

## Article

# Energy Management Strategy of Hybrid Energy Storage System Based on Road Slope Information

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**Abstract:** To maximize the performance of power batteries and supercapacitors in a hybrid energy storage system (HESS) and to resolve the conflict between the high power demands of electric vehicles and the limitations of high-current charging and discharging of the power battery, a vehicle power demand model incorporating road slope information has been constructed. This paper takes a HESS composed of power battery and supercapacitor as the object, and a rule-based energy management strategy (EMS) based on road slope information is proposed to realize the reasonable distribution and management of energy under the slope condition. According to the slope information of the road ahead, the energy consumption in the next period was predicted, and the supercapacitor is charged and discharged in advance to meet the energy demand of uphill and the energy recovery capacity of downhill to avoid the high current charge and discharge of the battery. Subsequently, the improved EMS performance was simulated under the New York City Cycle (NYCC) driving conditions with additional slope driving conditions. The simulated results indicate that compared to the existing EMS, the proposed EMS based on slope information can effectively distribute the power demand between the power battery and the supercapacitor, can reduce the discharge current and the duration of high-power discharge, and has a 20.4% higher energy recovery efficiency, effectively increasing the cruising range.



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**Keywords:** hybrid energy storage system; energy management strategy; slope information

## 1. Introduction

It is very important to design an energy storage system with high power and energy density to satisfy the power demands of an electric vehicle (EV) under different working conditions [1,2]. A high-power energy storage system needs to meet the power demand during acceleration and effectively recover energy during deceleration without affecting the system life cycle and efficiency [3,4]. Although many pioneering studies have been conducted to improve battery performance, large current spikes continue to present obstacles to extending the battery service life [1,5]. As a secondary source, supercapacitors (SC) are equipped with higher charging/discharging efficiency, high power density, and a longer lifespan [6,7]. SC can compensate for the lack of power battery by establishing a hybrid energy storage system with a battery supercapacitor [8,9]. An effective energy management strategy (EMS) can fully exploit the advantages of the hybrid energy storage system (HESS) by coordinating the power output between the battery and SC [10]. Existing strategies for HESS mainly consist of rule-based, optimization-based and artificial intelligence-based strategies.

The rule-based strategy just takes system energy states and momentary instantaneous power demand into consideration, and the power distribution mission is usually achieved

according to a series of predefined rules [10]. Representative examples include threshold [11,12], fuzzy logic [13,14] and filtration [15,16]. A rule-based controller is proposed based on considering the power demand of the load and the states of charge (SOC) of batteries and supercapacitors at the same time [11]. In [13], the author adopted a golden cut-off rule to optimize a fuzzy logic controller, and simulation results indicate that the designed controller could effectively achieve the goals they set. In [15], a controller adopted a low-pass filter to separate the load power into high frequency and low frequency, then distributed them to the SC and battery. In this manner, both the SC and battery's characteristics are exploited effectively. Obviously, the rule-based method developed by the experience or heuristics of experts is easy to be realized without considering prior knowledge of the road conditions [17].

Optimization-based methods consist of two methods, including global optimization and real-time optimization methods [18]. This kind of EMS is designed by minimizing the chosen cost function under specified constraints [19], including dynamic programming [20,21], genetic algorithm [6,22], particle swarm optimization [23], and convex optimization [24,25]. As for a serial hybrid electric tracked vehicle, an EMS based on stochastic dynamic programming was put forward, and the performance of the control strategy was tested through a simulation approach [20]. A genetic algorithm was utilized to resolve multi-objective optimization issues with a minimum total loss of HESSs and minimum battery capacity [6]. In order to solve the optimal power flow (OPF) issue, an efficient and reliable evolutionary-based method, in which particle swarm optimization algorithm was employed, was put forward by Abido et al. [23]. A novel method combining deterministic dynamic programming (DP) and convex optimization was proposed, and the method proved to obtain globally optimal results and better real-time performances compared to the conventional DP method [24]. A dynamic evolutionary model based on the first-kind Volterra integral equation is used to solve the load-levelling problem with storage [26]. However, there may be optimal local problems in real-time optimization methods. In the global optimization methods, the whole working condition should be known in advance. The global optimization problem is improved by predicting the uncertainties in a longer time domain, such as literature [27] which presented a novel approach to implement DSM in smart grids by including historical data and by taking into account the weather conditions with the proposed instability index and then the overall grid welfare is improved.

With the development of artificial intelligence technology, some researches have used neural networks (NNs) and reinforcement learning to solve energy distribution in HESS [28]. NNs for system control have been utilized to enhance transient performances of HESS power distribution [29]. Xiong et al. [30] adopted reinforcement learning theory to design an energy management strategy, resulting in obtaining the optimal power distribution between battery and SC. The artificial intelligence methods need much off-line operation under various conditions, which limits their application.

In fact, rule-based control strategies are regarded as the most widely used strategy in practical applications. Although the pioneering studies mainly focus their attentions on the energy management strategies of the HESS, most of these strategies are based on the current vehicle conditions and the current SOC of the power batteries and SCs, passively customizing the corresponding energy distribution strategies. Although these strategies have made specific achievements, they neglect the impact of the road environment and vehicle driving environment on the driving performance of the vehicle, resulting in imperfect energy distribution and recovery performance.

With the development of high-precision mapping technology, environmental perception technology and the popularization of 5G networks, vehicles can actively acquire information about the road environment and driving environment ahead in real-time, which provides the possibility for the realization of positive EMS. In particular, the slope information in front of the vehicle can be known in advance, which can predict energy consumption in the next period. Therefore, this paper takes a HESS of the power battery

and supercapacitor as the object and consider the influences of the road slope on the energy distribution to improve the rule-based energy distribution strategy.

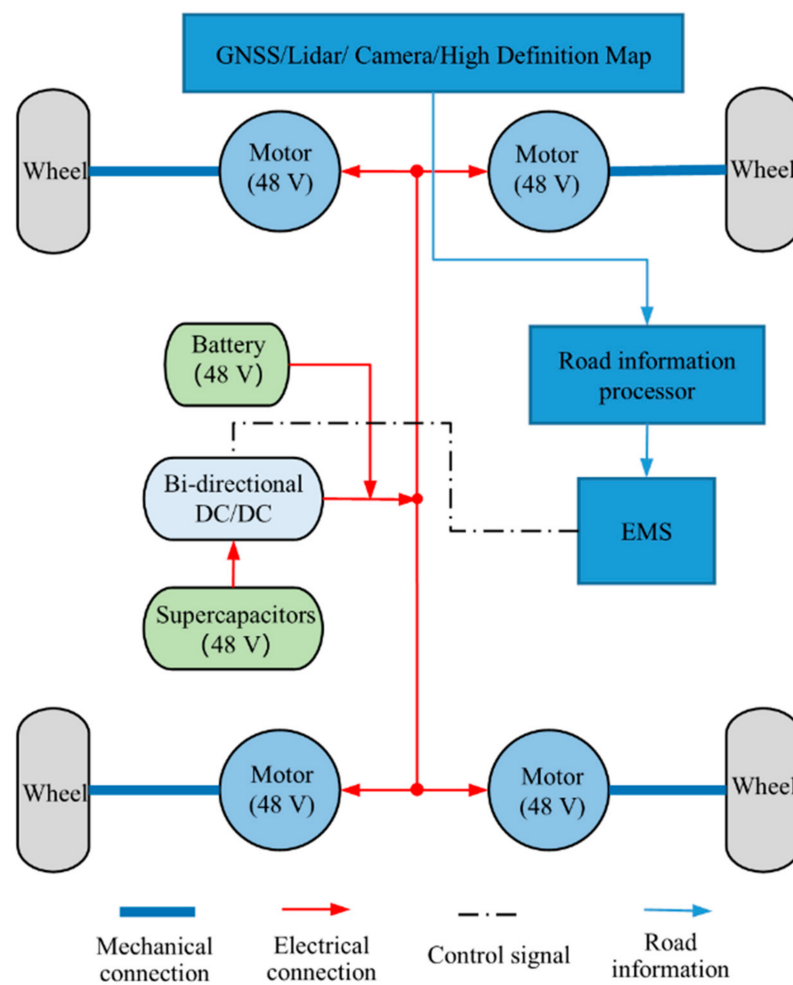
The improved EMS was proposed based on predicting the energy consumption in the next period. According to the slope information, the energy consumption or energy recovery capacity in the next period is predicted and then the supercapacitor is charged and discharged in advance to meet the energy demand of uphill and the energy recovery capacity of downhill and then to avoid the high current charge and discharge of the battery. The performance of the improved EMS was calculated by MATLAB/Simulink. The novel features of this paper are: (1) the improved energy management strategy considers the influence of road slope on energy consumption; (2) the additional energy consumption for uphill driving and the possible energy recovery for downhill driving are predicted. According to the predicted energy value, the power distribution between the battery and supercapacitor is adjusted in advance. Under the improved strategy, the vehicle can avoid high-current discharge of the battery when the vehicle goes uphill and can fully renew the braking energy when going downhill. The improved EMS is different from the general model predictive control [MPC]. For an MPC, the future value of the process output is predicted according to the current control input of the system and the historical information of the process [27]. For the improved EMS, the slope information of the road ahead is definite by using high-precision map and GNSS positioning and only the additional energy consumption or the possible energy recovery was predicted through dynamic calculation.

This paper starts from the topological structure of HESS, then a novel energy management strategy based on slope information is introduced. Subsequently, simulation is conducted to verify the effectiveness of the proposed energy management strategy. Finally, the conclusions are summed up.

## 2. Topological Structure of HESS

The topological structure is an important element of a HESS design that affects performance. The HESS structure for practical applications can be classified into two types based on the connection relationship between power batteries, SCs and DC/DC converters: a direct parallel structure and an active control structure [31]. The active control structure can be subdivided into three types: a parallel structure in which the power battery is connected in series with the converter, a parallel structure in which the SC and the converter are connected in series, and a parallel structure in which both the power battery and SC are connected in series with the converter.

The parallel topology is adopted in this study, considering the system efficiency, stability, and cost, as well as the difficulty of implementing the control strategy. The SC is connected in series with the DC/DC converter and then connected in parallel with the power battery, as shown in Figure 1. The introduction of a DC/DC converter resolves the voltage mismatch problem between the power battery and the supercapacitor by balancing the output voltage of the two energy sources and letting them supply energy for the load simultaneously [32]. The voltage changes faster when the supercapacitor directly supplies energy for the load because of its low specific energy, while the terminal voltage of the power battery changes more gently in the normal working phase. Therefore, DC/DC control of the parallel structure with an auxiliary energy source and a single converter connected in series can be easily implemented.



**Figure 1.** Hybrid power system topology.

A HESS must satisfy the power requirements of vehicles under urban road conditions, that is, the HESS energy and power output should supply the energy and power required by the vehicle to ensure both power and economy. In the designed system, the main power of the vehicle is borne by the power battery, and the supercapacitor provides the peak power during acceleration. Thus, the following energy and power constraints should be satisfied: first, the power output of the power battery must be less than or equivalent to the nominal maximum power output of the power battery; second, the energy stored by the power battery must meet the vehicle's designed driving range; third, the additional peak power required for the vehicle's acceleration or uphill process should not be greater than the energy provided by the supercapacitor; fourth, the capacity of the supercapacitor is greater than the energy recovered during braking or going downhill; fifth, the state of charge (SOC) of the power battery and the supercapacitor should be within a reasonable range [33]. The constraint conditions are shown in Equation (1), and the parameters of the rule-based energy distribution strategy need to satisfy these conditions.

$$\begin{cases} P_b \leq P_{b \max} \\ E_b \geq P_{ave} \times t \\ P_{sc \max} \geq P_{t \max} - P_b \\ E_{sc} \geq E_{brake} \\ 0.3 \leq SOC_B \leq 0.9 \\ 0.4U_e \leq U_{sc} \leq U_e \end{cases} \quad (1)$$



where  $P_b$  is the real-time power of the battery,  $P_{b\ max}$  is the maximum acceptable output power of the battery,  $E_b$  stands for the maximum energy that the battery holds,  $P_{ave}$  represents the average output power of the battery,  $t$  is the maximum cruise duration,  $E_{sc}$  represents the total energy stored by the supercapacitor,  $P_{t\ max}$  stands for the maximum driving power,  $E_{brake}$  is the maximum energy recovered,  $SOC_B$  is the SOC of the battery, and  $U_{sc}$  and  $U_e$  are the real-time voltage and the rated voltage of the supercapacitor, respectively.

### 3. EMS of HESS Based on Slope Information

One of the core technologies of the HESS is its EMS. The aims are to reasonably distribute the power of the power battery and the supercapacitor according to the driving conditions of the vehicle. Simultaneously, taking full advantage of SC could avoid high-current charging and discharging of the power battery, thereby extending the cycle life of the power battery. Additionally, the efficiency of braking energy recovery can be enhanced, and the economy of EV can also be improved under the condition of assuring vehicle power.

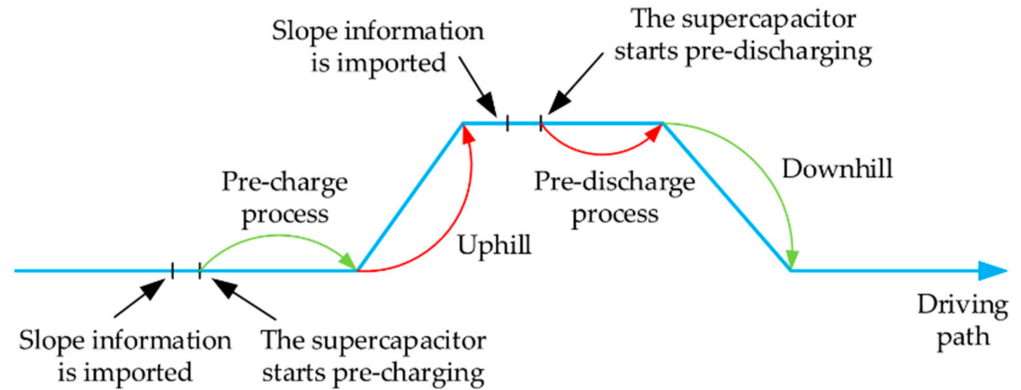
Existing EMS based on vehicle speed, logic threshold control, and fuzzy control are based on the current SOC of power batteries and supercapacitors, and the corresponding power distribution is passively formulated according to changes in the vehicle driving conditions, which is categorized as a passive control. Passive control results in a lagged control effect, namely, a hysteresis effect, especially for uphill and downhill conditions. As a long upward slope occurs on the road ahead, the power demands of the vehicle increase due to the slope resistance. To avoid high-current discharging of the power battery, the control system makes the supercapacitor output more power to meet the sudden increase in power demand. At this time, the energy consumption of the supercapacitor can be accelerated. When the SOC of the supercapacitor does not meet the high-power consumption, the forced high-power discharge of the power battery shortens its service life. When there is a long downhill road ahead, the vehicle enters the braking energy recovery mode. To avoid switching between the charging and discharging modes of the power battery within a short period of time, the supercapacitor recovers all the braking energy. At this time, the supercapacitor may be unable to fully recover the energy due to the high SOC, resulting in energy waste.

To compensate for the above shortcomings, the influences of the slope conditions on the power consumption in the energy distribution strategy are introduced based on the vehicle speed and designed an energy distribution strategy based on slope information. As shown in Figure 2, the strategy considers the impacts of the slope on the power requirements of the vehicle and uses vehicle navigation systems and high-precision maps to obtain the information of the road ahead; it also estimates the slope information of the driving path, plans to store a reasonable amount of energy in the supercapacitor in advance and makes the supercapacitor bear the burden of larger output power when driving uphill to satisfy power demands of the entire vehicle and effectively reduce the high-current discharging of the power battery. When driving downhill, the strategy allows sufficient braking energy recovery to avoid switching between charge and discharge modes of the power battery within a short period of time or wasting braking energy.

#### 3.1. EMS Based on Vehicle Speed When Driving on a Flat Road

Under normal driving conditions without slopes, the power required by the vehicle mainly comes from air resistance, rolling resistance, and acceleration resistance. The energy distribution depends on the current speed state. This paper designed an improved EMS on the basis of vehicle speed: the power battery provides steady-state power under the condition that the vehicle is running; that is, the power battery is used to overcome the air resistance and rolling resistance. The supercapacitor is responsible for the high-frequency and high-amplitude transient power of the vehicle during acceleration and braking; that is, the supercapacitor is responsible for the energy supply or recovery under acceleration or braking conditions to improve the adaptability of the system. Setting a reasonable SOC

threshold for the supercapacitor and prioritizing the use of the supercapacitor to recover energy during the energy recovery stage can prevent the frequent charging and discharging of the supercapacitor by the power battery and improve the energy efficiency of the vehicle.



**Figure 2.** Energy distribution strategy based on slope information.

The required power when the vehicle is running is as follows [34]:

$$P_{all} = \frac{1}{3600\eta} \left( Gf \cos \alpha + \frac{C_D A}{21.15} v^3 + Gv \sin \alpha + \delta m v \frac{dv}{dt} \right) \quad (2)$$

where  $\eta$  is the transmission efficiency of the power train;  $G$  and  $f$  stand for the vehicle weight and rolling resistance coefficient, respectively;  $C_D$  stands for the drag coefficient;  $A$  represents the windward area;  $\alpha$  is the slope;  $m$  and  $v$  represent the vehicle speed and mass, respectively.

When driving on a flat road, the power distribution can be resolved as Equation (3) if the slope resistance is ignored:

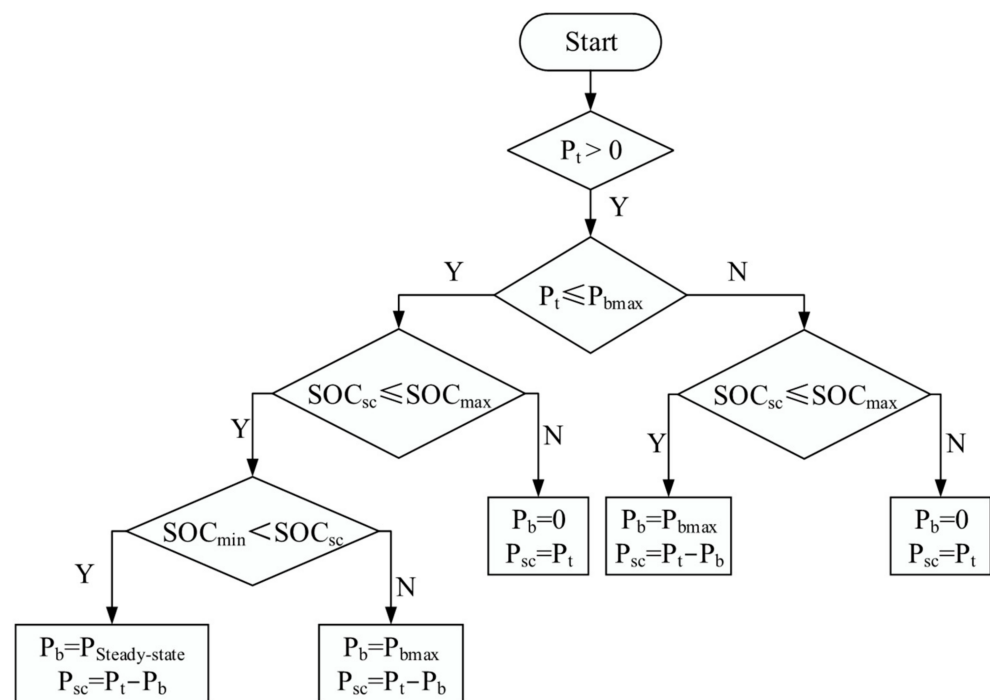
$$\begin{cases} P_b = P_w + P_f = Gf \cos(\alpha) + \frac{C_D A}{21.15} v^3 \\ P_{sc} = P_j = \delta m v \frac{dv}{dt} \end{cases} \quad (3)$$

where  $P_b$  and  $P_{sc}$  represent the real-time power of the battery and that of the supercapacitor, respectively;  $P_w$  and  $P_f$  are the rolling resistance and air resistance, respectively;  $P_j$  denotes the acceleration resistance.

Under driving conditions, the power output from the power battery and the supercapacitor is reasonably allocated according to the power demanded by the vehicle and the current SOC of the supercapacitor. The specific power distribution control strategy is shown in Figure 3. The specific control strategy is as follows:

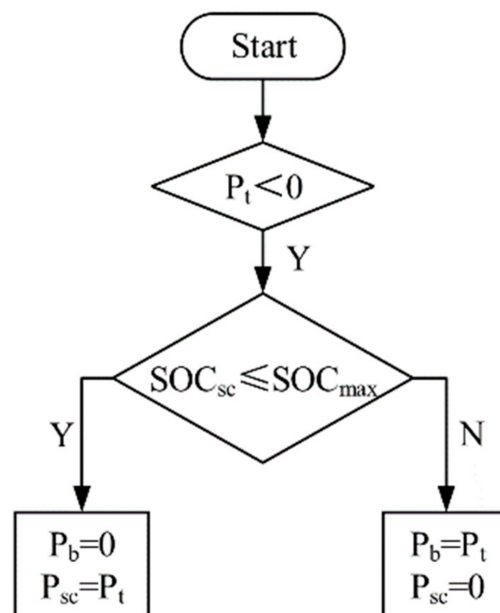
(a) When the required power is less than the maximum steady-state power and the current supercapacitor SOC is greater than the maximum control threshold  $SOC_{max}$ , the supercapacitor is used to provide all the necessary power. When the SOC of the supercapacitor is between the minimum control threshold  $SOC_{min}$  and the  $SOC_{max}$ , the power battery provides all the required power. As the  $SOC_{min}$  is larger than the SOC, to avoid excessive discharging of the supercapacitor, the power battery outputs the maximum steady-state power, part of which is used for driving and the rest for supercapacitor charging.

(b) The maximum steady-state power cannot achieve the power demand; that is, when the vehicle enters the acceleration phase, if the SOC of the supercapacitor is greater than  $SOC_{max}$ , the supercapacitor is used to provide all the needed power; when the SOC drops below  $SOC_{max}$ , to avoid high-current discharging of the power battery, the power battery provides steady-state power, and the supercapacitor provides the remaining power demanded.



**Figure 3.** Flow chart of power distribution under driving conditions.

Under braking conditions, the required power is less than zero, and the vehicle enters the braking energy recovery state. To reduce the amount of pulse charging during a short period of time while recovering as much braking energy as possible, the supercapacitor performs all its energy recovery when its SOC has not reached  $SOC_{max}$ , as shown in Figure 4; only when the supercapacitor SOC reaches  $SOC_{max}$  can it be transferred to the power battery for energy recovery, and part of the energy recovered is used for the internal consumption of the vehicle.



**Figure 4.** Flow chart of energy recovery under braking conditions.

### 3.2. EMS Based on Slope Information

#### 3.2.1. EMS Based on Slope Information When Driving Uphill

In this paper, the road information ahead is obtained through the Global Navigation Satellite System or the environment perception systems, such as a camera and 3D laser. Energy allocation based on the global path will inevitably lead to the neglect of local real-time driving conditions of the road, resulting in a poor distribution effect, so it is necessary to carry out real-time forward path perception. The algorithm must provide an adequate reflection distance to ensure sufficient pre-charge and discharge of the supercapacitor, so a pre-perceived distance needs to be determined. The relationship between the maximum slope length, the maximum slope, and the maximum speed limit was obtained according to the urban road engineering design specifications. Combined with the vehicle information and ignoring the acceleration situation in the uphill condition, the power battery can provide steady-state power for resolving both air resistance and rolling resistance, and the supercapacitor provides the climbing power to overcome slope resistance. According to the slope resistance formula, the maximum climbing power demand and the maximum energy consumption of the supercapacitor are calculated to estimate the longest pre-charge distance for all uphill conditions. This pre-charge distance is used as a trigger point. When the vehicle passes the trigger point, the energy consumption of the slope ahead is predicted.

The maximum required power of the supercapacitor is the power needed for climbing the road with the maximum slope at the maximum defined speed:

$$P_{sc\ max} = \frac{v_{max}}{3.6} G \sin(\alpha_{max}) \quad (4)$$

where  $\alpha_{max}$  is the maximum slope, and  $v_{max}$  is the maximum defined speed at this slope condition.

Currently, the maximum steady-state power of the vehicle is as follows:

$$P_{w\ max} = \frac{v_{max}}{3.6} (Gf + \frac{C_D A v_{max}^2}{21.15}) \quad (5)$$

The estimated climbing energy consumption of the supercapacitor is as follows:

$$W_{sc\ max} = P_{sc\ max} t = \frac{L}{V_{max}} P_{sc\ max} \quad (6)$$

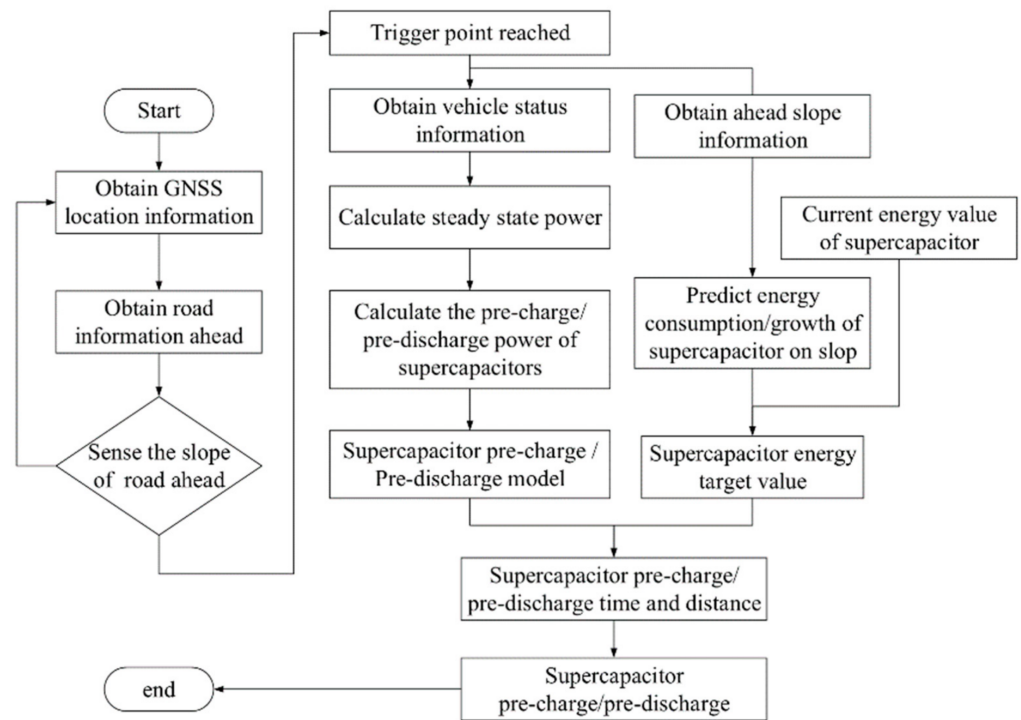
Therefore, the maximum pre-charge distance is as follows:

$$L_{max} = \frac{W_{sc\ max}}{P_{B\ max} - P_{w\ max}} V_{max} \quad (7)$$

In the equations,  $P_{sc\ max}$  is the maximum output power of the supercapacitor, which is equal to the power needed for climbing the road with the maximum slope;  $P_{B\ max}$  denotes the maximum battery output power; and  $L$  and  $V_{max}$  are the longest slope length and maximum slope climbing speed, respectively.

As shown in Figure 5, when the vehicle reaches the trigger point, the vehicle navigation system is used to obtain the information of the road ahead and predict the slope and slope length data of the road ahead. The current output energy of the supercapacitor can be obtained through the calculation of the terminal voltage of the supercapacitor; the design specifications of urban road engineering are queried to obtain the maximum design speed at the slope, which is used as the limit to estimate the speed of the vehicle. The estimated speed and slope information is used to obtain the estimated energy consumption to overcome the slope resistance. The energy needed to charge the supercapacitor can be estimated by subtracting the current remaining energy of the supercapacitor from the estimated energy consumption. The steady-state power at the current vehicle speed is obtained and subtracted from the maximum steady-state power of the battery to obtain the charging power of the supercapacitor. The energy needed to charge the supercapacitor is

divided by the charging power of the supercapacitor to obtain the pre-charge time, and the pre-charge distance can be calculated by multiplying the current vehicle and the pre-charge time. When the vehicle travels the target pre-charge distance, it enters the pre-charge mode so that when the vehicle reaches the uphill point, the supercapacitor is charged to the target SOC and can provide enough power for going uphill.



**Figure 5.** Flow chart of EMS based on ramp information.

The currently available output energy of the supercapacitor is as follows:

$$W_{sc} = \frac{1}{2}NC(U_t^2 - U_{min}^2) \quad (8)$$

The estimated loss of energy due to slope resistance is as follows:

$$W_s = F_t L = GL \sin(\alpha) \quad (9)$$

The charging power is as follows:

$$P_{b2sc} = P_{bmax} - P_w \quad (10)$$

The estimated charging distance is as follows:

$$L = v_t t = \frac{W_s - W_{sc}}{P_{b2sc}} v_t \quad (11)$$

In the equations,  $U_t$  is the real-time terminal voltage of the supercapacitor,  $U_{min}$  is the minimum voltage limit for supercapacitor discharge,  $C$  presents the supercapacitor capacitance,  $P_{bmax}$  denotes the maximum battery output power, and  $P_w$  stands for the steady-state output power.

### 3.2.2. EMS Based on Slop Information When Driving Downhill

To maintain a stable speed under the downhill condition, the vehicle needs to brake. To achieve enough braking energy recovery, the vehicle needs to discharge the supercapacitor in advance. The relationship among the maximum slope, maximum speed, and maximum



slope length is obtained through the urban road engineering design specifications, and the maximum amount of energy recovered is obtained based on the relationship and the energy recovery efficiency, that is, the recovery capacity that the supercapacitor needs to reserve. The supercapacitor is used to provide all the steady-state power to discharge the capacitor quickly. The maximum pre-discharge distance is obtained by multiplying the discharge time and the vehicle speed. This distance is used as the trigger point, at which the vehicle predicts the energy to be recovered on the slope ahead. The vehicle navigation system is used to predict the slope and slope length data of the road ahead, and these data and the current vehicle speed are used to estimate the amount of braking energy to be recovered. The available capacitance of the supercapacitor is calculated based on the current terminal voltage and the estimated voltage. The amount of energy to be pre-discharged is obtained by subtracting the available capacitance of the supercapacitor from the braking energy to be recovered. Then, the steady-state drive power at the current vehicle speed is obtained. Under the premise that the supercapacitor is used to provide all the drive power, the pre-discharge time and pre-discharge distance are estimated. When the vehicle reaches the target pre-discharge distance, it enters the pre-discharge mode. When the vehicle reaches the downhill segment, the supercapacitor has enough storage capacity for braking energy recovery.

When the motor generates power, the following equation can be obtained according to the power balance:

$$P_v = \frac{P_m}{\eta_m} \quad (12)$$

If the loss of electric energy in the transmission process  $\eta_r$  is considered, then the net energy recovered is as follows:

$$P_{sc} = P_m \eta_r = P_v \eta_m \eta_r \quad (13)$$

The total energy recovered is as follows:

$$W_{sc} = P_{sc} t = P_{sc} \frac{L}{V} \quad (14)$$

The supercapacitor pre-discharge is as follows:

$$W_{sc\_out} = W_{sc} - \frac{1}{2} NC(U_{max}^2 - U_t^2) \quad (15)$$

The estimated pre-discharge distance is as follows:

$$L = v_t t = \frac{W_{sc\_out}}{P_t} v_t = \frac{W_{sc\_out}}{\frac{v_{max}}{3.6} \left( Gf + \frac{C_D A v_{max}^2}{21.15} \right)} v_t \quad (16)$$

In the equations,  $P_v$  is the input mechanical power of the motor, and braking is necessary to keep a constant speed in the downhill segment;  $P_v = P_j = Gv \sin \alpha$ ;  $P_m$  is the motor output power;  $P_v = \frac{Tn}{9550}$ ,  $\eta_m$  represents the motor power generation efficiency, which is affected by motor loss and performance;  $U_{max}$  stands for the maximum rated voltage of the supercapacitor; and  $U_t$  denotes the real-time voltage of the supercapacitor.

#### 4. Simulation Analysis

To verify the optimization effect of the designed EMS based on the slope information, a hybrid energy vehicle model and the designed EMS simulation model are built with the adoption of MATLAB/Simulink software. The existing NYCC driving conditions are enhanced by adding slope driving condition data, and a simulation test is conducted for the driving conditions after adding the slope information. The proposed EMS based on slope information is compared with the existing speed-based EMS to verify its feasibility and accuracy.

#### 4.1. Simulation Model Parameters

In this paper, a small all-wheel-drive electric transport vehicle is used as a simulation platform, and urban road conditions are used as the driving environment for simulation. The main parameters of the vehicle are shown in Table 1.

**Table 1.** Vehicle simulation parameters.

Parameter Name	Value
Total weight (kg)	400
Axel distance (mm)	1080
Centroid height (mm)	450
Rolling resistance coefficient	0.02
Wheel rolling radius (m)	0.22
Windward area (m <sup>2</sup> )	1.22
Air resistance coefficient	0.31
Transmission system efficiency	0.92
Rotating mass conversion factor	1.03

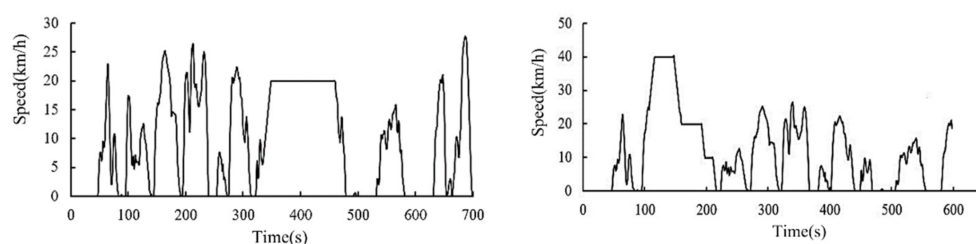
The vehicle uses a drive motor with a rated voltage of 48 V. The specific parameters of the HESS are presented in Table 2.

**Table 2.** Parameters of the hybrid power system.

Name	Capacity	Rated Voltage	Number
Power battery	80 Ah	48 V	1
Supercapacitor	630 F	2.5 V	19

In the simulation models, the battery and the supercapacitor were modelled as a first-order buffer [35]. The Rint internal resistance model was adopted for the battery, and RC model was selected to simulate the supercapacitor. The energy distribution control strategy in this paper only involves the calculation of DC/DC converter conversion efficiency. Therefore, the efficiency conversion model of DC/DC is established.

To simulate the uphill and downhill conditions of vehicles, the NYCC was adjusted. The standard NYCC driving conditions are urban traffic conditions and do not involve sloped roads. However, in the actual traffic and transportation environment, uphill and downhill road conditions are commonly expected. So the NYCC driving conditions are increased with uphill and downhill conditions and modified as follows: accelerate to 20 km/h at 339 s, drive at a constant speed for 50 s, and enter a road segment with a slope of 5% and length of 300 m at 401 s, as shown in Figure 6a; and accelerate to 40 km/h at 100 s, drive at a constant speed for 30 s, and enter a road segment with a slope of −5% with a length of 350 m at 147 s, as shown in Figure 6b.



(a) NYCC driving condition with a long uphill (b) NYCC driving condition with a long downhill

**Figure 6.** Incorporation of up and down slopes into NYCC driving conditions.

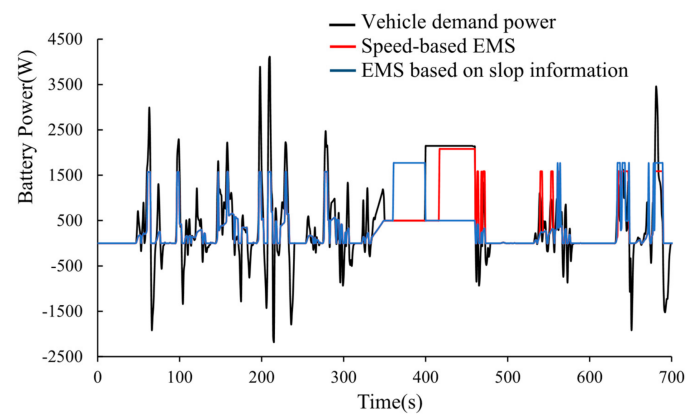
## 4.2. Simulation Results

For NYCC driving conditions with uphill and downhill slopes added, the improved speed-based EMS (no slope prediction) and the EMS based on slope information are used for simulation. Using the vehicle speed and slope information as inputs, the power battery power curve, supercapacitor power change curve, power battery current curve, power battery SOC curve, and supercapacitor SOC curve are obtained. The results are shown below.

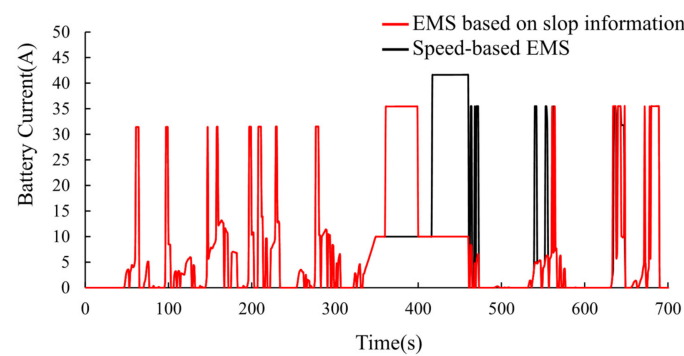
### 4.2.1. Uphill Simulation

From Figure 7a–d, 330 s ahead of the simulation time, the road slope is 0, and the two EMSs are based on vehicle speed. The power battery is responsible for the vehicle-stabilized speed driving power, and the supercapacitor is responsible for the energy distribution for acceleration power and braking energy recovery. Therefore, the two strategies have the same output power of the power battery, and the changes in the battery SOC and the supercapacitor SOC are the same. Compared with the vehicle demand power (power battery output power under a single energy source supply), the EMS can fully use the high-power density of the supercapacitor during the startup and acceleration phases as the vehicle demand power is high, and fully reduce the discharge of the power battery current to avoid battery high-power discharge. As presented in Figure 7a, during 197 to 201 s, 208 to 212 s, and 543 to 549 s of the vehicle's rapid acceleration time, the vehicle is at high speed and under high acceleration, and the peak demand powers are 3887.3 W, 4054.9 W, and 3437.5 W, respectively. The maximum stable output power set by the power battery is 1771.4 W, and the excess part of the power is provided by the supercapacitor. Compared with the output power of the single power battery, the output power is reduced by 54.43%, 56.31%, and 48.47%, achieving the peak clipping effect. In the braking process, the characteristics of supercapacitors that can be quickly charged with high current are fully utilized in the recovery of the braking energy to avoid switching between charge and discharge modes of the power battery within a short period of time. At 66 s, 215 s, and 514 s, the peak charging currents of the power battery for sudden braking of the vehicle are  $-1890.8$  W,  $-2175$  W, and  $-1886.1$  W, respectively. The supercapacitor performs rapid energy recovery, and the power battery does not change the discharge mode. The effect of filling the valley can better protect the battery, prolong its service life, and provide the vehicle with greater peak power to ensure mobility.

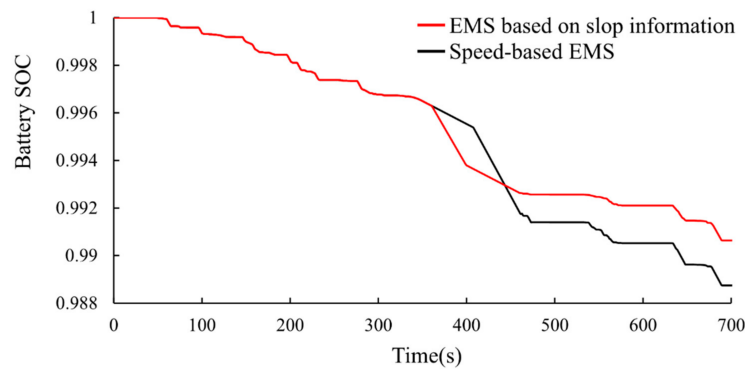
Figure 7b shows that at 350 s, the vehicle is travelling at a constant speed of 20 km/h, and the battery has a stable output power of 498.89 W and a stable discharge current of 9.98 A. At 363 s, the EMS based on the slope information predicts that the remaining SOC of the supercapacitor will not be able to satisfy the higher uphill power of the vehicle, so it enters the pre-charging mode, and the power battery output power increases to the maximum stable output power of 1771 W, its discharge current is 35.4 A, and the duration is 39 s. After the uphill segment is entered, the power battery stably outputs at lower power, and the climbing power is borne by the supercapacitor. Since the speed-based EMS cannot predict the demand for climbing, the peak power of the battery reaches 2079.6 W, and the discharge current is as high as 41.6 A for a duration of 43 s. The EMS based on slope information effectively reduces the discharge current and the duration of high-power discharge, effectively protecting the power battery. Figure 7c and d show that under EMS based on slope information, as the supercapacitor is pre-charged before going uphill, the battery SOC drops faster, and the supercapacitor SOC is higher than those under the speed-based EMS based on vehicle speed. After 400 s, the vehicle enters hill-climbing driving, the power demand of the vehicle increases, the power battery maintains a constant speed driving power, the supercapacitor bears a larger climbing power, and the power battery outputs steady-state driving power; thus, the SOC of the power battery decreases, the output power of the supercapacitor increases, and the SOC decreases faster. At 460 s, the vehicle finishes climbing, and the SOC of the supercapacitor is 0.368. At the end of the simulation, the power battery SOC was 0.9906.



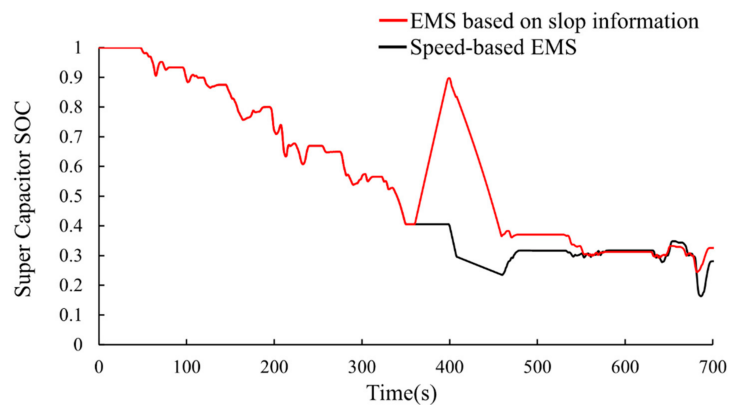
(a) Battery power using different EMSs.



(b) Battery current using different EMSs.



(c) Battery SOC with different EMSs

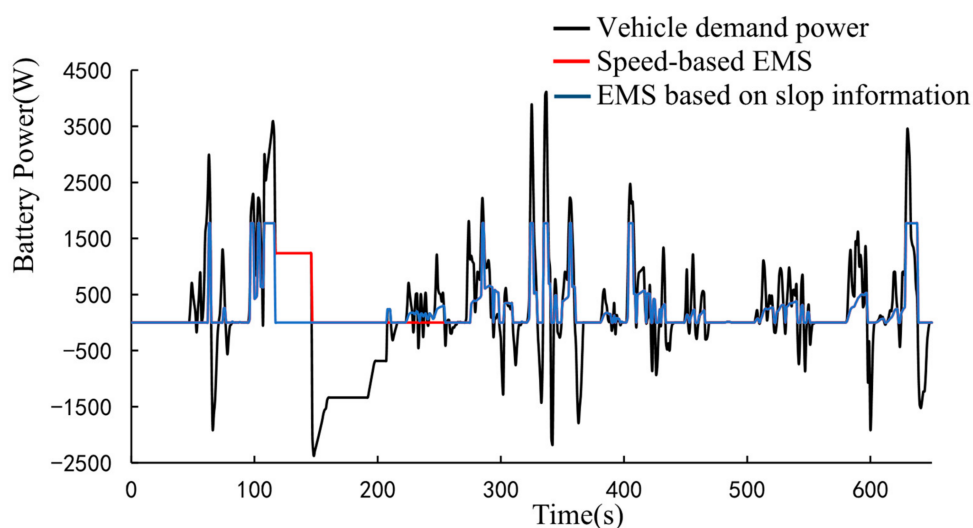


(d) SC SOC with different EMSs.

**Figure 7.** Simulation results of uphill working conditions.

#### 4.2.2. Downhill Simulation

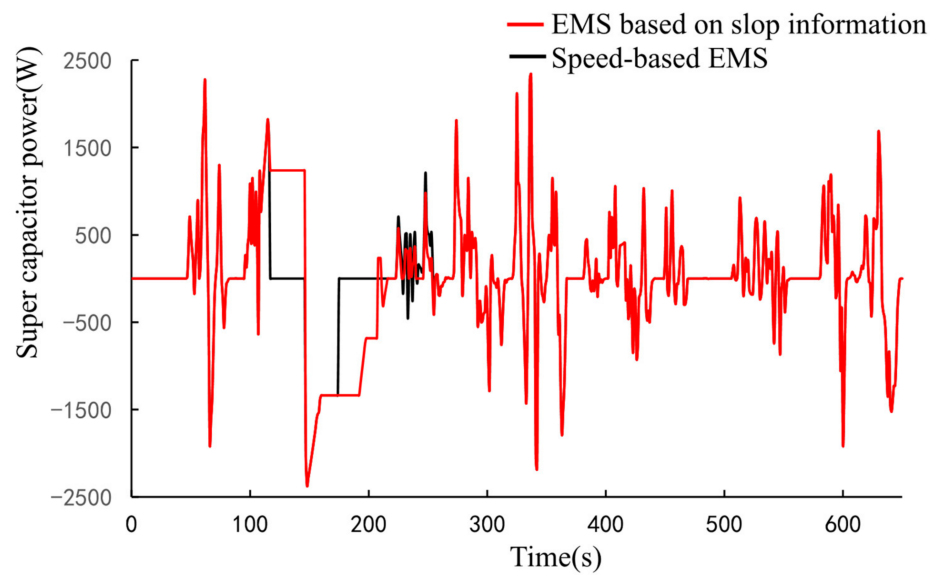
As the vehicle is coming to a downhill condition, the supercapacitor is discharged in advance to ensure that the supercapacitor has enough space to recover braking energy during the downhill process and avoid a short-term mode change in the power battery. As shown in Figure 8d, after 117 s, the remaining SOC of the supercapacitor is 0.769. The EMS based on the slope information predicts that the chargeable capacity of the supercapacitor cannot meet the energy recovery of the vehicle during the downhill process, so it enters the pre-discharge mode. The power battery stops outputting power, and all the power required by the vehicle is undertaken by the supercapacitor. As the output power of the supercapacitor increases, its SOC drops faster. At 147 s, when the vehicle enters downhill driving, the SOC of the supercapacitor is 0.42, which frees up enough capacity space for the subsequent energy recovery. The supercapacitor enters the charging mode, and its SOC continues to increase. At 207 s, the vehicle finishes driving down the slope, and the supercapacitor SOC reaches 0.857. In the speed-based EMS, because the supercapacitor is not discharged in advance, the energy recovery is stopped after the supercapacitor is charged to the full SOC. Figure 8a shows that before the vehicle enters the downhill segment, the supercapacitor pre-discharge stage, the power battery output power in the EMS based on slope information mode is 0, while in the speed-based EMS mode, the power battery still provides steady-state output power. Figure 8b shows that in downhill conditions, the EMS based on slope information can fully use the high-power density and fast-charging and fast-discharging characteristics of the supercapacitor, performing high-power discharge in advance and fully recovering the braking energy. Figure 8c shows that due to the pre-discharge before the downhill region and the full recovery of energy during the downhill, the EMS based on slope information yields a higher SOC for the power battery in the subsequent stages. The power battery SOC reaches 0.9951 at 700s, while in the vehicle speed-based EMS mode, the power battery SOC is only 0.9936.



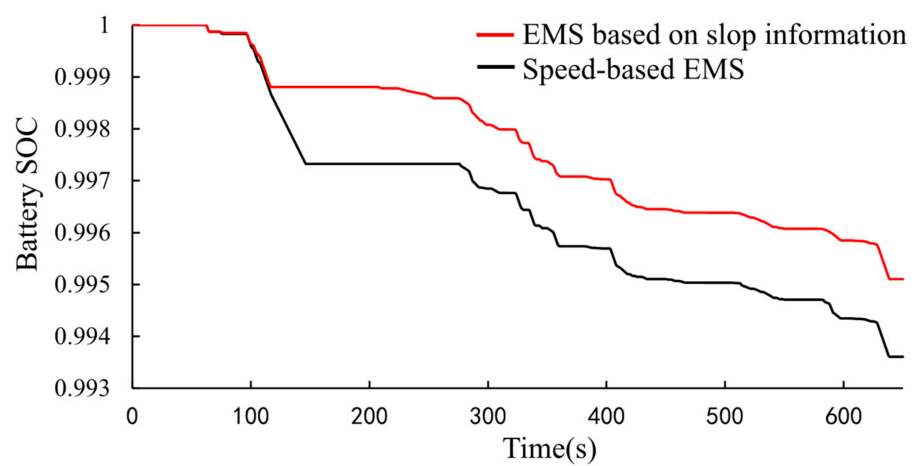
(a) Power of battery with different EMS.

Figure 8. Cont.

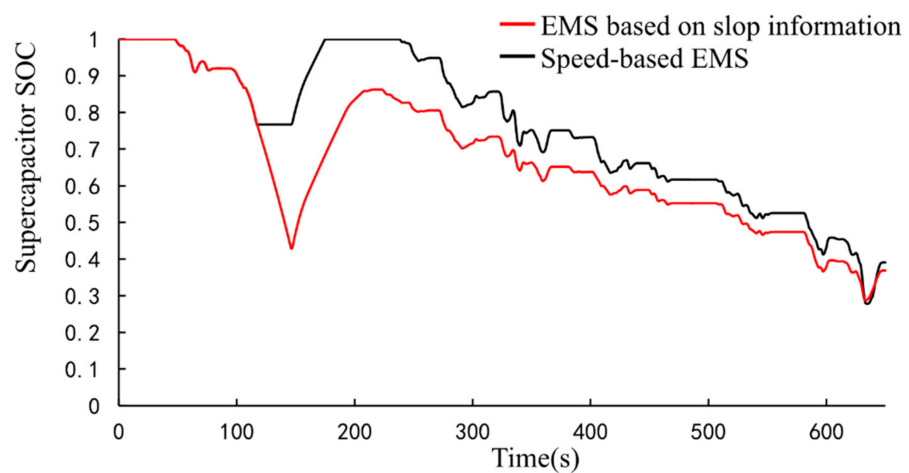




(b) Power of SC with different EMS.



(c) SOC of battery with different EMS.



(d) SOC of SC with different EMS.

**Figure 8.** Simulation results under downhill conditions.

In general, the EMS based on slope information ensures that the SOC of the supercapacitor meets the energy required for slope driving by pre-charging the supercapacitor before going uphill, avoids excessive discharge of the supercapacitor, and effectively reduces the power battery discharge power during the uphill process. Compared with that under the speed-based EMS, the peak discharge current of the power battery is 14.9% lower, which effectively extends the power battery lifespan, saves energy, and increases the driving mileage. Pre-discharge of the supercapacitor before going downhill ensures that the supercapacitor can fully recover energy, avoid the overcharging of the supercapacitor and the adverse effect of the large peak current of the power battery during the downhill process, and effectively extend power battery lifespan. Compared to that under the speed-based EMS, the energy recovery efficiency is 20.4% higher, effectively increasing the cruising range.

## 5. Conclusions

This paper studies the EMS of a HESS and analyzes the impacts of road slope information on vehicle energy distribution. By incorporating road slope information into the existing speed-based EMS, a rule-based EMS based on slope information is designed to exploit the performance of supercapacitors and power batteries completely. Compared with the existing speed-based EMS, this EMS can reduce the high-current discharge of the battery in uphill conditions and can fully recover the braking energy when going downhill, achieving better energy distribution control. The simulation is conducted by adopting MATLAB/Simulink software, and the results indicate that the EMS based on slope information can fully utilize the high energy density of supercapacitors and high-current charging and discharging characteristics. It can also improve the high-current discharging of the HESS and reduce power battery charge and discharge switching in a short time. Compared with speed-based EMS, this EMS based on slope information can better prolong power battery life and obtains better power performance while enabling the supercapacitor to absorb the braking energy, extending the driving range.

Although this article probes into the application of the energy management strategy of the hybrid power system based on road slope information, due to the limitations of academic level, research time and experimental conditions, some aspects still need to be further deepened, mainly as follows: (1) The designed energy management strategy of the hybrid power system based on road slope information is only designed to predict the slope ahead and allocate energy reasonably. In addition, there are also factors such as curves, traffic lights and speed limits. This has an impact on energy management strategies, and this road information can be added for in-depth research in the future. (2) When designing the energy management strategy, the influence of the driver model on the driving of the vehicle can be considered to fit closer to the actual driving scene. (3) On account of the limitation of experimental conditions, this paper verifies the designed energy management strategy of the hybrid power system through theoretical analysis and simulation experiments. The effectiveness of the strategy can be further verified through hardware-in-the-loop experiments or real-vehicle experiments.

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