

**ARTICLE**

# Research on 48 V Super Capacitor Micro Hybrid System with 12 V Power Supply Multiplexing Function

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**ABSTRACT**

48 V lithium battery micro hybrid system is the most fuel economy vehicle which can be mass produced at present. However, with the irreversible internal resistance increase of the key component 48 V lithium battery, and the capacity continues to decline, the system performance deteriorate. Worst case could be the system not functional in the middle and later age of vehicle life cycle. This paper studies the feasibility of using 48 V super capacitor as the replacement to 48 V lithium battery, and uses a 12 V module of 48 V super capacitor as the traditional 12 V power supply, further reducing the number of components or reducing the demand for parts of 48 V micro hybrid system. This paper analyses the 48 V super capacitor micro hybrid system scheme, based on which a prototype is built, and carries out the vehicle comparative test. The results show that: (1) The performance of 48 V super capacitor micro hybrid system perform comparably with 48 V lithium battery micro hybrid system, and 12 V multiplexing function does not cause power loss of super capacitor; (2) The SOC fluctuation of super capacitor is larger than that of lithium battery, but it can satisfy all test conditions through the strategy; (3) The voltage mutation of super capacitor is smaller than that of lithium battery. It can greatly reduce the impact of voltage on vehicle electrical appliances. The 48 V super capacitor micro hybrid system with 12 V multiplexing function is of great significance.

**KEYWORDS**

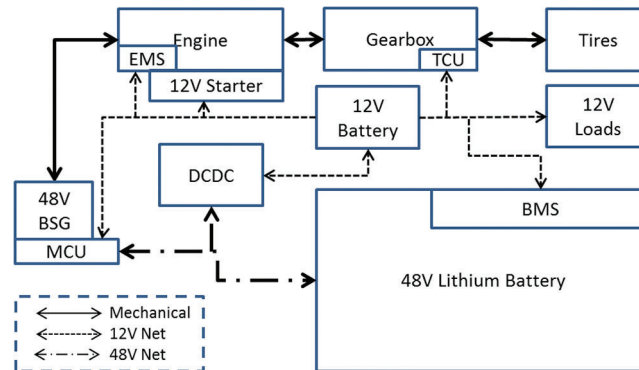
Super capacitor; 48 V; micro hybrid system; fuel saving

**1 Introduction**

In order to deal with the increasingly fuel economy requirement, vehicle manufacturers have developed fuel saving technology routes and put forward different fuel saving approaches according to the different time period. At present, the vehicle manufacturers led by Europe has chosen to upgrade the 12 V start-stop system to 48 V lithium battery micro hybrid system. The 48 V micro hybrid system has great advantages in terms of R&D difficulty and R&D cost compared to the strong-hybrid and pure-electric systems, and has a good fuel-saving effect. 48 V micro hybrid system is the most effective technology to achieve energy-saving and emission-reduction goals through low-cost at this stage [1]. Meanwhile, 48 V micro hybrid system are already strongly developing and beyond 2020 this technology is expected to evolve step by step into a



market [2]. The 48 V micro hybrid system contains various configurations, and 48VP0 is taken as the research object in this paper. In China, 48VP0 system vehicles were launched to the market in 2018. And mass-produced 48VP0 system vehicles has sold more than 30000 vehicles in 2019. 48VP0 system contains 48 V battery and DCDC (48 V to 12 V bidirectional DC Converter), changing the traditional 12 V generator to 48 V BSG (Integrated belt starter generator) motor, and optimizing control system, engine gear train and crankshaft. The whole vehicle system architecture is shown in Fig. 1 below.



**Figure 1:** 48 V lithium battery system architecture diagram

In terms of fuel economy, the 48VP0 system can increase energy recovery and optimize engine operating point on top of traditional 3.5% fuel saving rate of 12 V start-stop function, Simulation results show that under NEDC conditions, the fuel consumption of this model equipped with a 48 V micro hybrid system can be reduced by approximately 15% compared to the original vehicle [2]. According to the announcement of a 48 V lithium battery P0 system vehicle on the market in China, the fuel saving rate can reach 12%, without sacrificing the performance and drivability.

Expect fuel saving, the main advantages of 48 V lithium battery P0 system lie in its low cost, small amount of structural changes and easy to implement modularization. Moreover, due to the parallel shaft structure of the motor and the engine, it has minimum influence on the axial size, especially for the front drive and it has excellent carrying capacity.

The main disadvantage of 48 V lithium battery P0 system is that the engine and the motor are mechanically connected without flexible decoupling, so it has no pure electric driving function. Due to the low power level of 48 V BSG motor, its ability to adjust the operation point of engine is limited. In addition, the biggest disadvantage of the system is the performance degradation of 48 V lithium battery. Lithium battery is a kind of chemical battery, The working environment temperature, working current, voltage and discharge rate have attenuation effects on the positive and negative active substances, electrolyte and collector fluid of lithium battery in service [3]. According to the characteristic parameters of lithium battery, the internal resistance increases, the efficiency available energy decreases. In practical application, taking 10 years and 250000 km as the design life of the whole vehicle, in the fourth year of vehicle operation, the capacity of the battery core decreases to 79%, and the internal resistance increases by 27%. The specific test and data analysis are shown below. In addition, it is very difficult to ensure the consistency of the cell, especially the power battery cell. With the increase of the internal resistance of the battery cell, the difference of the cell will be enlarged. In order to prolong the service life and ensure the safety, the battery system will develop active equalization or passive equalization strategy [4].

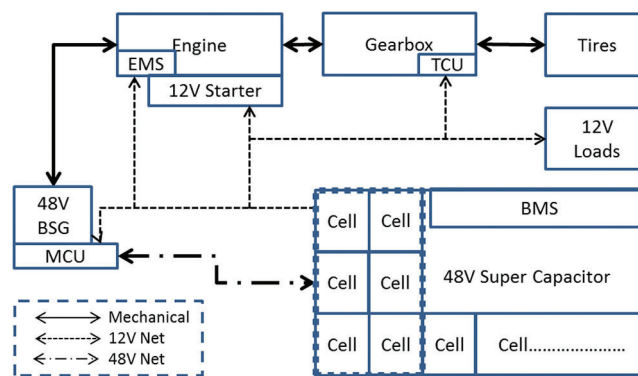
Super capacitor and lithium battery are the key parts of vehicle electrification. Both storage technologies are characterized and investigated. An extensive comparison of both technologies is made regarding a

specific energy storage device each. Both storage devices are subjected to a load which derived from the power flow that occurs within the driving cycles NEDC and WLTC. The Super capacitor solution acquires promising results, considerable fuel savings and costs saving in particular [5]. According to the characteristics of the P0 scheme of 48 V lithium battery, this paper proposes a 48 V super capacitor P0 system scheme. 48 V super capacitor is used to replace 48 V lithium battery, and several cells of 48 V super capacitor are used to form 12 V battery, thus canceling DCDC and 12V battery.

## 2 48 V Super Capacitor P0 System with 12 V Power Multiplexing Function

### 2.1 System Scheme Overview

The architecture of 48 V super capacitor system with 12 V power multiplexing function is shown in Fig. 2.



**Figure 2:** Schematic diagram of 48 V super capacitor system with 12 V power multiplexing function

48 V super capacitor and 48V lithium battery are composed of several cells in series and parallel. For example, the 48 V lithium battery on the market is generally composed of 12 or 13 cells. The function of 12 V power multiplexing is to select the appropriate number of cells from these cells to replace the traditional 12 V battery. As shown in Fig. 2 above, the advantage of this system architecture is that DCDC and traditional 12 V battery can be eliminated. Even if the 12 V battery cannot be completely eliminated, the capacity of the traditional 60 ah battery can be reduced to improve the lightweight of the vehicle and reduce the cost [6]. There are two ways to achieve the multiplexing function. One is to use several fixed cells, the advantage is that the structure is simple. The disadvantage is that the energy flux of these cells is much larger than that of other cells, resulting in larger attenuation of the performance than that of other cells, which will further lead to the poor consistency of the cells. Under the passive balance strategy, it will increase the energy waste and security risk. The other way is to use complex circuit and control alternating use of cell, it can avoid the consistency problem in the first way. The disadvantage is that the hardware and software control is complex and increases the cost. The biggest advantage of 48VP0 system is low cost. Therefore, this paper uses the first way. The problem of consistency can be solved by the very small internal resistance and long life of super capacitor.

### 2.2 48VP0 System Requirements

As mentioned above, Improving on their 12 V counterparts (2 kW–5 kW), 48 V micro hybrid system allow for extended start-stop and regenerative braking functionalities, providing fuel economy benefits of up to 10%–15% in standard passenger vehicles [7]. Through the real vehicle test, the fuel saving contribution of each function is shown in Tab. 1 below.

**Table 1:** Fuel saving contribution of each function in 48 V micro hybrid system

Function	Ratio of oil saving
Idle start-stop	3.5%
Slide start-stop	1.5%
Energy recovery	6%
Motor assistance	1%
System fuel consumption prediction	Max 12%

It can be seen that the start-stop function and energy recovery function contribute the most to fuel saving. According to different functions, compare the 48 V super capacitor P0 scheme with the P0 scheme of 48 V lithium battery.

### 2.2.1 Start-Stop Function

Compared with the traditional 12 V start-stop system, 48VP0 system has higher startup efficiency, better NVH and higher success rate. At present, many vehicle factories require to use 48 V to start the engine for the first time. In the low temperature environment, the traditional 12 battery can start the engine successfully at  $-30^{\circ}\text{C}$ , and start the engine successfully for 2~3 times below  $-35^{\circ}\text{C}$ . For the 48VP0 system, to ensure the engine successfully start in low temperature, it is necessary for the 48 V battery to have the discharge performance more than 4 kW in 2 s. However, in order to ensure the cost performance of 48VP0 system, there is no thermal management system for 48 V lithium battery. For 48 V lithium battery when uses lithium iron phosphate, the success rate of the first start-up cannot be guaranteed when the temperature is lower than  $-10^{\circ}\text{C}$ . The lithium battery with ternary lithium has discharge capacity of only 1.5 KW at  $-25^{\circ}\text{C}$ , which is not able to start the engine neither. Even with thermal management, it takes time to raise the 48 V lithium battery to the performance requirements in low temperature environment. Moreover, the lithium dendrite phenomenon will be triggered by the discharge of lithium battery in low temperature environment, which will greatly affect the life and safety performance of the battery. However, the lowest working temperature of super capacitor can reach  $-40^{\circ}\text{C}$ , and the low temperature has little effect on its discharge performance. For the selection of 48 V super capacitor, it is required to have the discharge performance above 4 kW at  $-30^{\circ}\text{C}$ .

### 2.2.2 Energy Recovery Function

As mentioned above fuel saving contribution, it can be seen that energy recovery is the main fuel saving function of 48VP0 system. Among, the braking energy recovery function of hybrid vehicles is recognized as an effective solution to reduce emissions and fuel consumption in the short to medium term [8] 48 V battery packs, with rated power capabilities on the order of 8 kW–16 kW, are rapidly becoming a new standard in the automotive industry. Under 48 V voltage, the power threshold is 14.4 kW.

On the other hand, the maximum current of the high voltage wire harness is 300 A in the hybrid system. Considering vehicle requirement, taking 1600 kg SUV as an example, under NEDC condition, the power distribution of feedback energy is shown in Tab. 2.

It can be seen from Tab. 2 that the power performance of 13 kW can recover 81.8% braking energy. Considering the reliability of belt drive and the cost of 48 V BSG motor, 13 kW is selected as 48VP0 system parts. As a result, 300 A is the rated current. According to calculation, the rated voltage of 48 V super capacitor is larger than 43.3 V. According to the 48 V BSG operating voltage range, 37 V~52 V is defined as the 48 V network voltage range.

**Table 2:** Percentage of regenerate energy at different regeneration power in NEDC

Power max charge [kW]	Percentage of regenerate energy [%]
20	100.0
16	91.3
13	81.8
10	62.8
8	52.8
5	31.1

### 2.2.3 Other Functions

In the transient performance point of view, engineering development and performance test were implemented. The results prove that the acceleration performance is almost the same as that of vehicle without 48 V system when 48 V BSG is in generating mode, while significantly improved when it is boosting [9]. The 48VP0 system can adjust the operating point of the engine through 48 V BSG power and power generation, and improve the vehicle drivability.

48VP0 system also has other functions, such as various researches and developments of 48 V mild hybrid system are being actively studied due to advantages in terms of cost. Some companies have proposed the system that downsizes engine by using a P0 configuration motor and electric supercharger. The P0 configuration motor and electric supercharger all support the power of an engine [10]. Given the relevance to this paper, no further details will be discussed.

### 2.3 48 V Super Capacitor Selection

At present, there are many super capacitors in market, and they are also used in the 12 V system vehicle. For example, a 48 V super capacitor and 300 F UC is connected to the motor load of excitation of 200 V through a 5 kW bi-directional buck boost converter [11]. In 48 V system, Hybrid super capacitor module (48 V, 416 F) was fabricated using an asymmetric hybrid capacitor with a capacitance of 7500 F [12]. After market research, selects representative super capacitors and lithium battery cells in the industry to compare their performance. According to the above demand analysis, select 15 super capacitor units are connected in series and 4 groups are connected in parallel to form a 48 V super capacitor. 48 V super capacitor and 48 V ternary lithium battery's performance parameters are shown in Tab. 3 below.

**Table 3:** Comparison between super capacitor and ternary lithium battery

Electrical specifications	Values	
Type	Super capacitor	LiCoMnNiO <sub>2</sub>
Cell configuration	15S4P	12S1P
Rated voltage V	45	44.4
Resistance m Ω	2.48	17.28
Current A	1000	300
Working Temperature °C	-40~65	-30~70
Low temperature performance	4.1 kW/-30°C	4.4 kW/-20°C
Stored energy wh	90	355.2
Cycle life	1000000	3000
Weight kg	26	5.6

The capacity of super capacitor is less than the ternary lithium battery. At the same time, the simulation by changing the capacity of the battery shows that continuously increasing the capacity of the battery does not greatly improve the fuel saving effect. Therefore, according to the above demand analysis, the capacity of the super capacitor is sufficient. As shown in the above table, the super capacitor combination of 15 series and 4 parallels is 20.4 kg heavier than the 48 V lithium battery. However, considering that 12 V multiplexing can reduce 12 V battery, DCDC and wiring harness and other accessories, so the total weight of the whole vehicle is equivalent.

The biggest advantage of super capacitor is the small internal resistance, which means that the same current output, less energy loss, less heat. In the whole life cycle of the vehicle, the super capacitor is more fuel-efficient under the same functions. For 48 V lithium batteries, discusses the various challenges and options of thermal management for the 48 V battery pack based on the usage pattern and environmental conditions. The lifetime for a passively cooled battery pack is estimated for a typical usage pattern. Active-air cooling is evaluated for the thermal management of the 48 V mild-Hybrid battery pack [13]. According to the search, thermal management of 48 V battery pack is critical for its optimal utilization to realize the mild hybrid functionality, to meet CO<sub>2</sub> reduction targets and useful life particularly under usage in hot ambient conditions [14]. The 48 V lithium battery with cooling system can extend the battery life, but reduce the cost performance of the whole system. However, super capacitors do not need a cooling system at all.

As shown in Tab. 3, the cycle life of super capacitors is much larger than that of lithium batteries. This means that the quality assurance of 48 V lithium battery is 3 years, and the super capacitor can reach 10 years. This can reduce the cost to users, especially for groups like taxi drivers.

#### 2.4 Test Apparatus

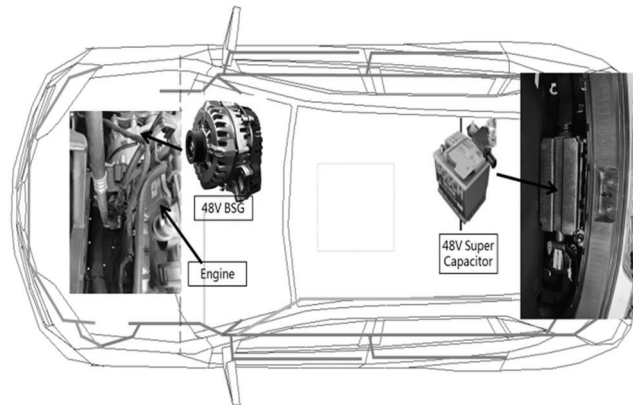
Reforming a vehicle factory SUV model 48 V lithium battery P0 system. The components and main performance parameters of the original vehicle are shown in Tab. 4 below.

**Table 4:** Parameters of original vehicle

Vehicle related parameters	Values
Model	SUV
Vehicle mass	1600 kg
Engine	105 kW/210 Nm
Rolling resistance coefficient	0.008
Air resistance coefficient	0.36
Frontal area	2.55 m <sup>2</sup>
Transmission system efficiency	0.8
Transmission case	7 DCT
Wheel radius	0.353 m
Tire adhesion rate	0.95
48 V BSG	13.2 kW PMSM

The layout of key parts in the whole vehicle are shown in the Fig. 3. In the front cabin of the vehicle, 48 V BSG replaces the 12 V generator and is connected to the engine through a belt. The 48 V super capacitor is installed in the trunk of the vehicle.





**Figure 3:** The layout of key parts in the whole vehicle

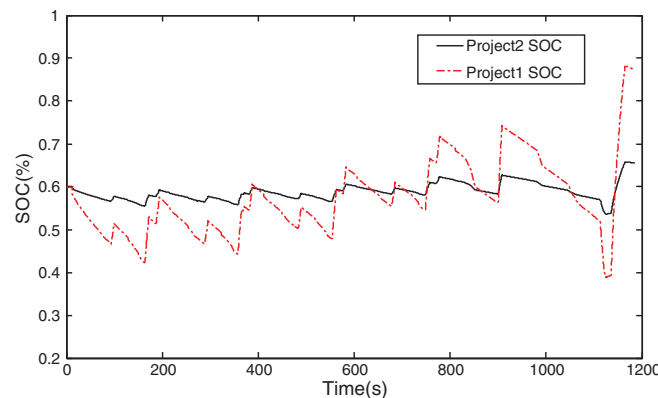
The experiment is executed based on adding 48 V super capacitor, removing DCDC and 12 V battery, reforming a 48 V super capacitor P0 system scheme and testing results is compared with the original 48 V lithium battery P0 system test data. In terms of strategy, on the basis of the original 48 V lithium battery P0 system, adaption and adjustment is made to for better control. Reference the relevant information [15].

### 3 Results and Discussion

The main tests carried out in this paper are NEDC test, urban road test in high-cold region, suburban road test in high-temperature region and Tip-in & tip-out test. Compare the performance of 48 V super capacitor and 48 V lithium battery in SOC and voltage, and performance degradation. The evaluation of durability is based on test data and refer to relevant research documents of parts [16,17]. Use Project 1 to represent the 48 V super capacitor P0 system. Use Project 2 to represent the 48 V lithium battery P0 system.

#### 3.1 NEDC Test

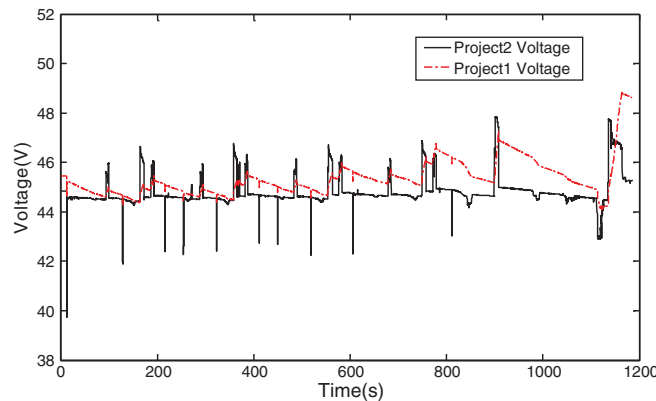
The NEDC test was completed on the wheel hub [18]. The test environment is 25°C, equipped with fans to simulate the windward condition. Mainly compare SOC and voltage. The test data are shown in Figs. 4 and 5.



**Figure 4:** SOC data comparison under NEDC condition

According to the data in Tab. 3, the capacity of super capacitor is 25.3% of the lithium battery. It can be seen from Fig. 3 that the SOC fluctuation range of super capacitor is larger than the lithium battery under the

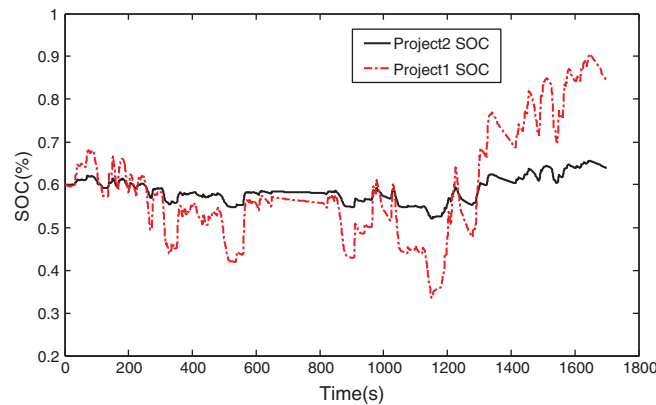
same vehicle requirement. In the Project 2, the SOC range is 53.6%~65.7%, and in the Project 1, the SOC range is 38.9%~88.1%. It is similar to capacity ratio. It should be noted that the SOC values in the test are within the reasonable range of the control strategy setting [19]. As Fig. 4, in the Project 2, when the vehicle accelerates or decelerates rapidly, the current is large. Due to the influence of internal resistance partial voltage of lithium battery, the terminal voltage of lithium battery will change suddenly. Because small internal resistance of super capacitor, its voltage did not show high change rate.



**Figure 5:** Voltage data comparison under NEDC condition

### 3.2 Urban Road Test in High-Cold Region

This test is carried out in high cold area, the roads are urban roads. The temperature on the test day was  $-26^{\circ}\text{C}$ , and the vehicle took 20 min to warm up at low speed. Because of the icy road, the maximum speed of the test was about 60 km/h. The test data are shown in Figs. 6 and 7.

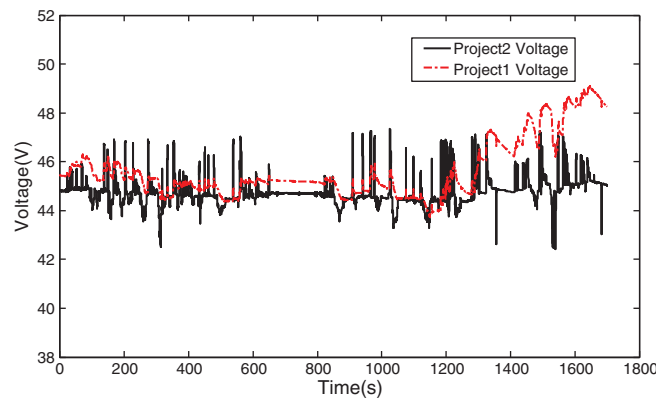


**Figure 6:** SOC data comparison under urban road test in high-cold region

It can be seen from Fig. 5 that the change of SOC before 1200 s is smaller. The main reason is that the power of lithium battery is limited at low speed and low temperature, and the power of the vehicle mainly depends on the engine. The power assistance and energy recovery function of 48 V lithium battery P0 system is limited. Before 1200 s, the SOC change of Project 1 is much larger than that of Project 2. Besides the capacity factor mentioned above. The main reason is that the performance of super capacitor is less affected by low temperature. The 48 V super capacitor P0 system has strong power assist and energy recovery function. From the change of voltage in Fig. 6, it can be seen that the charging capacity of



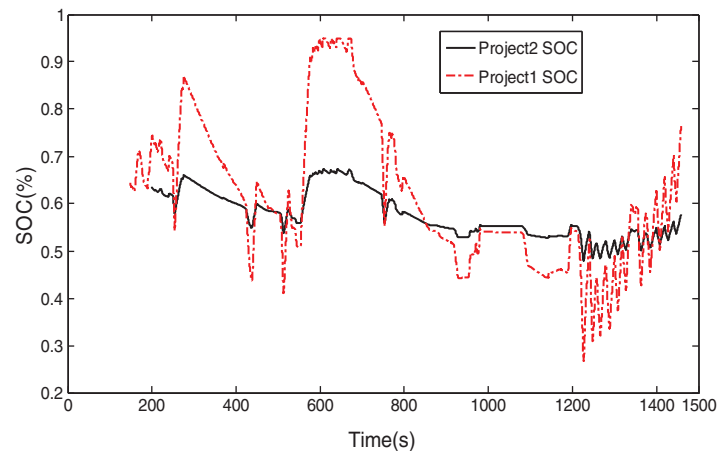
lithium battery is stronger than the discharge capacity in low temperature environment, and the positive voltage mutation is larger than the negative voltage mutation. After 1200 s, the positive voltage mutation is similar to the negative voltage mutation. This proves from the other side that based on the lithium battery layout and use strategy of the sample vehicle, it needs 20 min the performance can be recovered to be equivalent to the normal temperature in extreme cold conditions. And the super capacitor scheme is less affected by low temperature.



**Figure 7:** Voltage data comparison under urban road test in high-cold region

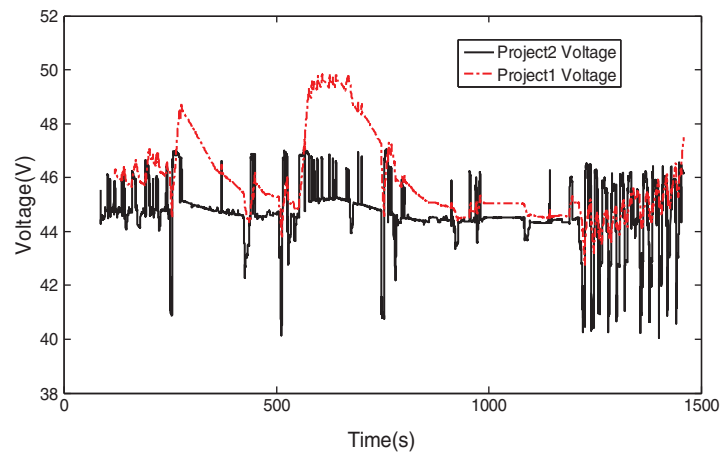
### 3.3 Suburban Road Test in High-Temperature Region

This test is carried out in high temperature area, the roads are suburban roads. The temperature on the test day was 42°C. The maximum speed of suburban roads is about 100 km/h. The test data are shown in Figs. 8 and 9.



**Figure 8:** SOC data comparison under suburban road test in high-temperature region

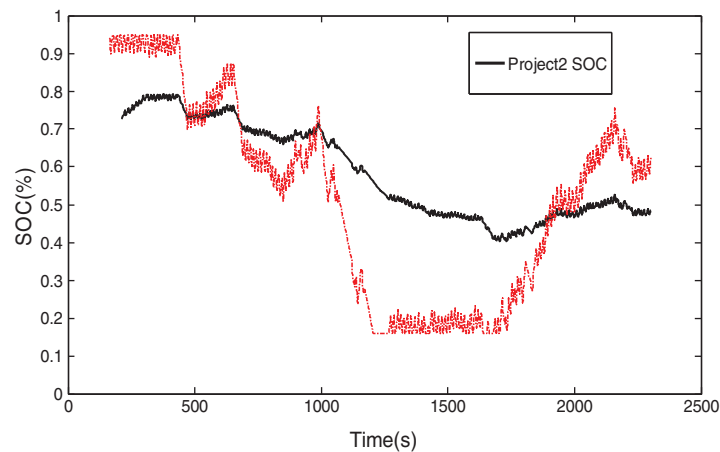
From the SOC data of about 600 s in Fig. 7 above, it can be seen that the recovery of braking capacity at high speed brings about a rapid rise of SOC. The SOC of the Project1 is close to 95% of the upper limit of the strategy. Similarly, at 1200 s, the acceleration time required in high speed is slightly longer, causing the SOC of super capacitor rapidly decreasing from 55% to 28%. It can be seen from Fig. 8, in the Project 2, the high speed demand for 48VPO system makes the voltage mutation more obvious.



**Figure 9:** Voltage data comparison under suburban road test in high-temperature region

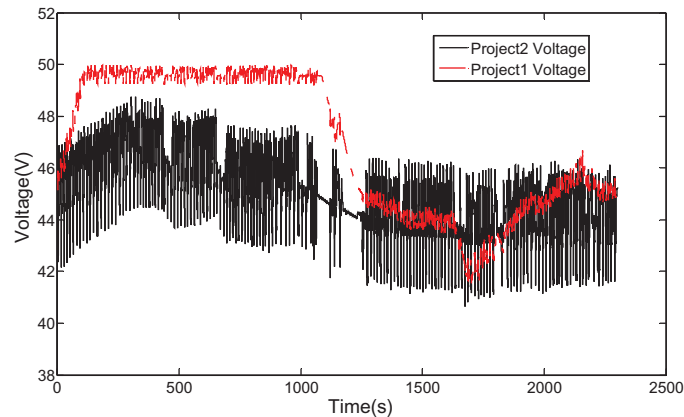
### 3.4 Tip-in & Tip-out Test

Tip-in & Tip-out test is a rapid acceleration or deceleration test. The road is a test road. The driver uses full throttle. After the vehicle accelerates to more than 100 km/h, then the driver deeply steps on the brake pedal, let the vehicle speed drops sharply to 0 km/h. Repeat the process. The test data are shown in Figs. 10 and 11.



**Figure 10:** SOC data comparison under Tip-in & Tip-out test

The owner will not drive like this when using the vehicle on a daily basis. It is mainly to verify the performance of 48 V super capacitor and 48 V lithium battery under extreme driving conditions. It can be seen from Fig. 9 above that braking energy recovery is more than that of motor assistance and vehicle load before 500 s. SOC increased rapidly and reached the upper limit of 95% in the strategy. After that, the intensity of rapid acceleration exceeds the energy recovery, finally reached the lower limit of 15% of the sample vehicle strategy in 1200 s. In this case, the control strategy will reduce the power consumption so that it can maintain the normal operation of the 12 V net.



**Figure 11:** Voltage data comparison under Tip-in & Tip-out test

#### 4 Conclusions

Given the shortcomings of the current 48 V lithium battery P0 system, this paper propose to use 48 V super capacitor replace 48 V lithium battery to build 48V super capacitor P0 system in the 48 V micro hybrid system. By decomposing the functional objective of the whole vehicle for 48VP0 system, then taking the selection of super capacitor and further optimize the design, make 48 V super capacitor reusable to replace the traditional 12 V battery, and cancel the DCDC. According to the model selection, reform the sample vehicle, carry out NEDC test, urban road test in high-cold region, suburban road test in high-temperature region and Tip-in & Tip-out test. According to a series of comparative tests, verifying that the 48 V super capacitor P0 system with 12 V multiplexing function is feasible. Then we draw conclusions as follow: (1) The performance of 48 V super capacitor P0 system is not inferior to that of 48 V lithium battery P0 system, and 12 V multiplexing function does not cause power loss of super capacitor; (2) The SOC fluctuation of super capacitor is larger than that of lithium battery, but it can satisfied all test conditions through the strategy; (3) The internal resistance of super capacitor is smaller than that of lithium battery, and the voltage mutation of super capacitor is less than that of lithium battery in comparison test. It is proved that in practical application, the super capacitor can greatly reduce the voltage impact and protect the electrical appliances on the vehicle. Of course, the disadvantage of the 48 V super capacitor P0 system is that the energy density is smaller than that of the lithium battery system. It is necessary to further optimize the integration, cancel DCDC and 12 V battery through 12 V multiplexing function to ensure the lightweight of the whole vehicle. At present, the production capacity and capital investment of super capacitor are far less than that of lithium battery. It is believed that with the further increase of fuel consumption pressure, the small internal resistance of super capacitor will be paid more and more attention. The continuous scientific research investment will further improve the energy density, and the production feasibility of 48 V super capacitor P0 system will be larger.

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