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Intelligent Vehicle Electrical Power Supply System with Central Coordinated Protection

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Abstract: The current research of vehicle electrical power supply system mainly focuses on electric vehicles (EV) and hybrid electric vehicles (HEV). The vehicle electrical power supply system used in traditional fuel vehicles is rather simple and imperfect; electrical/electronic devices (EEDs) applied in vehicles are usually directly connected with the vehicle's battery. With increasing numbers of EEDs being applied in traditional fuel vehicles, vehicle electrical power supply systems should be optimized and improved so that they can work more safely and more effectively. In this paper, a new vehicle electrical power supply system for traditional fuel vehicles, which accounts for all electrical/electronic devices and complex work conditions, is proposed based on a smart electrical/electronic device (SEED) system. Working as an independent intelligent electrical power supply network, the proposed system is isolated from the electrical control module and communication network, and access to the vehicle system is made through a bus interface. This results in a clean controller power supply with no electromagnetic interference. A new practical battery state of charge (SoC) estimation method is also proposed to achieve more accurate SoC estimation for lead-acid batteries in traditional fuel vehicles so that the intelligent power system can monitor the status of the battery for an over-current state in each power channel. Optimized protection methods are also used to ensure power supply safety. Experiments and tests on a traditional fuel vehicle are performed, and the results reveal that the battery SoC is calculated quickly and sufficiently accurately for battery over-discharge protection. Over-current protection is achieved, and the entire vehicle's power utilization is optimized. For traditional fuel vehicles, the proposed vehicle electrical power supply system is comprehensive and has a unified system architecture, enhancing system reliability and security.

Keywords: vehicle electrical power supply; battery management; vehicle electrical system, traditional fuel vehicle

1 Introduction

With the rapid development of vehicle electrical and electronic technologies, an increasing number of electrical/electronic devices have been applied to the vehicles, which results in increased system complexity and new safety challenges. In addition, large electronic controllers used in vehicles require a stable power supply for logic calculations and communication[1], this is usually ensured by a voltage regulator integrated within the controllers and supplied by a battery. However, the current development of battery capacity is not able to meet the high demand for vehicle electrical power consumption, which sometimes leads to over discharge in batteries[2]. Therefore, a smarter vehicle power management system is required to enhance power supply stability and safety[3].

Currently, power management on EV and HEV is being developed, particularly for estimating the current battery SoC. For example, EHRET, et al[4], reported the most commonly used methods for SoC estimation, such as discharge counting, ampere-hour counting, and open circuit voltage. However, every SoC estimation method has applicable conditions and errors in precision. Hence, algorithms and modelling are used to correct SoC estimations; these models include linear models and the Karman filter approach[5–6]. WANG, et al[7], presented a novel modelling method that uses a stochastic fuzzy neural network (SFNN) to promote development of battery estimating, monitoring and an energy control strategy. JUNG, et al[8], developed a battery monitor system (BMS) for a Ni-MH battery used in EV with several functions to optimize the control of charge and discharge of the battery status in real time. GRUJICIC, et al[9], presented a control scheme for polymer electrolyte membrane fuel cell (PEMFC) systems, which is critical to transient behaviour study of batteries with highly complex electrochemical changes. Many studies have been performed on BMS. However, most have focused on EVs/HEVs and cannot be

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directly used in traditional fuel vehicles.

In traditional fuel vehicles, research on battery management and vehicle electrical protection has been performed by a number of universities and companies. KAREGAR, et al[10] and NGUYEN, et al[11], proposed a current protection model based on fuzzy logic and an artificial neural network for power supply on-off control and current monitoring. WANG, et al[12], presented an intelligent circuit breaker that used a micro-processing chip to achieve protection requirements in the event of an over-current failure. Although having achieved over-current protection for power supply channels, these studies have not addressed battery management, and no appropriate measures have been taken to protect the battery. Therefore, in past decades, VARTA Automotive proposed a layered structure for battery monitoring, battery management and energy management, which addressed the battery and generator. Volkswagen developed a power management system for the Audi A6 and A8 models that managed the battery, generator and engine concurrently and utilized quiescent current management; improved battery and vehicle electrical protection was achieved. However, in the power management system, only the battery, generator and engine were considered. Therefore, their management system was rather simple and incomplete and cannot manage electrical safety protection in some complex conditions; for example, it cannot monitor every electrical device quickly and protect it from electricity during a failure. In the meantime, controller power is not isolated from the load power and easily disturbed by rough load power, resulting in poor electrical environment.

In this paper, we proposed an intelligent interactive vehicle electrical power supply system for traditional fuel vehicles that was designed based on a smart vehicle electrical/electronic device system and is a fully distributed system with twin coordinators[13–14]. In addition to the battery, generator and engine, all other electrical/electronic devices were integrated into this power supply system, including everything from simple lights to a complex control unit. Therefore, it can monitor every device's status and protect it from power failure. In a vehicle's electrical power supply network, the power supply for controllers and communications is isolated from that for rough load consumption. Therefore, it can supply clean controller power with no electromagnetic interference, creating a clean and safe electricity environment. The intelligent electrical power supply system monitors the power supply network regularly in real time and protects it from over current faults. Additionally, to achieve more accurate SoC estimations for a lead-acid battery in traditional fuel vehicles, a new algorithm style of a battery's state of charge was established. Battery over discharge protection was achieved. Therefore, we believe the proposed system can reduce the probability of power failure in any complex situation and significantly enhance a vehicle's electrical safety and stability.

2 Vehicle Electrical Power Supply Network Architecture

In the proposed SEED system, all electrical and electronic devices, from a simple light to a complex control unit, were all connected to the vehicle communication network. All constraints between switches and appliances were removed and replaced by central coordinators, which made direct electrical power connection between source and devices possible. Most devices require two types of power supply: one to supply the power required by traditional load (e.g., lights, ventilators, fans, horns, etc); the other to supply the power required by controllers and communication devices. Here, we define the power required by traditional load as load power (LP), the voltage and current of which changes roughly during functioning, and define that required by controllers and communication as controller power (CP), the voltage of which requires high stability. LP has a high current consumption, while CP has stable low current consumption. To prevent the pollution of CP by LP, the LP and CP networks are isolated from each other, and CP voltage is centrally converted in the Vehicle Electrical Power Supply System (VEPSS). VEPSS monitors battery status and controls LP and CP connection lines.

2.1 Load power network architecture

The LP network is connected to the LP source, the battery, the generator and all LP devices. All LP devices are divided into several groups, as shown in Fig. 1. $T_{i,j,k}$ stands for a normal LP consumer, $P_{i,j}$ an LP consumer zone, R_i an LP supply group, and q_i the LP connection line provided by VEPSS. $P_{i,j}$ are divided further according to the location of $T_{i,j,k}$, and R_i is grouped according to the power balance of current flowing through q_i.

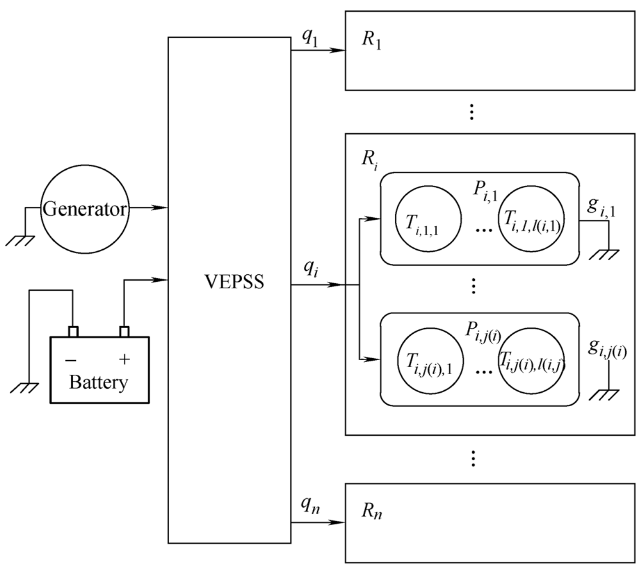


Fig. 1. Load power backbone network architecture

In the LP network, only the positive electrode was considered; the ground of all LP devices were connected locally within $P_{i,j}$. The connection within $P_{i,j}$ is shown in Fig. 2. Positive electrodes of all LP devices are connected to q_i, and all negative electrodes are connected together and then mounted to the chassis at one junction.

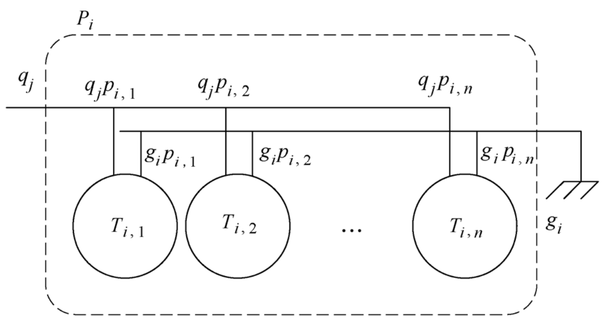


Fig. 2. Load power sub network architecture

Zoning rules for LP devices are as follows.

(1) LP supply condition

The LP supply condition is determined by all members within an LP consumer zone, defined as x_{Pi}.. For zones that require constant LP supply, their LP supply condition can be described by:

$$x_{Pi} = 1. \tag{1}$$

For the remaining zones, there are two conditions that must be considered.

When the vehicle is in ACC or ON or STA mode, defined as c_1; special coordinated mode (e.g., an emergency state); or power cut off delay mode, defined asc_2, the LP supply condition of P_i can be expressed as:

$$x_{Pi} = 1,\ x_{\mathrm{P}i} = \begin{cases} 1, & c_1 \vee c_2, \\ 0, & \neg c_1 \wedge \neg c_2. \end{cases} \tag{2}$$

(2) LP supply rated power

The rated current of each LP connection line was limited by the wire and should be balanced (e.g., maximum current of a typical wire is 50 A). In this way, the LP supply to all devices can be achieved with a minimum number of connection lines. Some LP supply groups only contain one LP supply zone, while others may contain multiple zones.

2.2 Controller power network architecture

The CP network connects all CP devices to VEPSS. Robust CP voltage stability is essential, and the current consumption of CP is typically low and stable. Hence, all CP devices are divided into 2 groups according to their different CP supply conditions: Q_1 and Q_2. CP network architecture is shown in Fig. 3. e_c is a CP that is supplied constantly, e_s is a CP that is supplied under certain conditions, and e_g is the isolated ground of CP. d_i is an electrical/electronic device (EED) in the backbone network of SEED system, γ_i is a gateway between the backbone network and sub networks, and w_i is the set of a sub networks that contains a number of individual EEDs.

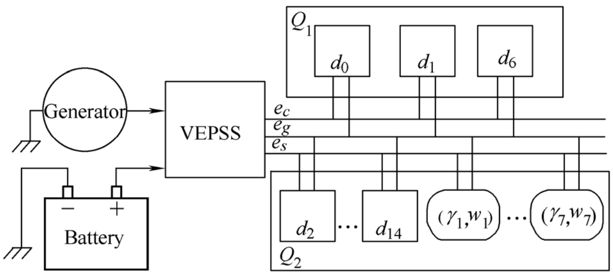


Fig. 3. Controller power backbone network architecture

CP network group Q_1 contains EEDs that require a constant CP power supply (e.g., the ignition key, remote lock, coordinators, etc). Q_2 contains the remaining EEDs.

The CP supply condition for Q_1 and Q_2 are described as x_{Qi}, which can be defined as:

$$x_{Qi} = \begin{cases} 1, & i = 1, \\ 0, & i = 2. \end{cases} \tag{3}$$

All members of Q_1 were designed as backbone nods in SEED system. In the CP sub network, γ_i and members of w_i are connected, as shown in Fig. 4. In Fig. 4, δ is a member of sub network w_k.

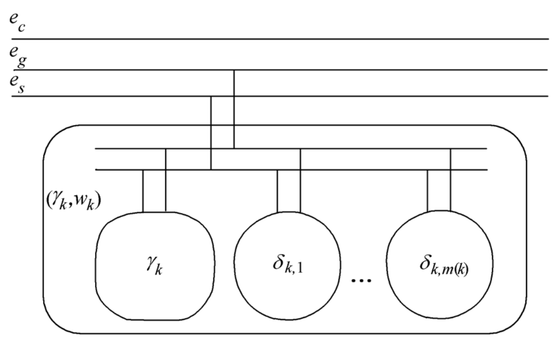


Fig. 4. Controller Power sub network architecture

2.3 VEPSS scheme

A typical VEPSS scheme is shown in Fig. 5 and is comprised of two parts: LP and CP.

The LP portion monitors the status of the battery, including its current, voltage and temperature, and provides LP connection lines for all LP supply groups. Switch control of the connection lines is implemented according to the LP supply conditions of the groups. The switch control function of the LP connection lines are integrated with short circuit cut off protection, which will be described in the next section.

The battery voltage of the shuttle bus is 24 V, and the battery voltage of the car is 12 V, while, stable constant voltages 12 V and 5 V are required by VEPSS. Thus, the battery voltage is converted to a stable CP voltage (typically 12 V and 5 V) by using two voltage regulators. The CP ground is connected with the LP ground only within the CP portion of the system, so that CP voltage quality is not polluted by LP. Both e_c and e_s are switch controllable, which makes it possible to cut them off when over-current is detected.

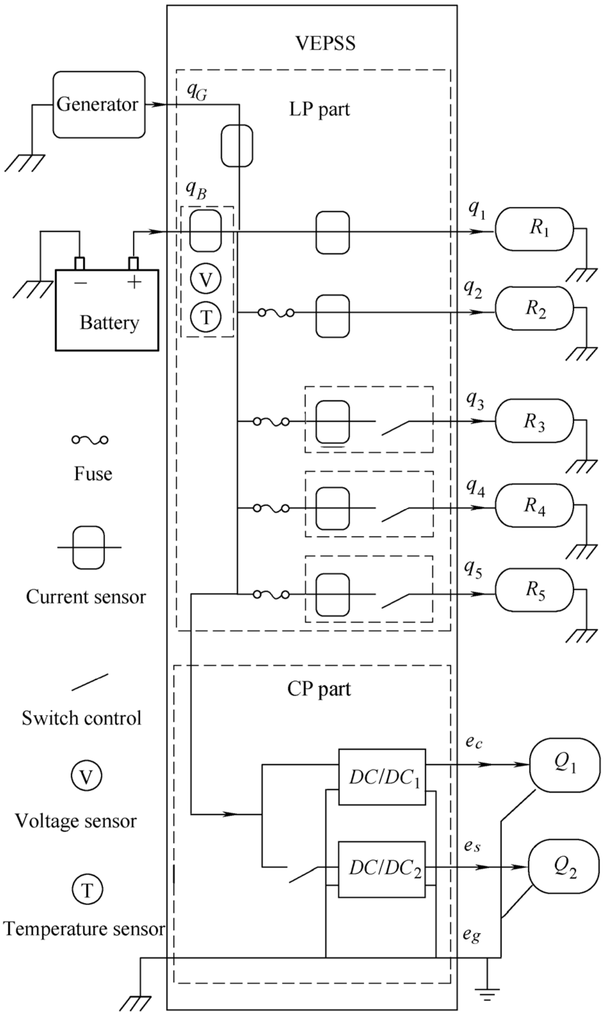


Fig. 5. Typical VEPSS scheme

All functions within Fig. 5 are achieved by a series of EEDs, connected in accordance with the system scheme protocol of a SEED system, as shown in Fig. 6. Definitions of EEDs are shown in Table 1.

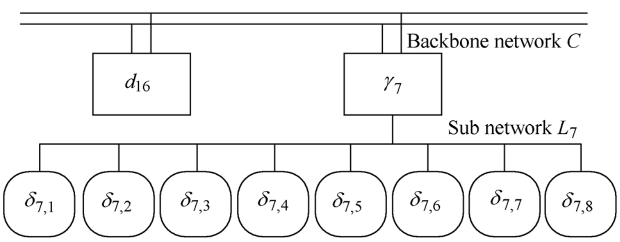


Fig. 6. Typical VEPSS unit connection scheme

Table 1. Typical EEDs in VEPSS

No.	Type	Abbr.	Function
1	CP management unit	d_{16}	Convert CP voltage, measure CP current, control connection lines
2	Gateway	γ_7	Connect backbone and sub network
3	Intelligent relay for q_3	$\delta_{7,1}$	Measure LP connection line current, switch line, and short circuit protection
4	Intelligent relay for q_4	$\delta_{7,2}$	Same as above
5	Intelligent relay for q_5	$\delta_{7,3}$	Same as above
6	Intelligent relay for q_6	$\delta_{7,4}$	Same as above
7	Current measurement unit for q_1	$\delta_{7,5}$	Measure current of LP connection line
8	Current measurement unit for q_2	$\delta_{7,6}$	Same as above
9	Current measurement unit for q_G	$\delta_{7,7}$	Same as above
10	Battery measurement unit	$\delta_{7,8}$	Measure battery current, voltage and temperature

3 Over Current Protection of Electrical Power Connection Lines

All controllable LP and CP connection lines are connected when the supply condition is reached and are cut off when the supply condition is not reached or when there is a short circuit detected. In SEED systems, VEPSS transmits current information of all connection lines, and then the coordinator decides if there is an over current in a line. Once an over current is detected, the coordinator will enter protection mode and send a cut-off command to VEPSS, which finally cuts off the problematic connection line. In certain urgent cases, when the connection line is severely short circuited, VEPSS cuts off the line automatically without waiting for the command from the coordinator.

3.1 Over current protection of LP connection lines

LP connection lines are protected in two modes: normal over current protection mode, and severe short circuit protection mode. Normal over current protection is performed by the coordinator, while the severe short circuit protection is performed locally by an intelligent relay.

3.1.1 LP connection line over current protection

Due to the frequent switch of LP devices, current flowing through LP connection lines changes frequently. Over current status is determined the coordinator, which compares the rated current to the present current, controls all LP consumer devices statuses and calculates the rated current of every LP connection line. Defining the measured current as I_M and the rated current as I_R, the over current status of a LP connection line can be divided into 5 zones, as shown in Fig. 7, where k_1, k_2, k_3 are defined as: $0<k_1<1<k_2<k_3$.

In zone 1, when I_M and I_R are both lower than I_0, it is not possible to determine the over current status due to current measurement error and inaccuracy. Hence, in zone 1, the LP connection line is considered safe. In zone 2, the over current status is judged to be lower than expected. In this case, the coordinator sends out a warning to remind the driver to check the device connections. In zone 3, the over current status is judged to be normal functioning. In zone 4, the over current status is judged to be weak over current; the coordinator sends out a warning to require a system examination. In zone 5, the over current status is judged to be severe over current, and the coordinator sends out a delayed cut off command, and the engine is not started.

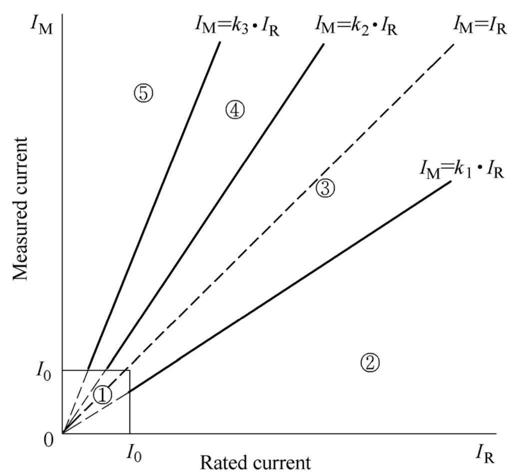


Fig. 7. LP connection line over current status definition

According to the study by KAREGAR[10], in zone 5, the delayed time was designed using Fig. 8. The relationship between the delay time t and the over load ratio $k(I_M/I_R)$ can be expressed as follows:

$$k^{\varpi} \cdot t = k_3^{\varpi} \cdot t_3, k \geqslant k_3, \tag{4}$$

where ϖ is a parameter normally set between 2 and 5.

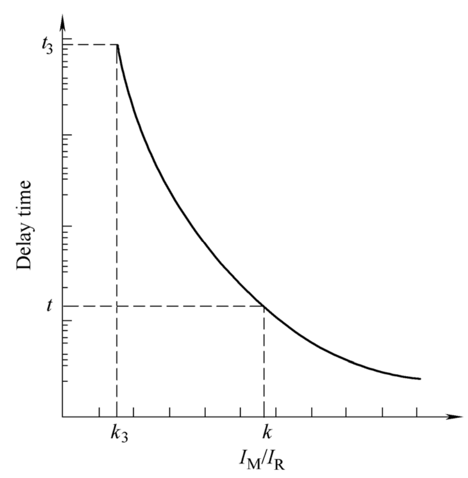


Fig. 8. LP connection line cut off delay time curve

3.1.2 LP connection line short circuit protection

When a severe short-circuit occurs, the hardware circuit shown in Fig. 9 cuts off the relay that controls the LP connection line immediately.

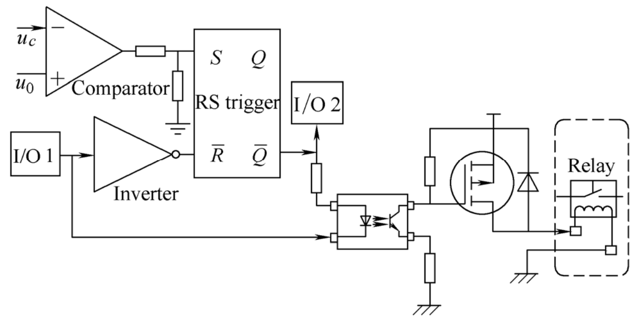


Fig. 9. LP connection line short circuit protection design

Normally, the current sensor signal u_c is lower than the set limit u_0. The I/O port of the microcontroller controls the relay directly. However, once u_c reaches u_0, the circuit switches off the relay regardless of the state of I/O port1 and sends out a short circuit signal to I/O port 2. The circuit resets when the I/O port 1 signal resets. The voltage value of u_0 sets the limit of the current that is considered to be a short circuit current, which generally triggers the circuit reaction when the measured current is 4 times larger than the rated current of the relay. The action time in this case is less than 50 ms.

3.1.3 Over current protection structure of the LP supply network

LP over current was set at 5 points in the LP supply network, shown as W_1–W_5 in Fig. 10.

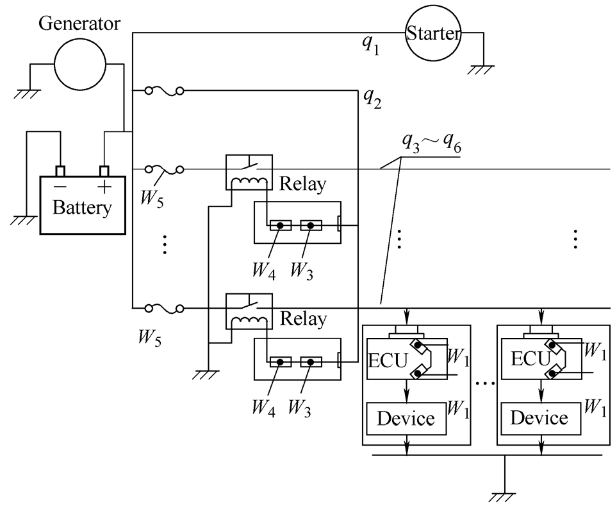


Fig. 10. LP over current protection points

W_1 and W_2 were designed within the EED, software algorithm protection and fuse protection. W_3 is the normal over current protection achieved by both the intelligent relay and central coordinator. W_4 is the short circuit protection within the intelligent relay. Finally, in the rare case where W_1–W_4 show problems, the fuse in the LP supply connection line is triggered.

The state mechanism of the LP supply connection line is shown in Fig. 11; only when the engine is off will the LP supply connection line be cut off.

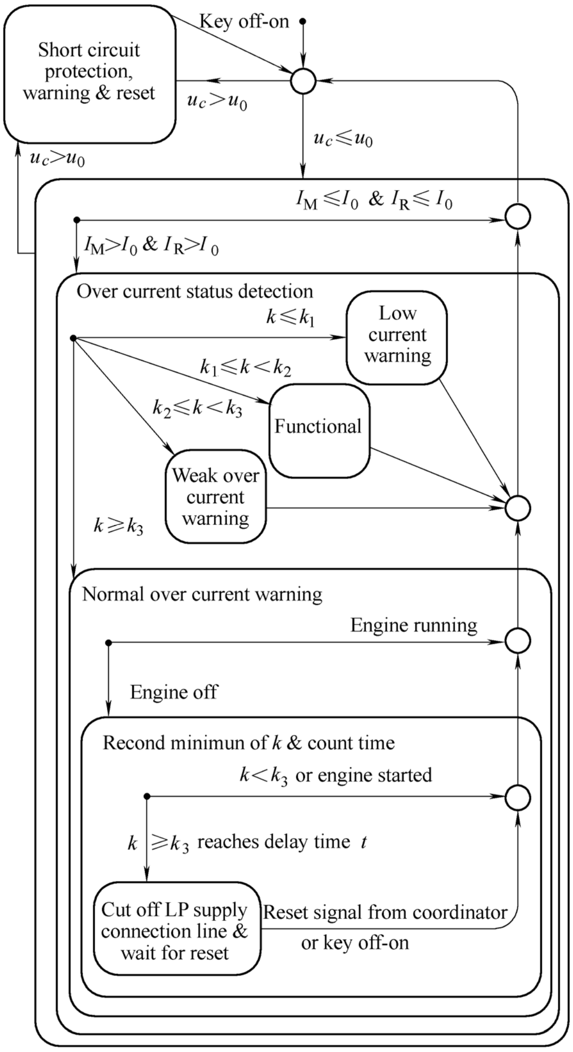


Fig. 11. LP supply connection line over current protection state mechanism

3.2 Over current protection of CP connection lines

Over current protection of the CP connection lines was also managed with the coordinator. CP consumption is quite stable and typically jumps between two stable values according to the vehicle key mode: on or off. When the vehicle is in ‘on’ mode, both e_c and e_s are supplied. When the vehicle is in ‘off’ mode, only e_c is supplied.

3.2.1 CP connection line over current protection in on mode

The over current status of CP is divided by 4 zones, as shown in Fig. 12, where m is defined as the over load ratio, andm_1, m_2, m_3 are constant parameters, where $0<m_1<1<m_2<m_3$. In zone 1, current is considered lower than expected, and a warning is sent to remind the driver to check the connection of the CP network; in zone 2, the current is judged to be functioning; in zone 3, the current is judged to be a weak over current; and in zone 4, the current is judged to be a severe over current. In zone 4, a similar time delay t_m curve exists, as shown in Fig. 8.

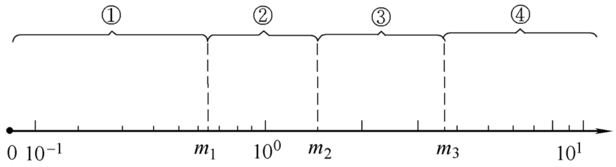


Fig. 12. CP over current status zones in on mode

The state mechanism was designed as shown in Fig. 13; only when the engine is off will CP be allowed to be cut off.

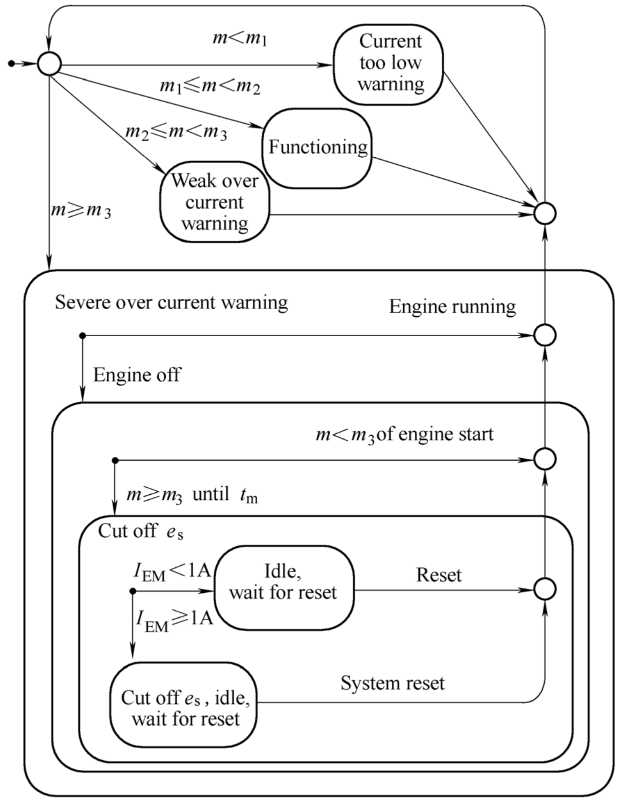


Fig. 13. CP over current protection state mechanism in on mode

3.2.2 CP connection line over current protection in off mode

In off mode, because CP current is very low, over-current status is only divided into three zones, as shown in Fig. 14, where $1<m_1<m_2$.

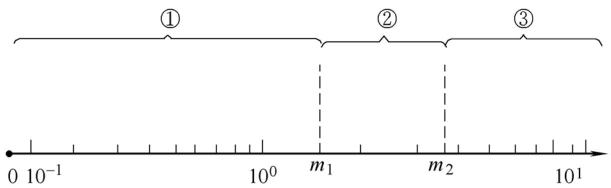


Fig. 14. CP over current status zones in off mode

Following the mechanism shown in Fig. 15, CP will be cut off when the severe over current status reaches its designed time delay.

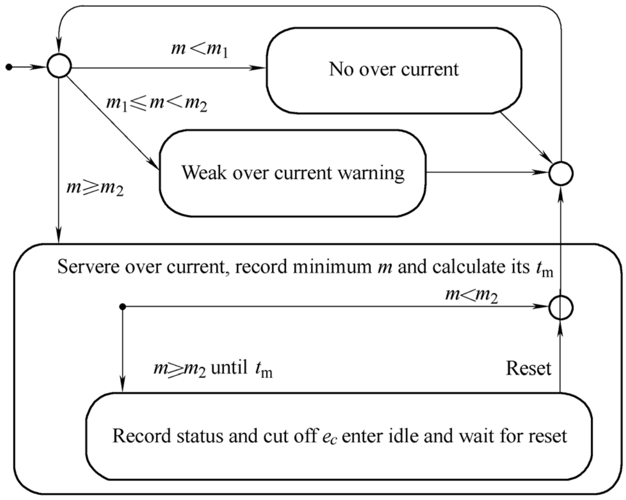


Fig. 15. CP over current protection state mechanism in off mode

4 Battery Monitoring and Over-discharge Protection

The intelligent vehicle electrical power network considers all electrical/electronic devices and manages power supply conservation in any situation. A new practical SoC estimation method was developed to achieve more accurate SoC estimation for lead-acid batteries in traditional fuel vehicles.

The basic status of the vehicle battery including current, voltage and temperature was monitored using a battery measurement unit continuously. Based on these parameters, the SoC and SoH were estimated in the coordinator. All LP devices were divided into several categories according to their importance. When the battery energy is low, the coordinator turns off the categories one by one to assure sufficient SoC remaining for the next engine start.

4.1 Battery SoC estimation

Recently, various battery SoC estimation methods have been proposed; however, most focus on EVs/HEVs and cannot be directly used with a traditional fuel vehicle's lead-acid battery, particularly for a battery that works in the proposed intelligent vehicle electrical power supply system.

In this paper, we propose a new practical SoC estimation method based on the Ampere-Hour method considering the correction of three states: engine launch, full charge, and long period off mode. This new method is shown in Fig. 16.

In any working condition, the ampere-hour method is always applicable. However, because long computation times with certain ampere-hour estimation methods would result in large errors in the SoC result, other estimation methods, such as the method introduced by PILLER, et al[15] should be used. After a long period in off mode (i.e., 2 hours), the open circuit voltage of lead-acid batteries was nearly linear compared with the battery SoC, the voltage could be used to calculate the current SoC and the result is close to the real value.When the engine was started, the battery discharged a current, which made it possible to calculate the essential resistance of the battery accurately; again, the ampere-hour SoC result was corrected here. When the battery was full charged, the SoC should be marked as 100%. In each SoC estimation method, the error imparted to the estimation result was also calculated; this error was used in each correction of SoC value. The ampere-hour method error was reset every time when the SoC was reset.

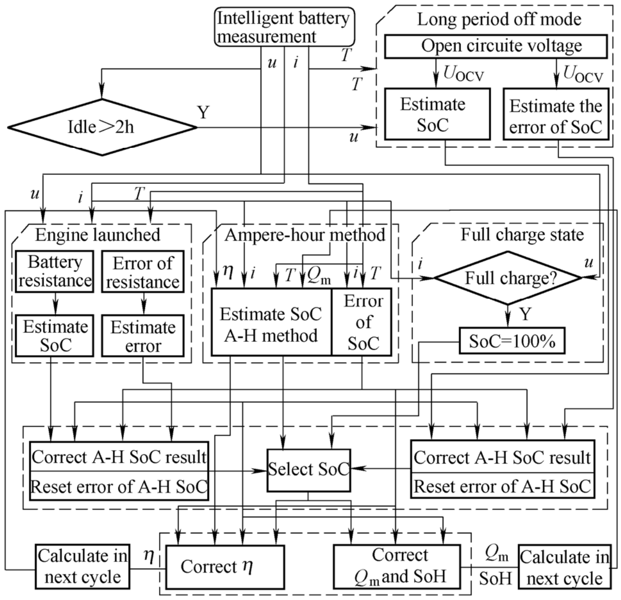


Fig. 16. Battery state monitoring structure

4.2 Battery over discharge protection

All EEDs were divided into five categories with different power consumption priorities. Categories were turned off when the battery SoC reached its limits. The battery state of function (SoF) was divided into six zones, as shown in Fig. 17.

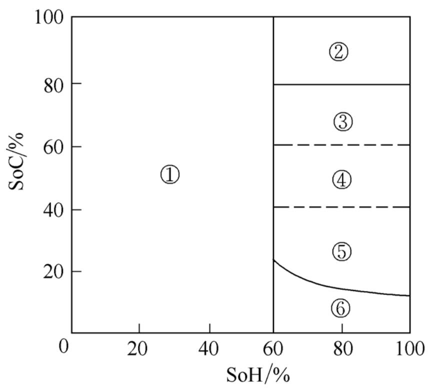


Fig. 17. Battery SoF zones

In zone 1, according to Salloux's study, the battery is out of use and should be replaced[16]. In zone 2, the battery is fully functional, and over discharge protection is not applicable. In zones 3–5, the battery is between fully functional and defective, so some unimportant EEDs are turned off or forbidden to turn on to ensure longer battery use. In zone 6, only necessary SoC remains for the next engine launch.

After defining l_1–l_6 as constant SoC limit values between 0–100%, the battery over discharge protection state mechanism is shown in Fig. 18.

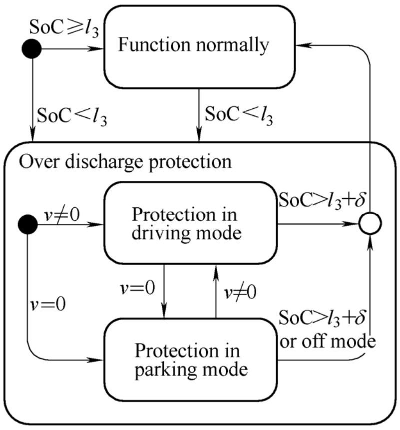


Fig. 18. Battery over discharge protection state mechanism

In driving and parking modes, EEDs were categorized differently, and the limitation of EEDs also differed. Hence, when SoC$<l_3$, the vehicle entered battery over discharge protection mode. Then, according to the velocity of the vehicle, the state mechanism was further divided into two sub state mechanisms: protection in driving mode and protection in parking mode, which could enter each other when the velocity changed.

4.2.1 Battery over discharge protection in driving mode

When the vehicle was driving, EEDs related to driving safety have the highest functioning priority, while signal lights, ventilators, fans, heating have the lowest priority. The sub state mechanism in driving mode is shown in Fig. 19, where $0<l_2<l_1<l_3$, and δ is a constant value that prevents frequent state to change when approaching limits. In all three states, EEDs of part of the categories are enforced to turn off, while others are not allowed to turn on.

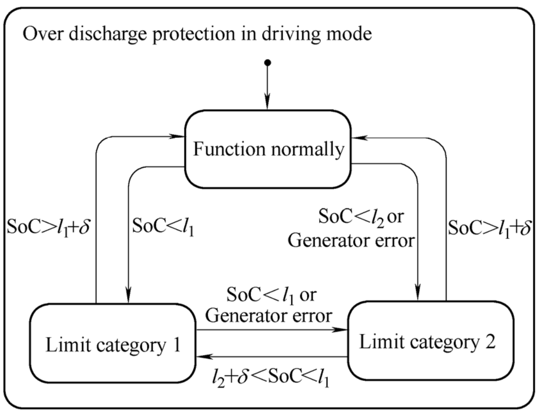


Fig. 19. Battery over discharge sub state mechanism in driving mode

4.2.2 Battery over discharge protection in parking mode

When the vehicle is parked, more EEDs can be restrained, and the vehicle can enter zone 6 only when the necessary SoC for the next engine launch is retained. The sub state mechanism is shown in Fig. 20, where $0<l_6<l_5<l_4<l_3<100\%$. When entering this mode, EEDs in category 3 are restrained, followed by categories 4 and 5; lastly, only a few EEDs that necessary for certain functions are kept on.

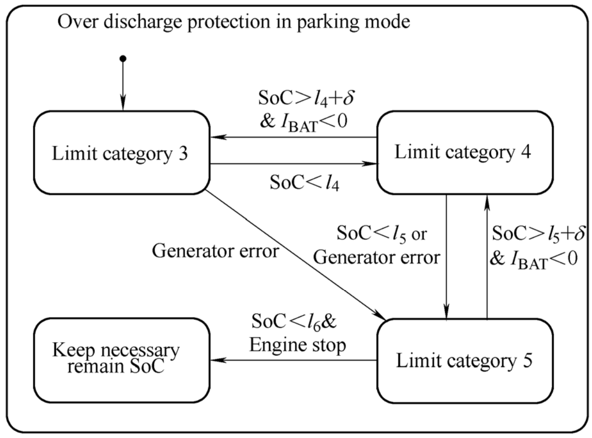


Fig. 20. Battery over discharge sub state mechanism in parking mode

5 Vehicle and Bench Tests and Results

The proposed vehicle electrical power supply network has been applied to a twelve-meter-long city shuttle bus. The harness scheme of the power supply network is shown in Fig. 21. All functions were tested on the experimental shuttle bus and a test bench.

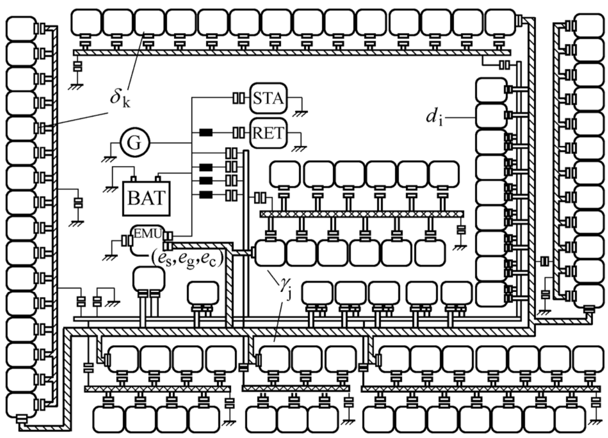


Fig. 21. Harness scheme of power supply network of the shuttle bus

5.1 Power connection line over current protection test results

The power connection line's over current protection for normal over current and that for an urgent short circuit were installed separately. Experiments were performed on a test bench. The test steps of normal over current protection were designed as shown in Table 2.

Table 2. Test steps of normal over current protection

Step	Duration t/s	Test current I/A	Expected Current I/A	Simulated status
1	120	2.9	5	Current too low
2	120	5.0	5	Functioning
3	120	6.8	5	Weak over current
4	240	14.6	5	Severe over current

The expected current remained set at 5 A, while the test current changed to simulate 4 different over current statuses. During the test, the engine state was set to off. The test results are shown in Fig. 22.

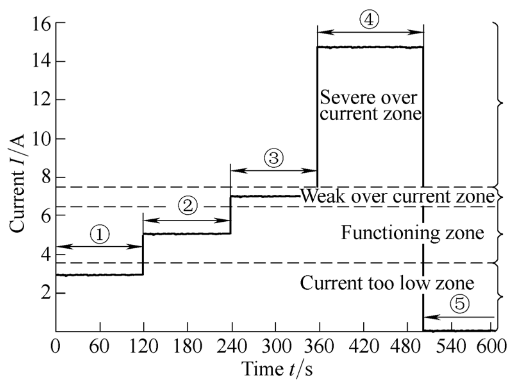


Fig. 22. Test results of normal over current protection

The coordinator detected different statuses in the power connection line from steps 1 to 4 and sent out warning signals. In step 4, the over current was shut down after 140 s, as designed in the software algorithm; step 5 then began, where the connection line was cut off automatically by the command of the coordinator, and the over current error was protected.

The short circuit protection was tested in a similar way but with the help of AV-900 battery test equipment that can produce ±900 A current flow. The rated current of the connection line was 50 A, and the critical threshold value was designed to be 200 A. The parameter of the tested current was set to 300 A for 1s. The testing results are shown in Fig. 23. The connection line was cut off when the current approached 200 A; the designed current of 300A was never achieved. The short circuit error of the power connection line was thus protected.

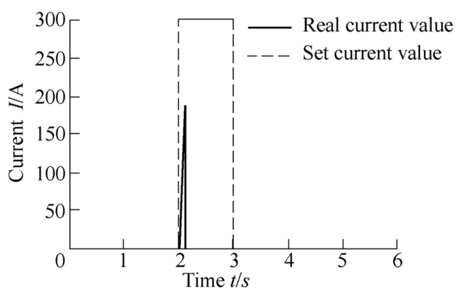


Fig. 23. Test result of short circuit protection

5.2 Battery monitoring and over-discharge protection test results

The battery monitoring function was tested in compromise functioning mode, which examined the variable current discharge and battery charge. An ending SoC value was set so that the test ended when the calculated SoC was approaching the set SoC. The battery was then discharged with an invariable current, and the real remaining SoC was calculated with the Ampere-hour method. The test was repeated several times, and 4 of the test results are as shown in Fig. 24.

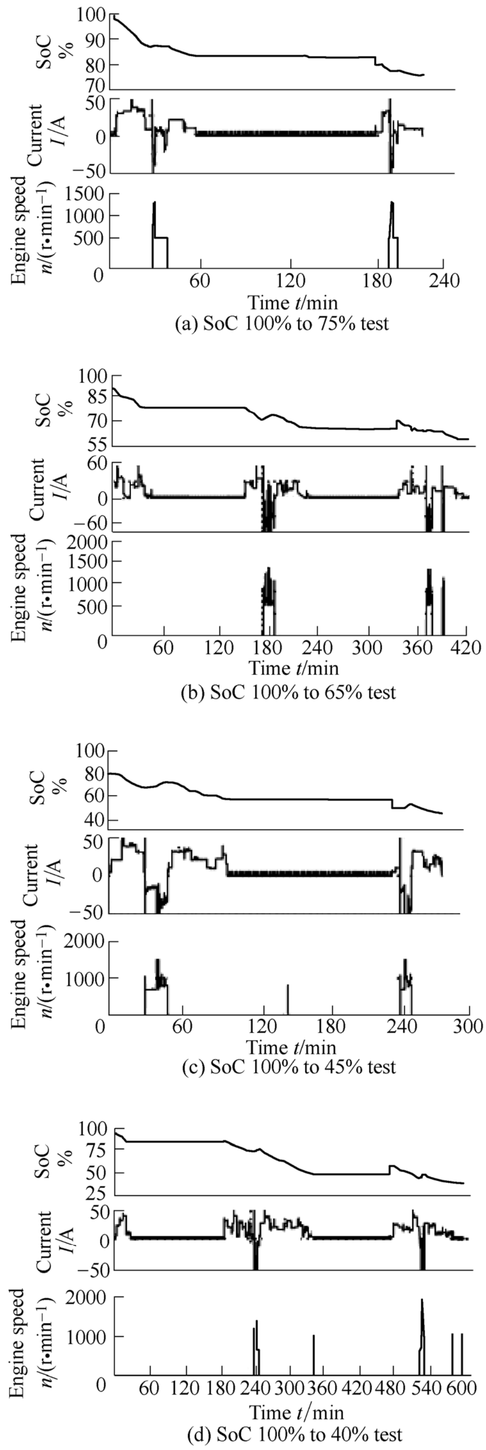


Fig. 24. SoC calculation in compromise functioning

The results and errors are shown in Table 3. The error between the calculated SoC and real SoC was within 5%, which is quite precise for battery over-discharge protection.

Table 3.　Comparison of calculated SoC and real SoC

Test No.	Curves	Calculated SoC S_C/%	Real SoC S_R/%	SoC error S_e/%
1	Fig. 24(a)	75.3	77.1	−1.8
2	Fig. 24(b)	64.3	59.5	4.8
3	Fig. 24(c)	44.7	48.3	−3.6
4	Fig. 24(d)	39.6	36.2	3.4

The battery over-discharge protection is based on the correct calculation of the battery SoC. The battery over-discharge protection mechanism was first simulated with a Matlab Simulink model and then tested on the test vehicle. The simulation condition was designed as shown in Fig. 25, where 4 power consumption modes simulated 4 different current discharges.

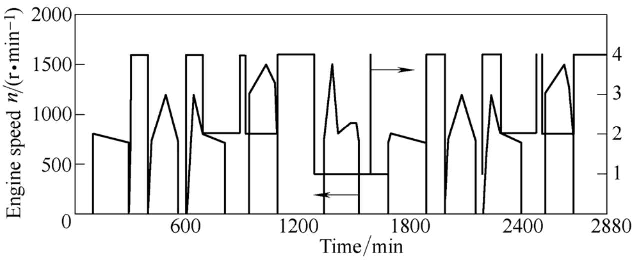


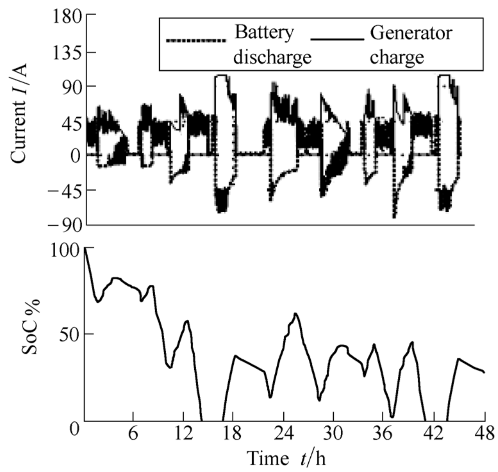
Fig. 25.　Long-term battery simulation test condition design

A comparison of the results produced with and without battery over-discharge protection is shown in Fig. 26. Fig. 26(a) shows that the battery SoC drops to 0% twice without over discharge protection, which would engine launch failure, while Fig. 26(b) shows that the battery SoC is generally above 50% and never below 40%, which ensures successful engine lunch at any time.

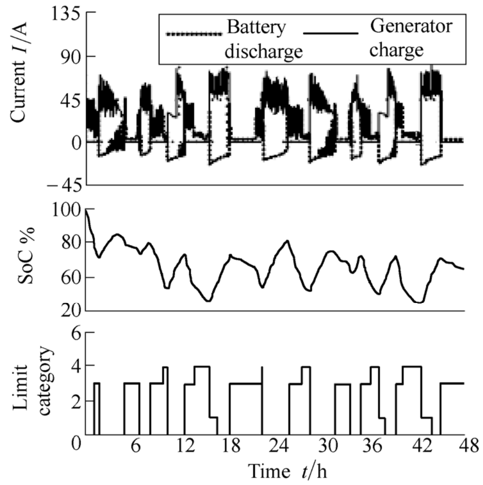
The battery over-discharge protection test was also performed on the experimental bus. The battery was fully charged, and then all devices were turned on to consume the most electrical power. The limited category signal was checked during the test, and engine launch was also tested after 7 days. The test results are shown in Fig. 27. The limited category varied according to the decrease of the SoC. After 5.5 h, the system entered sleep mode. 7 days later, engine launch was tested with manual switching of the ignition key, and the engine successfully launched. The battery over-discharge protection function worked as designed, and the lowest SoC limit for engine launch remained for at least 7 days.

6　Conclusions

(1) An intelligent vehicle electrical power supply system for traditional fuel vehicles was developed that considers all electrical/electronic devices and complex work conditions. The new architecture of electrical power connections prevents the pollution of CP by LP by isolating different load sources, separating the LP and CP connections, and creating a clean electricity environment with no electromagnetic interference.



(a) Simulation without battery over-discharge protection



(b) Simulation with battery over-discharge protection

Fig. 26.　Long-term battery simulation result

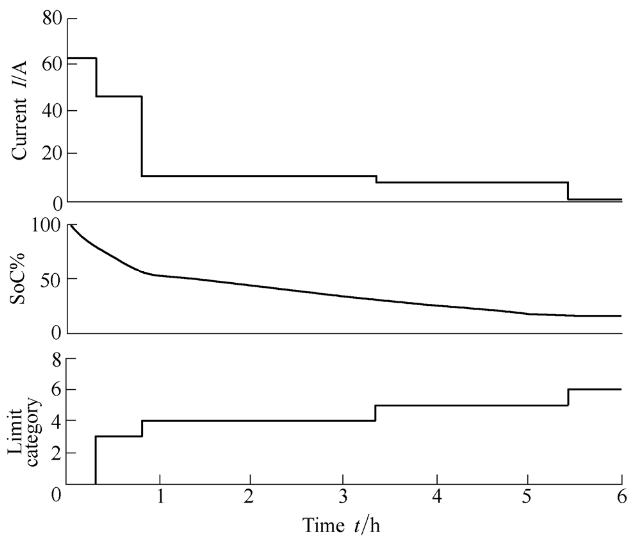


Fig. 27.　Battery over-discharge protection test on shuttle bus

(2) With the proposed system, the power connection between the power source and consumptions are unified, and the reliability of the system is improved.

(3) A new practical SoC estimation method based on the Ampere-Hour method for correction was proposed, which can achieve more accurate SoC estimations for lead-acid batteries in traditional fuel vehicles.

(4) Battery over-discharge protection, power over current protection and the optimization of the vehicle's power utilization were achieved, and the safety of the power supply system was enhanced.

(5) The proposed system has been applied and demonstrated in one city shuttle bus, which had 78 EEDs. The shuttle bus worked correctly during a 1000-km field test. The experimental results verify the feasibility of the proposed system.

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