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INDEPENDENT CONTROL STRATEGY for performance improvement of Super Capacitor on MMC DC-DC Converter

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Abstract: The vessel integrated power system (IPS) exhibits a rising demand for high-voltage and large-capacity energy storage systems in order to equip additional high-energy pulse loads and enhance power supply reliability. On the basis of this background, this paper focuses on a cascaded DC-DC converter that uses a modular multilevel converter (MMC) and dual active bridges (DAB) to create a super capacitor energy storage system. The abbreviation for the cascaded converter is MMC-DAB. In-depth analyses of the system's topology and modulation scheme are provided in this work. This paper suggests a control method that uses the DAB module of each branch to independently adjust the voltage of the sub-module capacitor while taking into account the drawbacks of the conventional bidirectional power control strategy. The traditional and proposed control's mathematical models.

Keywords: Vessel integrated power system, super capacitor energy storage system, bidirectional power control, sub-module capacitor voltage control.

I.INTRODUCTION

In the areas of ship propulsion, ship information technology, and DC power distribution, the vessel integrated power system has drawn a lot of interest. IPS will inevitably be one of the technical paths for renewable energy ships in the future [1]–[3]. Energy storage systems have recently become an essential component of the second-generation IPS due to the rising demand for improved ship power supply dependability, equipment of pulsed loads, and new high-energy weaponry [4], [5]. This means that the energy storage converter that is connected to the IPS medium voltage DC (MVDC) grid must have high voltage and big capacity, voltage conversion, electrical isolation, and bidirectional conversion.

The converter can employ series-parallel technology to align with the MVDC power grid; the input series output parallel (ISOP) structure is the most

Popular type of this technology and can raise the voltage and current levels of the converter [6]. To increase the power level of the train traction system,

[7] Proposes a power electronic transformer made of H-bridges cascaded by DABs. Multiple standardized DC-DC converters are connected in series and parallel in the literature [8], [9] to increase the converter's modularity and voltage and current levels. However, the majority of the aforementioned topologies use centrally series-connected capacitors and have weak fault redundancy capabilities, making them unsuitable for situations requiring a reliable and continuous power supply.

Due to its modular design and fault tolerance, MMC is frequently utilized in high-voltage and large-power applications [10]. The control techniques of a super capacitor energy storage system based on MMC are investigated for high-voltage rail transit vehicles in [11], [12]. These two papers present the corresponding energy management techniques while realizing the balanced decoupling control of super capacitor power. In [13], the charge state balance of energy storage elements is resolved by studying the control strategy of a modular multilevel energy storage system under the two operational grid voltage symmetry and asymmetry. A fault diagnosis technique for MMC super capacitor energy is presented in [14] based on the combination of a straightforward hardware detecting circuit and an FPGA diagnosis algorithm.

Between the MVDC grid and LVDC grid, an isolated bidirectional DC-DC converter must be employed in order to achieve electrical isolation and voltage conversion. DAB is a modular, symmetrical, bidirectional DC-DC converter having the capacity to isolate electrical signals. It has received a lot of interest in the fields of energy storage systems, DC micro grids, and electric cars [15][17]. A solid-state transformer that uses the cascaded structure of half-bridge sub-modules and DAB as the branch topology and ISOP as the overall structure is proposed in [18], [19]. This topology is appropriate for an MV distribution network since it supports the realization of fault tolerance and modular architecture. A three port DC-DC converter for IPS made up of MMC, DAB, and duplicate chopper circuits is presented in [20].

But in the aforementioned literature, the application scenario of connecting a resistive load to the LVDC bus of the MMC-DAB is studied. The sub-module capacitor voltage is controlled by MMC, and the LVDC bus voltage is controlled by DAB, according to their control strategy. The DAB module typically regulates the port current of the energy storage unit if this method is applied to an application scenario with an energy storage unit connected on the LVDC side. The LTER inductor must be connected between the DAB converter and the energy storage unit in order to properly manage the port current of the energy storage unit. The device's volume and weight will grow as a result, and the DAB control system's stability margin will be reduced. particularly when releasing the super

Based on the foregoing research, this study investigates the control scheme and stability of super capacitor energy storage system based on MMC-DAB in order to satisfy the application needs of the vessel integrated power system. The following are the primary inno- vations of this paper: (1) A control approach based on independent regulation of sub-module capacitor voltage is proposed and the bidirectional power conversion of a super capacitor energy storage system based on MMC-DAB is examined. (2) To validate the suggested control technique, a 1MW engineering prototype of the MMC-DAB energy storage system is built and produced.

This essay is divided into the following sections: The structure and fundamental ideas of the cascaded energy storage system based on MMC-DAB are introduced in Section II.

The traditional control approach is examined in Section III, and a mathematical model of the traditional control technique is developed. Additionally, the stability of the DAB closed-loop control system is examined. Section IV proposes a technique based on independent regulation of sub-module capacitor voltage, then compares and models the stability of the suggested strategy.

II. TOPOLOGY AND BASIC PRINCIPLE OF SUPER CAPACITOR ENERGY STORAGE SYSTEM BASED ON MMC-DAB

A.TOPOLOGY OF MMC-DAB

This essay's sections are divided into the following groups: The cascaded energy storage system based on MMC-DAB's topology and fundamental principles are introduced in Section II.

The traditional control strategy is examined in Section III, where the traditional control method's mathematical model is also constructed. Additionally, the DAB closed-loop control system's stability is examined. The method based on independent regulation of sub-module capacitor voltage is proposed in Section IV, and the proposed strategy's stability is modelled and compared. The aforementioned theory is tested by experiments in Section V using a 1MW engineering prototype. In Section VI, a conclusion is presented.

Bidirectional power conversion, a high level of modularity, and fault tolerance are the characteristics of MMC-DAB, which can be used to integrate high-voltage large-capacity energy storage units and enhance power supply reliability. The MVDC bus's voltage and current are shown in Fig. 1 as UMV and iMV, respectively. The LVDC bus's voltage and current are designated as ULV and iLV, respectively. The i-th sub-module of the MMC's capacitance and voltage are designated as Csi and usi, respectively. The MVDC side's inductance is designated as LMV. On the LVDC side, Cfi is the _lter capacitor for each branch. Leakage inductance and leakage inductance current of each branch's transformer are represented by Lsi and iLi, respectively.

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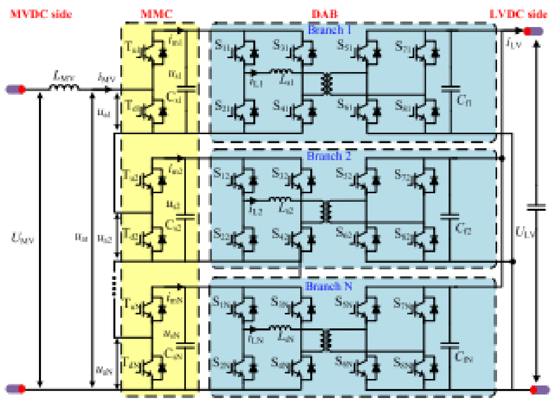


Fig(1): Topology of super capacitor energy storage system based on MMC-DAB

B.PRINCIPLE OF MMC

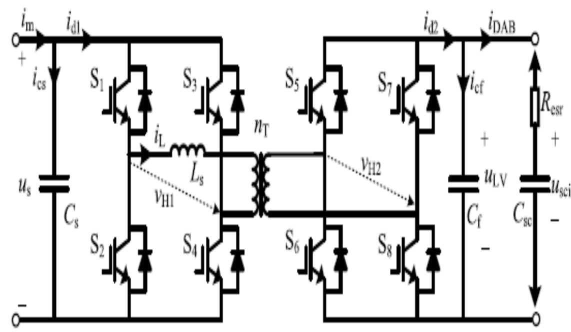
Half bridge sub-modules coupled in sequence make up MMC. When a branch fails, the energy storage system can swiftly bypass the sub module and switch off the entire branch to support ongoing operation.

MMC uses carrier phase-shift modulation to lessen the current ripple on the MVDC side. The upper and lower switches of the same half bridge sub-modules have complementary driving pulse signals. The driving pulse signals of the corresponding switches of adjacent sub-modules have a phase-shift angle of 2/N, where N is the total number of sub-modules. A switching cycle Tm is divided into N pieces by taking into account the relationship between the duty cycle of the higher switch and the carrier phase-shift angle. The sum of the cascaded input voltage inside each component

C.PRINCIPLE OF DAB

The topology of DAB is comprised of two H-bridges and high-frequency transformers, as shown in Fig. 2. Us is the DAB high-voltage side port voltage in Fig. 2. The DAB low-voltage side port voltage is known as uLV.The high-frequency transformer's transformation ratio is designated as nT. The low-voltage side capacitor is designated as Cf. The equivalent super capacitor of each branch has a capacitance and resistance of Csci and Resr, respectively.

By implementing voltage matching control when operating within the energy storage unit's rated voltage range, the DAB can match the voltage of the sub-module on the high-voltage side with the voltage of the energy storage unit on the LVDC side, which is helpful for optimizing the high-frequency circulation characteristics and current stress of the DAB.



Fig(2):Topology structure of DAB module

III. TRADITIONAL CONTROL STRATEGY AND MODELING

According to the conventional control strategy, as shown in Fig. 3, the control objectives for MMC's dual closed-loop control are the sub-module capacitor voltage and the current of the MVDC bus, while for DAB converters, the control objective is the LVDC side current of each branch. The PI regulator of the inner loop generates the shared duty cycle dm_ave of the sub-modules, while the outer voltage loop of the MMC controller generates the reference value of the current of the MVDC bus. The sub-module voltage balancing regulator produces the compensation duty cycle dm_exti to balance the sub-module's capacitance voltage while taking the difference between branches into account.

The total of the reference value and the actual value of the capacitance voltage across all sub-modules is represented in Fig. 3 by Nus_ref and us_All, respectively. Usi and us_ave stand for the capacitance voltage of each sub-module's individual and average values, respectively. The current of the MVDC bus's reference value and real value are represented by the variables iMV_ref and iMV, respectively.

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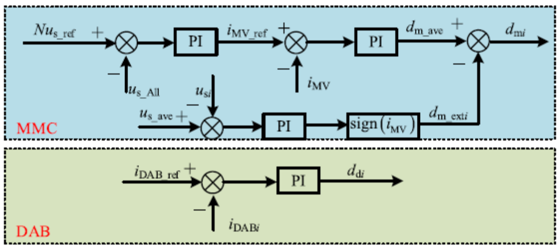

Fig (3): Block diagram of traditional control strategy of MMC-DAB

It is difficult to control the charging or discharging current when the DAB converter is linked with energy storage devices like super capacitors. A different inductor must be installed between the DAB and the super capacitor as a result. The DAB now utilizes single-loop current control. Given that MMC controls the voltage on the high voltage side of DAB.As shown in Fig.4, from the small signal model of DAB under the traditional control strategy.

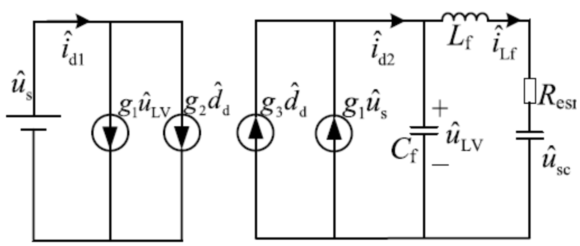

Fig (4): Small signal model of DAB module under traditional control strategy

The open-loop transfer function's frequency characteristic curve under the conventional control approach is depicted in Fig. 5 by MATLAB. The closed-loop system's relative stability is assessed using two of these parameters: Gm, which measures the amplitude margin of the open-loop transfer function of the closed-loop system, and Pm, which measures the phase margin. The stability of the closed-loop control system can be determined, in accordance with control theory, by determining whether the amplitude margin Gm>0dB and the phase margin Pm>$0^0$are satisfied. According to Fig. 5, the DAB control system is unstable when using the conventional control method since the amplitude margin Gm is 3.19 dB and the phase margin Pm is 6.96, which indicates that the DAB control system is unstable under the traditional control strategy.

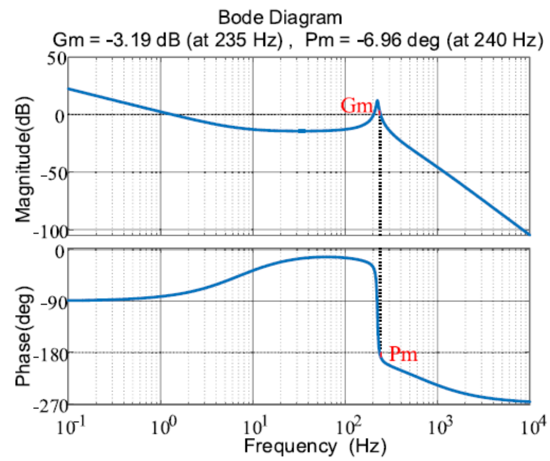

Fig (5): Open-loop frequency characteristic curve of DAB converter under traditional control strategy

In the above traditional control strategy, there are multiple PI regulators including the current control of MVDC bus, sub-module capacitor voltage balancing control of MMC and current control of DAB. There are many control variables, different regulators affect each other, and PI parameters are difficult to adjust. At the same time, when the DAB converter controls the current of the energy storage port, the system damping is small, which is difficult to realize the rapid charging and discharging of the super capacitor, and it may be also a problem of system instability.

IV. INDEPENDENT CONTROL STRATEGY OF SUB-MODULE CAPACITOR VOLTAGE AND MODELING

It is difficult to control the charging or discharging current when DAB is connected to energy storage devices like super capacitors; therefore, it is necessary to set an alternate inductance or interface converter at the input port of the super capacitor, but doing so will increase the system's structural complexity and volume weight. The DAB converter in each branch independently controls each sub-module capacitor voltage without controlling the charging or discharging current, which can simplify the converter structure and decrease the volume and weight of the system. This allows for more convenient control of the charging and discharging current of super capacitors. The following section will go into more detail about the control strategy this study suggests.

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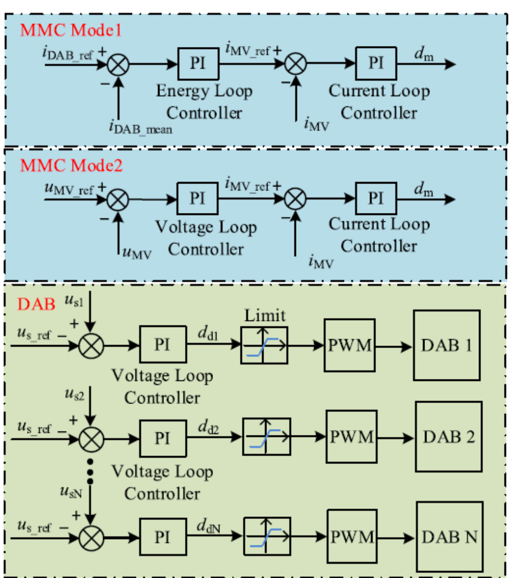
According to the control technique suggested in this paper, as depicted in Fig. 6, MMC employs double closed-loop control. The control objective of the outer loop is chosen in accordance with the operating mode, whereas the inner loop uses the inductance current on the MVDC side as its control objective. The voltage of the sub-module capacitor, which is controlled by N separate voltage regulators, is the control goal of each branch of the DAB converter in all modes. The port on the MVDC side can operate in one of two ways: (1) To realize the bidirectional energy flow between the MVDC bus and super capacitor, a bidirectional power source is attached to the MVDC bus in mode 1. In Mode 1, the DAB serves as the outer loop's control objective of the MMC.

According to Fig. 6, iDAB_ref and iDAB_mean represent the reference value and average of the super capacitor's charging or discharging current, respectively. The reference value and real value of the MVDC bus' current rental are denoted by the variables iMV_ref and iMV, respectively. The voltage of each sub-module capacitor's reference and actual values are, respectively, us_ref and us1 usi. The outer phase-shift ratio of each branch's DAB converter, which is produced by the voltage loop, is denoted by the numbers dd1 ddN.



Fig(6): Block diagram of independent control strategy of sub-module capacitor voltage for MMC-DAB.

The MVDC bus current is the MMC inner loop's control parameter in Mode 1. The reference value iMV_ref of the bus current produced by the outer loop controller is deducted from the actual value iMV of the current of the MVDC bus. The PI controller then generates the sub-module duty ratio dm. The system's outer loop, which controls system power and the super capacitor's charging or discharging current, is its energy loop.

The reference output current iMV_ref of the MVDC bus is created by the PI regulator after the difference between each DAB's reference output current (iDAB_ref) and the average current (iDAB_mean) of all N DAB is computed. And, Controlling the resistance voltage on the MVDC side is required in Mode 2 due to the resistance being linked at the MVDC side. Therefore, the MVDC bus voltage must be regulated by the MMC's outer loop. The voltage reference uMV_ref is deducted from the actual voltage uMV of the MVDC bus. To create the current reference on the MVDC side, the voltage error is transmitted to the PI regulator. Mode 2 shares the same inner control loop as Mode 1. The super capacitor energy storage device on the LVDC side must be supplying power to the resistance on the MVDC side for this control technique to work.

The voltage of the sub-module capacitor is always the control goal of the DAB converter of each branch, regardless of the MMC's working mode. The voltage of the sub-module capacitor is individually regulated by the voltage loop regulator used by DAB of each branch. The voltage reference value of the sub-module for DAB voltage matching control is us_ref D nTusc. The reference value us_ref is subtracted from the actual value usi because it is a negative feedback system. The driving pulse signal is then produced by the PWM generator, and the phase-shift ratio ddi of the DAB is generated by the PI controller.

The lower inductance can be omitted when the DAB regulates the voltage of the sub-module capacitor without regulating the current of the super capacitive energy storage system. The load on the DAB

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converter's primary side can be compared to a current source. Thus, Fig. 7 displays its modest signal model.

Since the energy storage unit is connected to the LVDC bus, the voltage on the LVDC side can be thought of as constant. The state variable for modelling is therefore decided to be the voltage of the sub-module capacitor. Additionally, its state equation can be written as

$$C_s \frac{d\hat{u}_s}{dt} = \hat{i}_m - \hat{i}_{d1} = \hat{i}_m - \left(g_1 \hat{u}_{LV} + g_2 \hat{d}_d\right)$$

The transfer function from disturbance source to state variable is expressed as after applying Laplace transformation to the aforementioned state equation.

V. SIMULATION

A . Energy Management Strategies

The simulation model is depicted in Figure.4. The squared SC voltage is relevant to the energy-based strategy because the SC energy is proportional to it. The link between the lowest SC voltage value Usc-min and the current observed SC voltage, which was also utilized to determine the SOC % of the SC in this study, served as the definition of the SOC-based strategy.

The Simulation Model of MLI with ESS is shown in Fig. 4. The SC SOC is defined to be linear with the voltage of the SC if the battery SOC is a nonlinear relationship with the battery voltage. The HESS is specifically impacted by this. The square of the SOC-based approach is the coefficient of the voltage-based algorithm, which is the last step. Despite the fact that all methods are calculated using SC voltage values

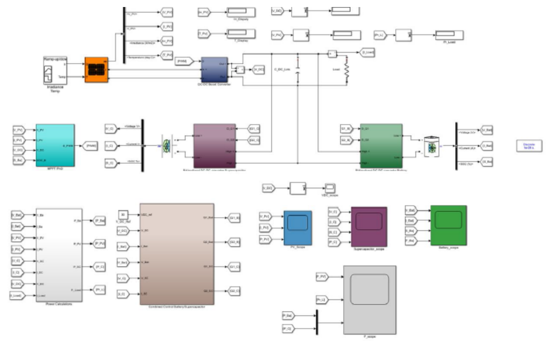


Figure 7. Simulation Model of MLI with ESS

In addition, a SC charging control block, seen in Figure 5, was used in conjunction with the aforementioned techniques to assist the SC in energy recovery when there is no need for vehicle power. If the absolute value of the traction current was less than e, the SC would be charged with a predetermined current. The value of in the simulation was 0.05 A. That was a relatively low value to prevent chitchat.

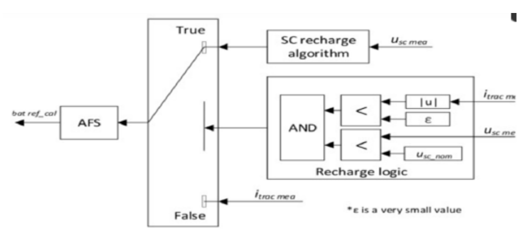
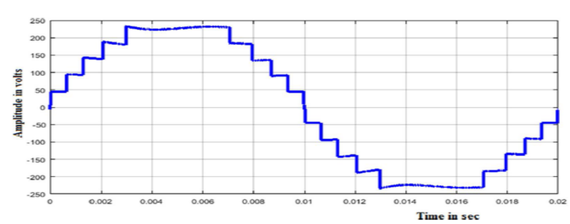


Figure 8. Super capacitor recharge control block

VII Simulation Results



Figure, 6.Eleven level output of MMI

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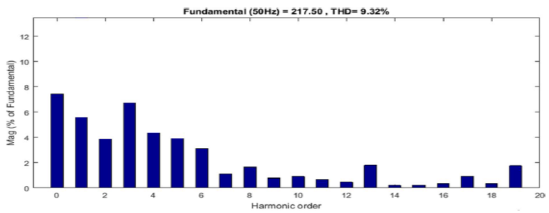

Figure 7. Voltage THD for RL load

Each input variable for the switching angle and modulation index in the proposed model is collected from the controller, and the output data is evaluated. Figure 6 displays the voltage produced by an 11-level inverter. As indicated in Figure 7, the next step is to fine-tune the ideal output variables for the eleven level output voltage with the least THD and for minimising the error speed. The simulation's output demonstrates the validation of input-output data pairings in order to produce the optimised THD. The acquired, carefully chosen data are trained.

A. PV OUTPUTS

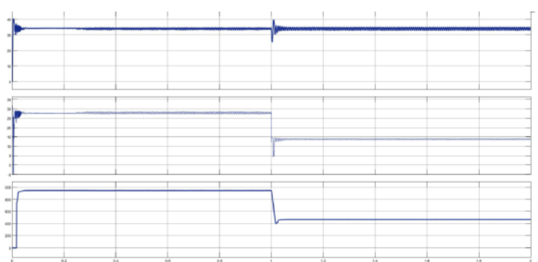

Figure 8. PV Outputs voltage and current

B. Battery Outputs

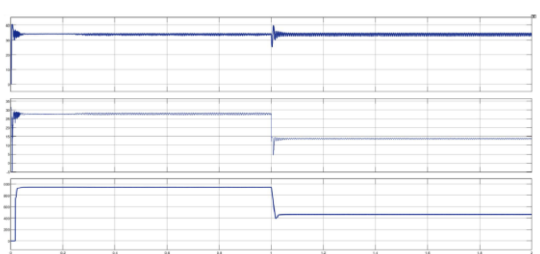

Figure 9. Battery Outputs voltage and current

C. Super Capacitor Outputs

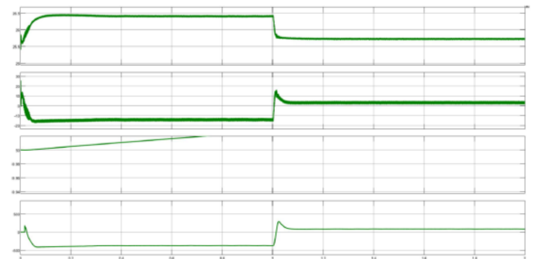

Figure 10. Super Capacitor Outputs voltage and current

The PV outputs, battery outputs, and super capacitor outputs are displayed in Figures 8, 9, and 10. In conclusion, urban cycles with significantly different and successive driving circumstances benefited the most from the energy-based approach. When used in less fluctuating driving settings, the SOC-based and voltage-based techniques performed better than the energy-based one. The battery voltage drop was also significantly reduced as a result of the battery's rms current and peak current being significantly reduced. The semi-active HESS design and the EMS thereby prevented negative effects on the electric drive system. As a result, it became clear that the battery/SC dual-source system and the suggested filtering procedures were better suited for electric vehicles than for other EV types that operate with smoother driving.

CONCLUSIONS

Using the SC stored energy, SOC, and voltage, this research offered three straightforward but efficient filter-based algorithms for the power allocation of a battery/SC EV. Our objective was to demonstrate the viability of an actual implementation. Additionally, the simulation development can be applied to the system control and EMS. To identify the best option, these proposed solutions were compared to one another before being examined alongside a pure battery car and a traditional filtering system under the identical working conditions. According to the results of the simulation, the HESS and EMS were crucial in safeguarding the battery under erratic driving circumstances. In the HESS with energy-based strategy, the super capacitor of the battery was only around one-third that of the battery only vehicle.

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