Research on the Fast Charging of VRLA

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Abstract
VRLA can be the energy storing device of the HEV (Hybrid Electric Vehicle), photovoltaic system and so on. The most important factor that restricts the improvement of these fields is the service lifetime of the battery cannot reach the expectation. In the charging process, traditional charging method has serious polarization phenomenon. It will decrease its service life. Aimed at the purpose of reducing the polarization phenomenon, this paper proposed the changing current depolarization pulse charging method which is combining the dynamic model of the battery on the basis of analyzing the existential issues in the pulse charging method. By building the hardware circuit to achieve the function and verify their feasibility. The results indicate that, compared with pulse charging method, the new method makes battery fully charged in shorter time obviously and the temperature of batteries rise more slowly.

Keywords: fast charging, polarization phenomenon, the changing current depolarization pulse charging method, charging efficiency

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1. Introduction
Facing the growing phenomenon of resource shortage and environmental degradation, more emphasis is put on the development of new energy [1]. The development of the energy storing device is a significant link of the new energy utilizing. VRLA with its advantages of stable performance, low price and high cost-effective is widely used in the new industry of HEV, photovoltaic system and so on [2]. It’s a vital task to longer the service life of the VRLA.
The charging method in hand cannot follow the optimum charging current curve correctly so that the polarization phenomenon is obvious. The polarization phenomenon closely related to the charging efficiency [3]. To solve those questions, this paper put forward the changing current depolarization pulse charging method which uses the phase changed current, and monitors the endpoint voltage, current, temperature and the SOC of the battery in the circuit. Once the voltage is greater than the specified value, power source stops charging to the battery and adds the depolarization pulse. Lots of experiments’ result support that the negative pulse could eliminate the polarization effective [4].

2. The Polarization Phenomenon of the Battery and the Acceptable Charging Current
2.1 The creation and the damage of the polarization phenomenon
In the charging process, there will be a large scale of current across the battery so that the electromotive force of the battery would deviate slightly from its equilibrium values. This phenomenon is called the polarization of the electrode plate [5]. The polarization phenomenon consist of three main parts: Ohmic polarization, electrochemical polarization and concentration polarization. Ohmic polarization and electrochemical polarization will decrease or even eliminate in milliseconds or in microseconds when the charging current decreased to a low value or stopped charging. While the concentration polarization needs longer time to eliminate, it always costs a few seconds [6].

The influence of the polarization phenomenon in the charging process mainly includes three parts [7]. Firstly, the overvoltage produced by polarization phenomenon would hinder the increase of the charging current. Then it makes the hydrolysis aggravate and generates a mass of gas which not only delays the charging process but also corrodes the plate seriously. Secondly, hydrolysis would create a large amount of heat which would raise the temperature of the electrolyte. If the temperature rises to a certain extent, electrode plate would buckle, even
damage. Finally, hydrolysis wastes heat which reduces the power of the charging process efficiency.

2.2 The acceptable charging current

The scientist of American, MAS, studied the polarization phenomenon in the charging process [8]. On the assumption of lowest gas chromatography rate, he put forward the optimum charging current curve, as shown in Figure 1.

During lots of experiments and theory analysis, the relationship of max acceptable charge current and time are concluded as

$$I = I_0 e^{-\alpha t}$$

(1-1)

$I$ is the max acceptable charge current. $I_0$ is the max charge current during the beginning of charge, which is determined by the using state of battery. $\alpha$ is the acceptable charge ratio.

3. Analysis of the Polarization Phenomena of Traditional Charging Methods

Constant current method and constant voltage method cannot very good follow the optimum charging current curve so that in the charging process the efficiency is very low and the cost of time is very long. And also it doesn’t have a measure to eliminate the polarization phenomena. In the charging process, it would produce a lot of bad phenomena such as gas chromatography, exotherm and so on. Finally, it would shorten the life of the battery and waste electric energy [9].

Three-stage charging method combines the constant current method with the constant voltage method. During the primary charging process, the current is well below the acceptable charging current. It would reduce the charging efficiency. During the late charging process, the current is above the acceptable charging current for a long time [10]. It results serious polarization phenomena with a mass of gas. This phenomenon not only delays battery charge process but also corrodes the plate seriously.

Pulse charging method uses intermittent pulse. In charging process, this method stops charging for a while to make the oxygen and hydrogen which produced by the chemical reaction have enough time to recombination so that it can be absorbed better and part of the polarization phenomena can be eliminated. It will finally appear as the battery could absorb more power [11]. Even though in the pulse charging method the phenomenon of polarization decreases somewhat. This method cannot eliminate the polarization phenomena thoroughly. The main reason lies in that the charging current curve cannot very good follow the optimum charging current curve.

4. Dynamic Circuit Model of Lead-Acid Battery

In Figure 2, the meanings of parameters are provided as following: E: respects electromotive force of battery. R0: respects Ohmic resistance. I: respects the charging current of the battery. G: respects the point of the gassing branch. U: respects output voltage.
Figure 2. Dynamic circuit model of Lead-acid battery

Figure 2 describes the internal structure of the battery as a dynamic circuit model. As the complexity of the battery charging and discharging process, all the variables are representing the non-linear circuit of battery and affected by many parameters. It can simplify gassing phenomenon of the battery into a gating process [7]. During charging, the voltage in point G will increase, it reflects the degree of polarization. When the voltage in G is higher than \( V_{G_{th}} \), the charging efficiency will decrease and the battery will separate out gas. While the voltage in G is lower than \( V_{G_{th}} \), it only generates a bit gas and the weak polarization phenomena.

It’s a good way to properly stop charging for a while and then charge the battery with high discharge current in a short time when the voltage in point G approaching a fixed value that we set before experiment as the gassing branch electromotive force. It will release the electricity which accumulate in the charging process and remit the polarization phenomena.

The voltage in point G is provided as following:

\[
V_G = U - R_0 \cdot I \tag{1}
\]

In the formula \( R_0 \) is affected by many parameters, such as \( \theta \) (the temperature of the electrolyte), \( Q_e \) (the charge that the battery have already released), \( I \) (the current of the battery). It can represent as follow:

\[
R_0 = f(\theta, Q_e, I) \tag{2}
\]

In charging process, the parameters(\( \theta, Q_e, I \)) of the battery must be monitored and the voltage \( U \) and the current \( I \) need to be detected. In the end of the discharging process, the electromotive force of battery E should be detected. According to the dynamic circuit model in Figure 2, \( R_0 \) can be calculated. Then \( V_G \) could be got based on equation (1). Through PID control algorithm, it can control the output voltage of the main circuit to make the \( V_G \) approach to \( V_{G_{th}} \) closely.

5. The Appearance of the Changing Current Depolarization Pulse Charging Method

As experiment shows that, in the charging process, it’s a good way to discharge the battery in high rate current, because this measure could improve the charging receiving ability. That is to say, the optimum charging current will not decrease with an exponential decreasing trend [12, 13]. Finally the performance for that, the high rate current discharging can make the battery increase the charging speed. It shows in Figure 3.

The changing current depolarization pulse charging method mainly divided into four phases, as Figure 4:

1) The first step(0\(-t_1\)): In this section, large current is used to charge the battery. It makes the voltage of the battery rising rapidly. As is shown in Table 1, it’s proper to charge the battery with the current of 0.5C in the first round.

2) The second step(\( t_1\)-\( t_2 \)): This phase is called the test phase. The first stage makes the polarization phenomena quite serious, that is, the voltage in point G approaching to a fixed value \( V_{G_{th}} \), then MCU gives commands to make the battery stop charging. This method leaves enough time for plate and the electrolyte to chemical reaction.

3) The third step(\( t_2\)-\( t_3 \)): This phase is called the instant discharge phase. In this section, the amplitude of the discharge current had 2.5 times more than the charge current’s. At the
same time, the test components real-time monitor the voltage in point G. As soon as the voltage in point G down to a specified value, stop charging.

4) The fourth step($t_4$-$t_5$): This phase is called the delay phase. This method leaves enough time for plate and the electrolyte to chemical reaction. And it leaves enough time for the system to prepare for the next round.

In the second round, the charge current down to 0.4C, while in the third round the current down to 0.3C. By such analogy, once the current reach to 0.2C, all the charging process ended. Experiment data is shown as Table 1.

![Inherent charging curve](image1)

**Figure 3.** Battery inherent and expanded charging characteristics schemes

![Inherent charging curve](image2)

**Figure 4.** The changing current depolarization pulse charging method

<table>
<thead>
<tr>
<th>Initial current and the way current change</th>
<th>The interval stop charging, [s]</th>
<th>Charging time, [min]</th>
<th>SOC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C-0.75C-0.5C-0.25C</td>
<td>30</td>
<td>201</td>
<td>80%</td>
</tr>
<tr>
<td>0.75C-0.5C-0.25C-0.1C</td>
<td>60</td>
<td>180</td>
<td>88%</td>
</tr>
<tr>
<td>0.5C-0.4C-0.3C-0.2C</td>
<td>30</td>
<td>148</td>
<td>96%</td>
</tr>
<tr>
<td>0.5C-0.4C-0.3C-0.2C</td>
<td>60</td>
<td>165</td>
<td>92%</td>
</tr>
</tbody>
</table>

The changing current depolarization pulse charging method combines dynamic circuit model of lead-acid battery. It monitors the voltage in point G to control the gas volume within a certain range. In charging process, stop charging for a while and discharge with high rate current to make the oxygen and hydrogen which produced by the chemical reaction in the battery have enough time to recombination, so that it can be absorbed better and most of the polarization phenomena can be eliminated. It will finally appear as the battery can absorb more power.
6. Main Circuit for Batteries Charging

The advantage of the asymmetrical half-bridge topology is the inherent zero-voltage-switching (ZVS) capability and thus potentially higher efficiency. So the paper adopts the asymmetrical half-bridge power converter as the DC/DC charging cell which is shown in Figure 5. During the positive pulse charging period, the switches $Q_1$ and $Q_2$ operate with asymmetrical duty ratios which require short and well-defined dead time between conduction intervals. The operation principle of the asymmetrical half-bridge DC/DC cell can be explained as follows.

![Figure 5. The asymmetrical half-bridge DC/DC cell](image)

At first the upper switch $Q_1$ and the rectifying diode $D_3$ are turned on. The energy stored in the DC bus capacitor is transferred to the load. Then the upper switch $Q_1$ is turned off and the rectifying diode $D_3$ is still conducting, the freewheeling current starts to charge $C_{p1}$ and discharge $C_{p2}$. Thus, the voltage across the upper switch $Q_1$ increases linearly and the voltage across the lower switch $Q_2$ decreases linearly. The decreased voltage arrives at the voltage $V_{Gth}$ across series capacitor $C_s$ at the end of this state, the voltage across transformer primary and secondary windings become zero and the diode $D_4$ is turned on. Due to the resonance of the circuit $L_r$ and $C_{p2}$, the voltage across the lower switch $Q_2$ arrives zero and the inductor current has already flown through the anti-parallel diode $D_2$. Therefore, as long as the lower switch $Q_2$ is turned on before the inductor current changes its direction, zero-voltage turn-on of $Q_2$ can be achieved. At this moment, the voltage across transformer primary winding is equals zero, the inductor current increases linearly. At the end of charging process, the diode $D_3$ is turned off, the energy stored in the series capacitor $C_s$ is transferred to the load through transformer windings and diode $D_4$.

7. Experiment Result

The system used the 12V12Ah lead-acid battery. In the charging process, MCU monitors the charging current, temperature and time. Compared the data of pulse charging method with the changing current depolarization pulse charging method; we get the following data conclusion. Figure 6 shows the change of SOC in respectively. Figure 7 indicates the change of the temperature in two charging methods. The experimental indicates that the changing current depolarization pulse charging method can save about half of the time than pulse charging method.

With the current of 11.15A, two methods are applied to charge the battery respectively, as the changing current depolarization pulse charging method and pulse charging method. The changing current depolarization pulse charging method costs about 148mins. The pulse charging method needs about 100mins. Compared with other methods, the changing current depolarization pulse charging method heats up slower. It's good for the inner structure of the battery.

The changing current depolarization pulse charging method monitors the voltage in point G in real time. Once $V_G$ is over $V_{Gth}$, add in negative pulse to decrease gas evolution and
polarization phenomena. This method short the charging time greatly and control the temperature within the appropriate bounds.

8. Conclusion
This paper introduces the charging method, changing current depolarization pulse charging method which is based on dynamic circuit model of lead-acid battery, which is a good fast charging method. It has a good performance in the aspect of short charging time, improve use efficiency, longer service life and reduce energy loss. It has stronger practical value.

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Title of manuscript is short and clear, implies research results (First Author)


