, battery, and UC by utilizing the fewest number of electronic converters possible. This work suggests a TSO-based P&O energy management control approach to control the EV. Because of the reduction in the dynamic battery charging and discharging currents, the proposed TSO-P&O fully utilizes UC while managing the battery. The suggested TSO-P&O extends battery life and shows that it is a very dependable, long-range power source for an electric automobile because of the aforementioned factors. The control mechanism allows seamless transition between the UC charging and discharging stages. The numerical simulations in MATLAB show that the recommended TSO-P&O approach accomplishes the EVs by achieving the maximum speed of 91.93 km/hr with a faster settling time of 4.930 ms when compared to ZFZE algorithms. To further enhance the battery capacity of HEVs, the design of the suggested framework could be enhanced in the future by using a hybrid optimization-based technique.

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