Hybrid Energy Storage Control Method for Isolated Island AC Micro-grid Based on Consistency theory

SONG Chao1*, XU Zhichao1
1School of Electrical Engineering, Dalian University of science and technology, Dalian, Liaoning Province, 116052, China
*Corresponding author’s e-mail: 445980536@qq.com

Abstract. In the traditional hybrid energy storage control method of isolated island AC micro-grid, due to the difference between different types of hybrid energy storage in the hybrid energy storage system, the control stability is low. Therefore, a hybrid energy storage control method of isolated island AC micro-grid based on consistency theory is proposed. Based on the consistency theory, the voltage and SOC of the isolated island AC micro-grid hybrid energy storage system are subject to the consistency control. On this basis, the power of the hybrid energy storage system is subject to the consistency control. Thus, the research on the control method of the isolated island AC micro-grid hybrid energy storage based on the consistency theory is completed. The experimental results show that the proposed control method based on consistency theory has better control stability.

1. Introduction
There are two typical operation modes of micro-grid: under normal circumstances, the micro-grid and the conventional distribution network are connected to the grid, which is called grid-connected mode. When a fault of the power grid is detected or the power quality fails to meet the requirements, the micro-grid will be disconnected from the power grid in time and operate independently, which is called island mode [1]. In the operation of island power grid, due to the intermittent and randomness of the output power of renewable energy, its safety and availability are weak [2-4]. Therefore, in addition to power generation system, isolated island power grid also needs to configure energy storage links of a certain capacity of energy storage link, so as to coordinate the power balance between power generation and electricity consumption and maintain the stable operation of the power grid. Due to the advantages of high reliability, low cost, mature technology and high energy density, battery is widely used in energy storage link and becomes the first choice of energy storage system of island power grid [5]. Consistency theory can balance the power distribution between different types of energy storage in hybrid energy storage. Based on the above, a hybrid energy storage control method for isolated island AC micro-grid based on consistency theory is proposed. The effectiveness of the proposed hybrid energy storage control method based on the consistency theory for isolated island AC micro-grid is verified by comparative experiments.

2. Research on Hybrid Energy Storage Control Method of Isolated Island AC Micro-Grid Based on Consistency Theory
Based on the theory of consistency, through the hybrid energy storage system voltage consistency control, charged state consistency control, it implements the control of the micro-grid hybrid energy
storage system for an island communication power consistency. The concrete implements process as described in the following content.

2.1 Voltage Control of Hybrid Energy Storage System Based on Consistency Theory

The voltage of the hybrid energy storage device is controlled, mainly the supercapacitor. The consistency control of supercapacitors is mainly to calm the fluctuation of AC bus voltage and maintain the consistency of terminal voltage of supercapacitors. The structure of supercapacitor control is shown in figure 1.

![Figure 1. Voltage control block diagram of supercapacitor](image1.png)

Imbalance of power in the hybrid energy storage system will make AC bus voltage fluctuations, therefore, the bus voltage in the controller should be controlled, using the average difference of bus voltage $v_{avg}$ and a reference value $v_{ref}$ as the input of the controller, and the output of the controller is to make correction, the supercapacitor current control reference value $v_{avg}$ to the average bus voltage $v_{ref}$ stability in the reference. Transfer function of bus voltage controller $G_{U_i}$ is:

$$G_{U_i} = k_{PU_i} + \frac{k_{IU_i}}{s}$$

(1)

In formula (1), $k_{PU_i}$ represents the proportional term gain of the controller, $k_{IU_i}$ represents the integral term gain of the controller, and $s$ represents the integral parameter of the transfer function. In order to make the supercapacitor voltage is the same, the controller of the supercapacitor voltage of consistent control of the adjacent get the supercapacitor voltage through communication network in the energy storage unit, with its own terminal voltage difference, weighted summation, the results obtained in the input to the controller, getting the other modifications of the reference current value, the realization of hybrid energy storage device in the system all the voltage of the supercapacitor is consistent. It realizes the consistency of the hybrid energy storage system voltage control.

2.2 SOC State Control of Hybrid Energy Storage System Based on Consistency Theory

The consistent control block diagram of SOC state of hybrid energy storage in isolated island AC micro-grid is shown in figure 2.

![Figure 2. SOC consistency control block diagram](image2.png)
According to the SOC consistency control block diagram in figure 2, the specific control process is as follows:

To realize the parallel battery SOC dynamic equilibrium in discharge process, under the premise of balancing load demand of island power grid, according to their remaining energy distribution load power, it makes more residual energy storage battery has larger SOC rate. And the remaining energy battery SOC rate with smaller, so SOC gradually converges in different battery. Using the form of nonlinear logarithmic function to construct SOC change rate relations between different batteries, the SOC change rate relations between parallel batteries are designed as follows:

\[
\frac{SOC_a}{SOC_\beta} = \frac{1}{m_p} \left[ \frac{-\ln(1 - SOC_a)}{-\ln(1 - SOC_\beta)} \right]^n
\]

\[
\begin{align*}
[-\ln(1 - SOC_a)]^n &> [-\ln(1 - SOC_\beta)]^n & \quad & \text{SOC}_a > \text{SOC}_\beta \\
[-\ln(1 - SOC_a)]^n &\leq [-\ln(1 - SOC_\beta)]^n & \quad & \text{SOC}_a = \text{SOC}_\beta \\
[-\ln(1 - SOC_a)]^n &< [-\ln(1 - SOC_\beta)]^n & \quad & \text{SOC}_a < \text{SOC}_\beta
\end{align*}
\]

In formula (2), \( \alpha \) and \( \beta \) are constant, \( \alpha, \beta \in [1, z] \), and \( \alpha \neq \beta \); \( m_p \) and \( m_p \) represent active sag coefficient, rad/s/W; \( n \) is the acceleration factor, and \( n \geq 1 \). According to formula (2), when the SOC between parallel batteries is not balanced, the SOC change rate within each battery is different, and the logarithmic function makes the SOC change rate between parallel batteries larger than the linear one, proving that the designed proportional relationship has a faster balancing speed. The acceleration factor \( n \) can adjust the rapidity of this proportional relationship. With the increase of exponential acceleration factor \( n \), the SOC change rate proportional relationship between parallel batteries also increases, indicating that SOC in different parallel batteries can get consistent faster.

According to the analysis of formula (2), in order to realize SOC balance in the discharge process, the battery with higher SOC should provide more active power, but its output power is limited by the capacity of the interface inverter, which may not meet the requirements of the droop controller. In this case, SOC balanced droop controller adjusts the given frequency according to the output power limit, so that the battery interface inverter can work for a long time at the maximum output active power point, and output as much active power as possible to balance the SOC between parallel batteries. The active droop coefficient \( m_p \) is designed as follows:

\[
m_p = \frac{m_{p0}}{n[-\ln(1 - SOC)]^n}
\]

In formula (3), \( m_{p0} \) represents the droop coefficient of common active work. The sag coefficient in formula (3) is input into the sag controller, which not only has a larger SOC change rate ratio relationship, but also has a smaller voltage frequency deviation of the island micro-grid. The expression of frequency deviation of the island micro-grid is as follows:
\[
\omega^* - \omega = k_i \frac{m_{i0}}{\tau} \left( \frac{1}{k_i} P_{\text{max}} \right) < 2\% \omega^*
\]  

(4)

In formula (4), \(\omega^*\) represents rated voltage frequency, rad/s; \(\omega\) represents the actual voltage frequency; \(k_i\) represents the storage battery interface inverter capacity coefficient, and \(k_i \in (0, 1]\); \(\tau\) represents the boundary value of the change range of \(n \left[ -\ln (1 - \text{SOC}_i) \right] \); \(P_{\text{max}}\) represents the maximum active power of the battery, and the boundary value \(\tau\) should make the island micro-grid offset less than 2\%. By restricting the output active power and voltage frequency offset, the state of charge of the battery in the hybrid energy storage system is controlled uniformly.

### 2.3 Power Control of Hybrid Energy Storage System Based on Consistency Theory

Based on the consistent control of voltage and state of charge of hybrid energy storage device, the consistent control of hybrid energy storage system is realized. Control the power \(S\) of all energy storage devices within a certain range \(S_{\text{limit inferior}} < S(t) < S_{\text{superior limit}}\). Control all hybrid energy storage in the same discharge state, that is, all hybrid energy storage devices have a common discharge ratio, that is:

\[
\frac{P_1}{P_{\text{max}1}} = \frac{P_2}{P_{\text{max}2}} = \cdots = \frac{P_i}{P_{\text{max}i}}
\]  

(5)

In formula (5), \(P_i\) represents the output power of the \(i\)-th energy storage device, and \(P_{\text{max}i}\) represents the maximum power provided by the \(i\)-th energy storage device. In the hybrid energy storage system, the control status information of each energy storage device can be expressed as:

\[
u_i(t) = f_i \left[ c_{i0}(t) u_0(t), c_{i1}(t) u_1(t), \ldots, c_{in}(t) u_n(t) \right]
\]  

(6)

In formula (6), \(u_i(t)\) represents the control information of the energy storage device of the \(i\)-th node at time \(t\), and \(u_0(t)\) represents the control information of the node at time \(t\). \(c_{ij}\) represents the communication connection between the \(i\)-th energy storage device and the \(j\)-th energy storage device. If the communication can be conducted between the \(i\)-th energy storage device and the \(j\)-th energy storage device, then \(c_{ij} = 1\), otherwise \(c_{ij} = 0\). In addition, if the \(i\)-th energy storage device can communicate with the control device, then \(c_{i0} = 1\), otherwise \(c_{i0} = 0\); if \(c_{ij} = 1\) is suitable for any energy storage device, it means that all energy storage devices can get information from themselves. For some reason at some point, the communication between the hybrid energy storage devices will break down. In view of this situation, consistency control is adopted for the energy storage system. According to consistency control theory, the power control process is as follows:

In the energy storage system, the terminal voltage of the \(i\)-th energy storage device is expressed as \(U_i\), the output current is \(I_i\), and the output active power can be expressed as:

\[
P_i = U_i I_i
\]  

(7)

If there is formula (8):

\[
u_i = \frac{I_i}{P_{\text{max}i}}
\]  

(8)

To achieve the consistency of formula (6), only the consistency of \(u_i (i = 1, 2, \ldots, n)\) is needed. Consistency algorithm of energy storage device can be described as follows:

\[
u_i(t) = k_i \left\{ \sum_{j=1}^{n} c_{ij} \left[ u_j(t-t_d) - u_i(t-t_d) \right] + c_{i0} \left[ u_0(t-t_d) - u_i(t-t_d) \right] \right\}
\]  

(9)
In formula (9), \( k_i > 0 \) is the control gain of the energy storage device. The calculation formula of \( k_i \) is:

\[
k_i = \frac{1}{\sum_{j=0}^{n} c_{ij}}
\]

Then, the control information of the \( i \)-th energy storage device is:

\[
u_i(t) = u_i\left(t-t_d\right) + u_i(t) \times t_d
\]

(11)

For control information of control device node, when \( S(t) < S_{\text{inferior limit}} \), there is:

\[
u_0(t) = k_p \left[ -S_{\text{inferior limit}} \right] - S(t) \left[ \frac{S_{\text{inferior limit}}}{P_{\text{max}}} \right]
\]

(12)

In formula (12), \( k_p \) represents the control regulation factor, which is used to adjust the speed of reaching a consistent state. The formula (13) can be obtained:

\[
u_0(t) = u_0\left(t-t_d\right) + k_p \left[ S_{\text{inferior limit}} - S(t) \right] t_d, S(t) < S_{\text{inferior limit}}
\]

(13)

When \( S(t) > S_{\text{superior limit}} \), the same is as the above. Therefore, the power output required by each energy storage device in a certain period can be expressed as:

\[
P_i(t) = u_i(t) \times P_{\text{max},i}
\]

(14)

In formula (14), \( P_i(t) \) represents the power output by the \( i \)-th energy storage device in a period of \( t \). The power consistency control of hybrid energy storage system is realized by formula (14). So far, the research on hybrid energy storage control method of isolated island AC micro-grid based on consistency theory has been completed. Through the comparative experiment, the consistency control is verified to be able to implement the control more efficiently, and the control stability of different control methods is compared with the traditional control method.

3. Experiment

Using the proposed hybrid energy storage control method of isolated island AC micro-grid based on consistency theory, communication with traditional hybrid energy storage control method of isolated island AC micro-grid, the three kinds of control methods for micro-grid silos communication control stability of the hybrid energy storage system are compared.

3.1 Experimental Process

First, setting the experimental parameters, the specific parameters are shown in table 1.

| Serial number | Parameter name                              | Value |
|---------------|--------------------------------------------|-------|
| 1             | Effective value of AC bus voltage           | 380 V |
| 2             | Bus voltage frequency                      | 50 Hz |
| 3             | Converter switching frequency              | 20 kHz|
| 4             | DC side voltage of converter               | 800 V |
| 5             | Filter inductance                          | 2 mH  |
| 6             | Filter inductance parasitic resistor        | 0.1 Ω |
| 7             | Filter capacitance                         | 3μF   |
In the experimental environment with the above experimental parameters, the control of isolated island AC micro-grid hybrid energy storage system is implemented, and the control results of isolated island AC micro-grid hybrid energy storage system are obtained, and compared with the traditional control methods.

The control effect comparison results of the three control methods are shown in figure 3.

![Figure 3. Comparison results of control stability of three control methods](image)

Figure 3 shows the equivalent load power of the hybrid energy storage control system of the isolated island AC micro-grid by using three control methods respectively under the condition that the AC bus voltage remains constant. As can be seen from figure 3, with the traditional control method 1 and control method 2, the change curve of equivalent load power of the hybrid energy storage control system of the isolated island AC micro-grid is not smooth as time goes by, indicating that its control stability is not high enough. And using hybrid energy storage control method of isolated island AC micro-grid based on consistency theory, through the implementation consistency control of battery energy storage system, supercapacitor hybrid energy storage device such as voltage, SOC, and the power of, it makes the resulting curves of equivalent load power is very smooth. Compared with other two kinds of traditional control method, the result shows that it has higher control stability.

4. Conclusions

Aiming at the disadvantage of control stability of traditional island AC micro-grid hybrid energy storage control method, a hybrid energy storage control method of isolated island AC micro-grid based on consistency theory is proposed. Through the comparison experiment, and the comparison with the traditional hybrid energy storage control method of isolated island AC micro-grid, the experimental results show that the proposed hybrid energy storage control method of isolated island AC micro-grid based on consistency theory can effectively improve the control stability of the traditional control method, and has a higher control stability. It is hoped that it can provide some basis for research on hybrid energy storage control of isolated island AC micro-grid.

References

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