The circuit design of solar electric vehicle

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Abstract. According to the characteristics of ultracapacitor (UC) and lead-acid battery, a novel and simple circuit of hybrid power system (HPS), which is consisted of UC group and battery set, is designed to realize the basic strategy: to use the UC group to process all solar energy and most of the peak current. However, since the battery set has a much higher energy density than the UC group, it is used to supply power when vehicle run on cruise speed. Both UC group and battery set supply the driving power for vehicle start-up, acceleration and climbing. The results of simulation show that the proposed novel and simple circuit, which is composed of UC group and battery set in parallel, can realize the reasonable energy use of vehicle.

1. Introduction
Large-scale electric vehicle (EV) deployment in the transportation sector has the potential to reduce greenhouse emissions, increase renewable energy penetration, and save fuel cost for drivers \cite{1}. So two major trends in energy usage that are expected for future smart grids are: 1. Large-scale decentralized renewable energy production through photovoltaic (PV) system; 2. Emergence of battery EV as the future mode of transport \cite{2,3}. Solar electric vehicle (SEV) is an ideal "zero emission" vehicle that saves oil resources, and can increase the utilization rate of non-petroleum resources, which is undoubtedly an effective way to solve the oil scarcity and environmental problems.

Some research has been done in references \cite{4-8} on UC group or the HPS, and the related progress has been made. For example, in reference \cite{9}, a new economical and practical control system of EV with HPS is developed, and the HPS based on DC brush-motor is designed in reference \cite{10} and relevant experiments are made.

UC group and battery set are connected to the DC bus by an interface circuit. The power is supplied by the UC group and battery set in parallel when vehicle is started accelerated and climbed. When the vehicle is been braking, the motor energy is fed back and stored in the UC group. There is not a recognized optimal combination topology in the UCs-battery set HPS. In order to optimize the energy management of the HPS to achieve the optimal charge and discharge control, some aspects still need to be carried on the thorough research. At present, the design and control of the HPS is still in its infancy.
2. The Structure of HPS

The HPS of SEV is mainly composed of PV panel, maximum power tracker (MPPT), UC group, lead-acid battery set, motor drive controller and motor. Its structure is shown in figure 1, the UC / battery connection is one of the main circuits of the SEV.

![Diagram of HPS structure](image)

**Figure 1.** The power system structure of SEV.

In the SEV, the main power of the vehicle is provided by the battery set, while the instantaneous high power is provided by the UC group during starting, accelerating and climbing. In this way, the solar energy can be fully utilized and the battery set can be frequently operated in the state of high current discharge.

3. Circuit Simulation of HPS

Figure 2 is selected as connection circuit. In figure 2, the D1 is an anti-charge diode that prevents PV panel from being damaged by UC group or battery set when there is no solar radiation. When there is plenty of solar energy, it can stop battery set being charged so that all PV panel's electricity is absorbed by UC group. When the vehicle travels at cruising speed, the electric energy needed to drive the vehicle is supplied by the battery set alone, the switch S2 is off, the UC group is charged by the PV panel, and if the vehicle starts, the acceleration requires a peak power. At this point, the S3 is closed quickly, and the driving power of the vehicle is provided by UC group and battery set together. When the vehicle stops, the battery set are recharged by the PV panel and switch S1 is closed. In order to protect the switch S1, the switch S2 and R are used to discharge the UC group to their voltage and the ones of battery set are equal. The UCs have a large decrease in voltage after meeting a peak power demand. In order to make full use of the solar energy to avoid charging the battery set to the UCs, a diode D3 is added to the design circuit. Switch S4 is closed only when there is no sunlight and the battery set are required to charge to the UCs. The energy flow strategy for SEV is shown in figure 3.

![Connection circuit diagram](image)

**Figure 2.** The connection circuit.
Figure 3. The energy flow strategy of SEV.

Figure 4 shows the equivalent circuit diagram of the battery set supplying the motor load while supplying the motor load and supplying the super-capacitors with closed switch S3 when the PV panel has no power output.

The component parameters in the circuit are shown in figure 4. The parameters of the components in the equivalent circuit without sunlight are shown in Table 1. Figure 5 shows the simulation of a constant current pulse output without sunlight.

Table 1. The parameters in equivalent circuit without solar energy.

| Parameters | Output current $I_o$ (A) | The capacity of C $C$ (F) | The internal resistance of UC $R_{uc}$ (Ω) | The internal resistance of battery set $R_s$ (Ω) | The original voltage of UC $V_{uc}$ (V) | The original voltage of UC $V_{uc0}$ (V) |
|------------|-------------------------|--------------------------|------------------------------------------|------------------------------------------|----------------------------------|----------------------------------|
| Value      | 150                     | 50                       | 0.1218                                   | 0.1802                                   | 48                               | 48                               |

In figure 5, the output of the circuit is a constant current pulse is shown in figure (a), the current supplied by UC is shown in figure (b), the current supplied by battery set is shown in figure (c), and a characteristic curve of voltage variation of UC group.

It can be seen from figure 5 that the discharge current of the battery set increases with the decrease of the discharge current of the UC group. The UC group discharges from t1 to t2, and the UCs are recharged by the battery set from t1 to t2. At intervals $t \in [t_1,t_2]$, the current of the UCs can be expressed as follows:

$$i_{uc}(t) = \frac{(V_{uc0} - V_s) + I_0 R_s}{R_s + R_{ESR}} e^{-\frac{t}{\tau}}$$

(1)

Here: $V_{uc0}$ — The initial voltage value of UC group (V); $V_s$ — Voltage value of battery set (V); $I_o$ — Output rectangular current (A); $\tau$ — Time constant, $\tau = (R_{uc} + R_s)C$; $C$ — UC group capacity (F); $R_s$ — Internal resistance of battery set (Ω); The current expression of the battery set is:

$$i_B(t) = I_0 - i_{uc}(t)$$

(2)
From t1 to t2, assuming that the voltage of UC group is equal to the one of the battery set, the expression for the current $i_{UC}$ becomes:

$$i_{UC}(t) = \frac{I_0 R_g}{R_a + R_{ESR}} e^{-\frac{t}{\tau}}$$

(3)

From t2 to t3, the expression for the current $i_{UC}$ is:

$$i_{UC}(t) = \frac{(V_{ESS} - V_B) R_g}{R_a + R_{ESR}} e^{-\frac{t}{\tau}}$$

(4)

Here, $V_{ESS} = I_0 R_g (e^{\frac{t_2-t_1}{\tau}} - 1) + V_{CCO}$ (V) (It is the voltage of the UC group at the moment.).

When the sunlight is sufficient, the equivalent circuit is shown in Figure 6, in which the parameters of each element are shown in Table 2. Figure 7 is a simulation result of a constant current pulse output in this case.

| Parameters | Output Current $I_o (A)$ | The capacity of UC $C (F)$ | The internal resistance of UC $R_{ESR} (\Omega)$ | The internal resistance of battery set $R_B (\Omega)$ | The initial Voltage of UC $V_{ESS} (V)$ | The original voltage of battery set $V_{BO} (V)$ |
|------------|--------------------------|----------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------|---------------------------------------------|
| Value      | 150                      | 50                         | 0.0609                                       | 0.1802                                        | 57                                    | 48                                         |

Table 2. The parameters of the equivalent circuit with solar energy.

As shown in figure 7, as long as the voltage of UC group is greater than the one of battery set, as can be seen from the simulation results in figure 7. With the decrease of the discharge current of UC group, the discharge current of battery increases gradually.

UC group are charged with PV panel while discharging from t1 to t2, while the PV panel charge UC group from t2 to t3. At intervals, $t \in [t_1, t_2, t_3]$, the current of the UC group varies over time as follows:

$$i_{UC}(t) = \frac{(V_{ESS} - V_B) + (I_0 - I_{PVm}) R_g}{R_a + R_{ESR}} e^{-\frac{t}{\tau}}$$

(5)

Here, the current $i_{PVm}$ from the PV panel, because the maximum power tracker device is used, the output current of the PV panel is considered to be a constant value when the weather conditions don’t vary very large, and the current expression of the battery $i_B$ is:

$$i_B(t) = I_0 - i_{UC}(t) - i_{PVm}$$

(6)

From t1 to t2, assuming that the voltage of UC group through being charged equal to the voltage of the battery set, the expression for the current $i_{UC}$ becomes:

$$i_{UC}(t) = \frac{(I_0 - I_{PVm}) R_g}{R_a + R_{ESR}} e^{-\frac{t}{\tau}}$$

(7)

Figure 4. The equivalent circuit of UC group / battery set parallel structure without solar light.

Figure 5. The discharge waveform of UC group / battery set system without solar energy.
4. Application of HPS

The design of the HPS circuit is applied to the EVG-222 electric vehicle produced by Guangzhou Dongfang Electric Vehicle, which mainly includes three experiments: the starting acceleration test of pure EV. The starting acceleration test of SEV and the SEV with sufficient sunlight are carried out in this paper.

The basic parameters of the SEV sample are summarized as follows:

Vehicle full load mass: 630kg; Rolling resistance coefficient: 0.015; Air drag coefficient: 0.20; Windward area: 1.94 m²; Wheel radius: 0.24m; Motor: 3kW; The maximum output power of a series DC motor of: 3kw is: 10.5 kW; Battery set: 6 x 8V lead acid battery set and type: 8V145Ah8EP

Maximum speed: 35km/h; Average speed: 14km/h; Total transfer efficiency: 80%; Output voltage of PV panel after booster circuit: 60V; System voltage: 48V.

If the minimum charge state of the battery set is 30%, the charge range for the battery set to work normally is: [0.3 \Omega_{max}, \Omega_{nom}]. Here, \Omega_{nom} is the rated charge of the battery set. When solar radiation is small, the PV panel must overcome the internal loss and the output power value is negative, in the actual use of the process in order to avoid in the sun without light or radiation intensity is very small, PV panel reversely is charged by UC group, a reverse diode is connected in the output circuit of the PV panel. The output power of the PV panel is zero.

The purpose of the experiment is to verify the application of the optimization results to the improvement of vehicle starting acceleration performance in SEV.

Figure 8 is the solar radiation intensity during the experiment (data is sampled once per 0.004s), because the influence of temperature change can be neglected, because the experimental time is less than 15 minutes, namely, T=21°C.

Figure 9, figure 10 and figure 11 show that a vehicle is accelerated from zero to the maximum speed 35km/h, the output voltage and current value of the UC group and the battery set (the data are sampled once every 0.004 s), the initial state of the battery set is SOC=0.6 and the voltage of the UCs is 48V.

Figure 9 shows the starting acceleration test results without PV panel and UC group. Figure 10 shows the experimental results of vehicle starting acceleration under the solar radiation. Figure11 is the physical map of the experimental vehicle.
From the results in figure 9, figure 10 and figure 11 and figure 12, the following conclusions can be drawn:

1) The maximum current of the battery set can reach 180 A when the battery set is used alone, so the loss of life and available capacity of the battery set is larger, and the voltage drop decreases more at the beginning, and then recovers gradually;

2) When sunlight is plentiful, PV panel can fill the capacity of UC group. The experimental results show that the voltage of the UC group decreases more than 140 A when the peak power comes, and the
maximum discharge current of the battery set decreases greatly. In order to protect the battery set from the high current discharge caused by hydrochloric acid vulcanization and other phenomena;

3 ) When the PV panel is turned off, it can be understood that there is no sunshine or insufficient sunlight, and the UC group charged by the battery set because in the present invention, in order to simplify the circuit reduction loss, there is no booster changer device between the battery set and the UC group, so that the maximum discharge current of the UC group is around 40A, which also protects the lead-acid battery set from the impact of large current discharge to a certain extent.

5. Conclusions
In this paper, the random load of a solar electric vehicle is decomposed into two kinds: average load and dynamic load. According to the characteristics of UC group and lead acid battery set, the energy utilization strategy of solar electric vehicle is established. In order to make full use of experimental resources and according to the characteristics of solar electric vehicle, a simple parallel circuit structure of UC group/battery set is proposed and designed in this paper. It can not only make full use of solar energy but also avoid the high current discharge of lead-acid battery set. The economic performance and practicability of the compound energy system are greatly improved.

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