

Adaptive Allocation Strategy for Power Storage in Isolated DC Microgrid with Unmatched Line Impedance and Abnormal Communication

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Abstract—An adaptive droop control strategy is proposed for a parallel distributed multi-energy storage system of an isolated DC microgrid with unmatched line impedance and abnormal communication. System line impedance mismatch can cause unbalanced load power distribution and reduce service life of distributed energy storage unit (DESU). Therefore, an improved droop control based on mixed coefficient compensation of state of charge (SOC) and voltage is designed, which can adaptively adjust a power characteristic curve according to the sampling period, so as to ensure precise distribution of load power while minimizing voltage deviation. Considering the stability of the system under communication anomaly, a non-communication backup control based on Metropolis acceptance criterion is proposed, which only uses internal data to adaptively adjust the droop coefficient. In addition, a gradual smooth handover strategy is designed through gradient coefficient to optimize control stability under communication anomaly. Finally, effectiveness and correctness of the proposed control strategy are verified by mathematical analysis and RTDS/DSP hardware-in-the-loop experiments.

Index Terms—Communication, DC microgrid, improved droop control, line impedance.

I. INTRODUCTION

WHILE traditional energy sources promote global economic development, they also further aggravate environmental pollution. Therefore, how to efficiently use renewable energy (RES) instead of traditional energy is becoming a hot research topic [1]–[3]. As a way to effectively integrate renewable energy, such as photovoltaic and wind turbines according to regional conditions, microgrids have attracted wide attention [4]–[6]. Traditional AC microgrid has many problems such as phase, reactive power and harmonics, while a DC microgrid, as a new form of microgrid, does not have

these problems [7]–[9].

Intermittency and randomness of distributed energy can affect stable operation of microgrids, so a certain amount of DESUs should be configured to ensure stability of DC bus voltage and provide necessary energy support [10]–[12]. However, due to inconsistency of line impedance, traditional droop control of DESUs may cause imbalance of output power and SOC deviation in the process of charge and discharge, and reduce service life of DESUs [13], [14]. Therefore, scholars put forward different solutions to solve DESUs output power and SOC imbalance. In [15]–[17], methods of compensating DC bus voltage and improving accuracy of power sharing are mainly achieved by adding a voltage offset to the droop controller. Closed-loop regulation can improve steady-state power sharing accuracy of parallel converters. However, equivalent output impedance of each DESU is not consistent due to use of a fixed droop coefficient, and the power controller needs to be further adjusted when load changes rapidly. In order to overcome the influence of rapid load change, improved droop control schemes using a coefficient adjustment method are proposed in [18], [19]. But it is necessary to use a single current feedback loop to adjust, and further attention must be paid to convergence speed and stability. A DESU output power allocation method with bus voltage drop compensation is proposed in [20], and SOC equalization speed is improved by an acceleration factor. While changing the sag coefficient, balance of SOC is achieved by secondary compensation of bus voltage deviation, but only the state of energy storage discharge is studied, so it needs to be further optimized.

Improved droop control schemes in the above research cannot take into account the influence of line impedance. However, inconsistency of line impedance in DC microgrids may lead to failure of droop control to achieve accurate power distribution according to the original droop coefficient. So [21] designed a multi-agent synovium algorithm. This algorithm only uses DESU discharge with high SOC and DESU charge with low SOC to realize SOC rapid balance. However, when the difference of transient output power is large, fast compensation cannot be realized, which may still lead to overcharge and over discharge of DESUs. A droop control scheme based on SOC power index is designed in [22]. However, it is necessary to set a larger sag coefficient, which will lead to larger bus voltage drop. A decentralized power sharing strategy considering different line impedances is pro-

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posed in [23], which takes into account the effect of line impedance on accuracy of DESU output power allocation. Although the above references have achieved optimization of control objectives, most of them only improve droop control by changing a single initial voltage value or drop coefficient, and rely too much on information exchange between different energy storage units. In case of communication failure, the system cannot obtain dynamic information, which will affect stability of microgrid.

In order to solve these problems, fully decentralized control methods can be adopted for DESUs, which do not require excessive reliance on communication links or central controllers [24]–[28]. In [24], a fuzzy logic control method based on droop control is proposed to balance SOC between batteries by adjusting the virtual resistance of low-voltage DC microgrid. In [25], a virtual DC motor control strategy based on SOC is proposed. However, this does not take into account the effect of DESU capacity on SOC balance. In [26], [27], droop control based on SOC balance scheme is proposed to maintain good power quality, but the P-f droop control method is not suitable for DC microgrid. [28] proposed an adaptive droop control scheme for distributed DESU, but the effect of line impedance was not considered, which would lead to large voltage deviation.

Based on the above analysis, an improved control scheme using an adaptive droop control coefficient is designed, respectively, under normal communication and communication failure to achieve output power and SOC balance among DESUs. Firstly, disadvantages of traditional droop control and influence of mismatched line impedance on DESU output power distribution are analyzed in detail, and an improved droop control scheme based on communication is proposed. In order to obtain compensation effectively, a dynamic consistency algorithm is used to dynamically track SOC and output power status. Further considering the operating status of the system under communication failure, non-communication backup control is proposed. Based on the Metropolis acceptance criterion, this method only relies on internal information of each energy storage unit. Secondly, in order to realize a smooth switch between the two modes, a corresponding control strategy is designed. Finally, mathematical analysis and RTDS experiment can effectively verify accuracy of the proposed scheme.

II. ANALYSIS OF TRADITIONAL DROOP CONTROL FOR ISOLATED DC MICROGRID

A. Typical Structure of DC Microgrid

A DC microgrid as shown in Fig. 1. Maximum Power Point Tracking (MPPT) mode is generally adopted in a DC system when the DC microgrid is in island operation. As output power of RES fluctuates in real time due to light intensity or wind power, it is necessary to compensate the power shortage through charging and discharging of the units. However, due to differences in line impedance, traditional sagging control is not good, so improvements are needed to ensure that each DESU can achieve a balance of power and SOC.

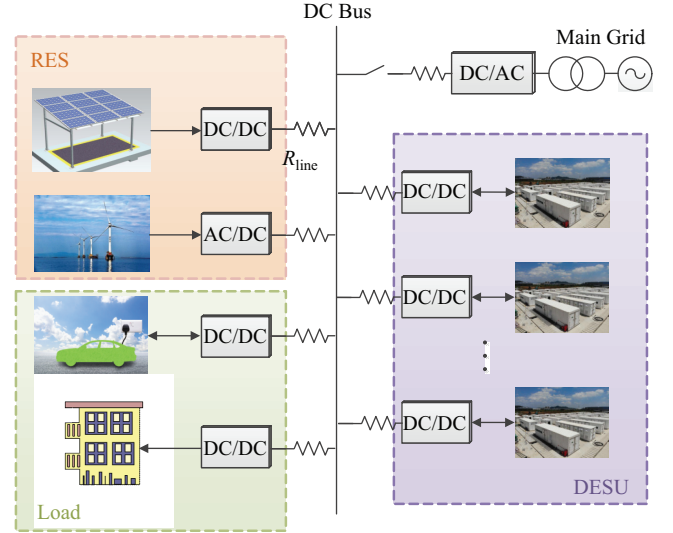


Fig. 1. DC microgrid structure.

B. Analysis of Traditional P-U Droop Control

Droop control is widely used in the field of microgrid because it can effectively balance the quantitative relationship between two outputs. P-U droop control is more commonly used in DC microgrid.

$$U_i = U_{\text{ref}} - k_i P_i \quad (1)$$

where U_{ref} is the voltage reference value; U_i , k_i and P_i are the output voltage, droop coefficient and output power of the i th DESU, respectively.

The SOC of DESU is an important indicator to represent output capacity of the current energy storage unit. The calculation method is as follows [29]

$$SOC_i = SOC_i^* - \frac{\lambda \int I_i dt}{C_i} \quad (2)$$

where SOC_i^* and SOC_i are the initial and iterative value of SOC; λ is a particular constant; C_i and I_i are the capacitance and output current.

When the SOC is within the limit range, output voltage U_i can be maintained stably through charging and discharging of the energy storage unit, so it can be regarded as a constant and can be obtained by (2)

$$SOC_i = SOC_i^* - \frac{\lambda}{U_i C_i} \int P_i dt \quad (3)$$

To derive (3), there is

$$SOC_i' = -\frac{\lambda P_i}{U_i C_i} \quad (4)$$

In order to improve the system stability margin, a DC/DC converter is usually used to connect multiple groups of energy storage units with the same specifications to the DC bus.

Figure 2 shows a simplified model of parallel connection of energy storage units. Where, R_i , R_j , P_i , P_j and R_{load} are equivalent values, representing line impedance, output power and load of the two energy storage units, respectively.

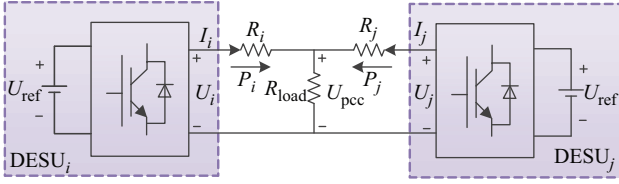


Fig. 2. Simplified parallel model of energy storage unit.

The equivalent output power of DESU_i can be obtained

$$P_i = \frac{(U_i - U_{pcc})U_i}{R_i} \quad (5)$$

Combined with (1), (4) and (5), it can be obtained

$$\frac{SOC'_i}{SOC'_j} = \frac{C_j(R_j + k_j/U_j)}{C_i(R_i + k_i/U_i)} \quad (6)$$

From the above equation, it can be seen the SOC balance of DESU is affected by line impedance, so SOC balance of DESUs cannot be effectively realized. Fig. 3 shows the droop characteristic curve under traditional P-U.

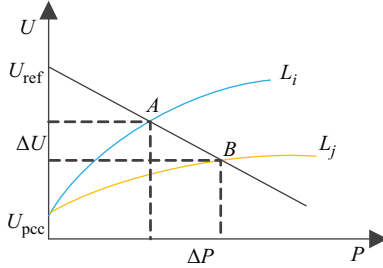


Fig. 3. Droop characteristic curve of traditional P-U.

In Fig. 3, L_i and L_j represent DESU load characteristic curves when line impedance is R_i and R_j , respectively. The actual working point of DESU is the intersection point of droop curve and load curve, as shown in A and B. Voltage deviation and output power deviation between the two groups of DESU are ΔU and ΔP respectively. under traditional P-U droop control, the mismatched line impedance will reduce accuracy of DESU output power distribution.

III. DYNAMIC SOC OPTIMIZATION CONTROL STRATEGY

A. Eliminate the Effect of Unmatched Line Impedance

DESU control strategy based on communication conditions will have higher output power and SOC equalization accuracy, so it is widely used in practical applications. The improved droop control strategy is as follows

$$k_{i(n+1)} = k_{i(n)} + M_{i(n)} \quad (7)$$

$$M_{i(n)} = \begin{cases} k_s \frac{SOC_{i(n)} - SOC_{ave(n)} + SOC_{c(n)}}{SOC_{i(n)}^\beta}, & P_{i(n)} > 0 \\ k_s \frac{DOD_{i(n)} - DOD_{ave(n)} + SOC_{c(n)}}{SOC_{i(n)}^\beta}, & P_{i(n)} < 0 \end{cases} \quad (8)$$

$$DOD_{i(n)} = 1 - SOC_{i(n)} \quad (9)$$

where $k_{i(n)}$ is the droop coefficient of DESU of group i in the n th sampling period. k_s is SOC equilibrium coefficient. $SOC_{i(n)}$ and $SOC_{ave(n)}$ are the mean values of SOC and SOC of DESU of group i in the n th sampling period. $SOC_{i(n)}^\beta$ is the acceleration term. DOD is the discharge depth of DESU.

On the basis of traditional droop coefficient, a compensation M_i is added to Equation (7) to set that it can be automatically changed. Taking the discharge state as an example, compensation can amplify the difference between real-time SOC value of each DESU and SOC mean value through the accelerating factor $SOC_{i(n)}^\beta$, then deviation between SOC can be gradually eliminated by selecting a reasonable compensation coefficient k_s .

In particular, in order to minimize voltage deviation in case of lagging tracking speed of the controller, a SOC voltage compensation term is added, specifically as

$$SOC_{c(n)} = \frac{\int_0^t (U_{i(n)} - U_{ref}) dt}{k_c C_{max}} \quad (10)$$

where K_c is the coefficient of compensation term. C_{max} is the maximum rated capacity of DESUs.

In order to reduce communication pressure, a completely decentralized neighbor communication structure is adopted, that is, a dynamic mean consistency algorithm is adopted to obtain the average value of required information. As shown in Fig. 4, Z groups of DESU connected to the system are regarded in this paper as a network composed of Z nodes and a series of edges, with each edge represented as a two-way communication between two different nodes. Each DESU will store its own initial state quantity, and the value K of the iteration counter will be updated once after each two-way information exchange. Finally, all DESU only need to use the communication line, combine the linear combination of its own state information with the state information of the nearest neighbor after iteration of DESU, and final average state information can be obtained [30]. The calculated expression is

$$\begin{cases} \varepsilon_{ave-i}[k+1] = \varepsilon_i[k] + \delta \sum_{j \in N} \theta_{ij}[k+1] \\ \theta_{ij}[k+1] = \theta_{ij}[k] + \varepsilon_{ave-j}[k] - \varepsilon_{ave-i}[k] \end{cases} \quad i \neq j \quad (11)$$

where ε_{ave} represents the average value of P, U and SOC. i and j represent two different two-way communication nodes, respectively. δ is the scale factor, θ_{ij} represents the cumulative error between two nodes, and its initial value is set to 0.

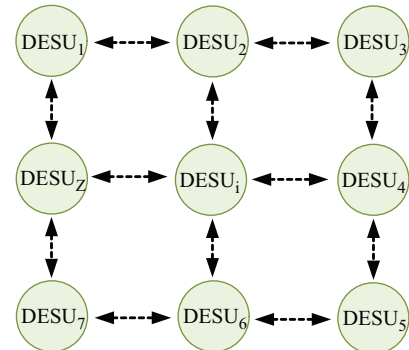


Fig. 4. Nearest neighbor communication structure.

where R_{load} is equivalent load impedance.

Since voltage sags of common points within adjacent sampling periods are very small, they can be approximately equal. φ_n is defined as the output power ratio of the n th sampling cycle of DESU. If all DESUs are divided into group A and group B according to $N_{i(n)} \geq 0$ and $N_{i(n)} < 0$, then output power of each group of DESUs meets the requirements of

$$P_{L(n)} = \varphi_{L(n)} P_{L+1(n)} \quad (32)$$

where $L = 1, 2, 3, \dots, Z-1$.

Two DESUs are randomly selected from each group and denoted as $A1$ and $B1$, respectively, then

$$P_{1(n)} = \varphi_{1(n)} P_{2(n)} \quad (33)$$

According to (31)–(33)

$$P_{1(n)} = \frac{\varphi_{1(n)} \frac{U_{pcc}^2}{R_{load}}}{1 + \varphi_{1(n)} + \chi} \quad (34)$$

$$P_{2(n)} = \frac{\frac{U_{pcc}^2}{R_{load}}}{1 + \varphi_{1(n)} + \chi} \quad (35)$$

where $\chi = \sum_{L=2}^{Z-1} \frac{1}{\prod_{i=1}^L \varphi_{i(n)}}$.

Taking discharge of DESU as an example, Fig. 7(a) and (b) show the relationship between output power of DESU and the output power ratio of first sampling period when output power of DESU is $R_1 < R_2$ and $R_1 > R_2$, respectively. As can be seen from Fig. 5, when $R_1 < R_2$, $\varphi_{1(n)}$ is located at the right of the intersection, and moves to the right of maximum deviation position first along with sampling period, and then gradually moves to the left of the intersection position, finally achieving output power balance among different DESUs. Similarly, when $R_1 > R_2$, $\varphi_{1(n)}$ locates to the left

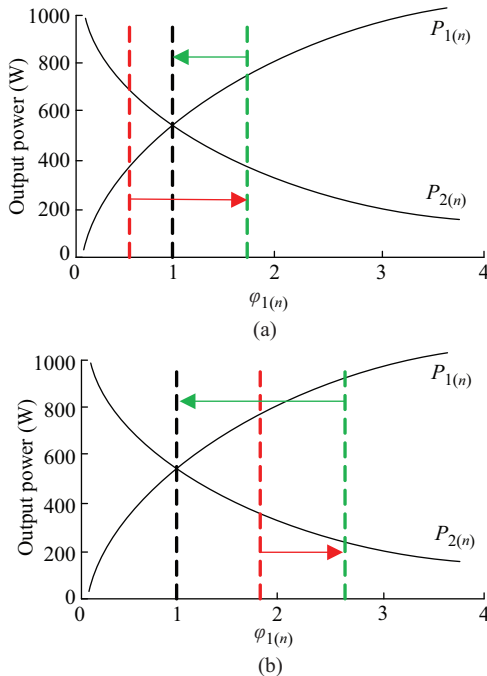


Fig. 7. The relation between output power and $\varphi_{1(n)}$. (a) $R_1 < R_2$. (b) $R_1 > R_2$.

of the intersection, then moves to the right first and then to the left with the sampling period, and finally stabilizes at the intersection.

IV. CASE ANALYSIS

For further verification, a microgrid model including energy storage unit, photovoltaic and load was built based on the RTDS platform. RTDS platform uses compiler software (RSCAD) to build a DC microgrid model, and transmits operation commands to RTDS devices through routers. In a real-time simulation system, control parameters are transferred to DSP operation, and the output signal is transmitted back to RTDS through the pulse width modulation module (PWM), so that real-time digital simulation and physical equipment are interconnected. The whole real-time digital simulation process is updated every 50 kHz by the digital signal processor. Experimental equipment is shown in Fig. 8. As a closed-loop experimental platform of digital physics, RTDS has the advantages of fewer devices, convenient operation and high practicability compared with other experimental platforms.

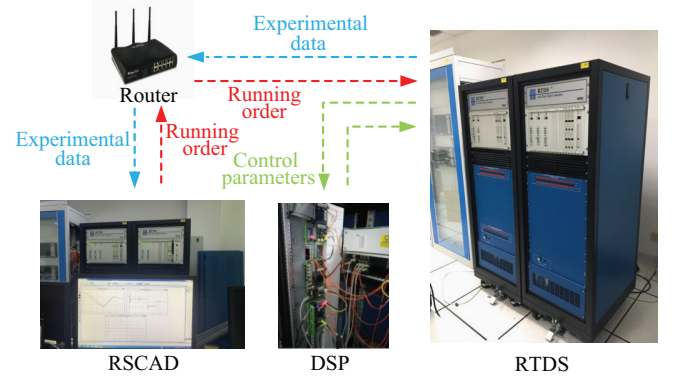


Fig. 8. RTDS real-time digital experiment platform.

Based on Matlab/Simulink platform and RTDS hardware in the ring platform, the following four conditions are designed, respectively. Case 1 compares the strategy proposed in this paper with strategy proposed in reference [22] under stable discharge conditions. Case 2 verifies stability of this strategy under linear load. Based on real-time digital experimental platform of RTDS and DSP interconnection, Case 3 validates policy stability under light intensity and local load mutation, and Case 4 validates smooth switching between modes under communication failure. Relevant parameters of the system are shown in Table I.

A. Stable Discharge

In this case, control strategy switches from traditional droop to improved droop at 3 s. Meanwhile, in order to facilitate observation, initial SOC value of the energy storage unit was set as 0.7, and simulation results were shown in Fig. 9.

It can be seen from Fig. 10 that before 3 s, due to mismatching of system line impedance, deviation between output power and SOC between different DESUs became larger and larger, which seriously affected stability of the system. As shown in Fig. 9(a) and (b), the improved drooped control strategy was

TABLE I
SYSTEM PARAMETER

Parameters	Values
reference voltage (U_{ref})	400 V
DESU1 resistance (R_1)	0.3 Ω
DESU2 resistance (R_2)	0.5 Ω
DESU3 resistance (R_3)	0.7 Ω
public load (R_{pub})	120 Ω
voltage deviation (ΔU)	$\pm 5\% U_{ref}$
initial droop coefficient (k_0)	1e-3
power compensation coefficient (k_p)	5e-7
power compensation coefficient (K_s)	6e-4
voltage compensation coefficient (K_u)	3e-5
annealing temperature (T)	40
sampling period (T_{sample})	1e-4 s
Acceleration factor (β)	3

switched after 3 s. However, output power and SOC balance effect of the strategy proposed in this paper was significantly better than of [22], and the control strategy proposed in [22] could not completely eliminate deviation of output power and SOC caused by mismatching of system line impedance. As can be seen from Fig. 9(c), the strategy proposed in [22] cannot solve the problem well of voltage drop formed after control. On the contrary, the proposed strategy can effectively avoid voltage drop of the DC bus.

B. Linear Load Variation

This case is used to observe work of the proposed control scheme under the condition of linear load variation. This case linearly increases local load at 4 s and 6 s and removes local load at 8 s on the basis of Case 1. Linear change rate ratio is set to 1:2:3, and simulation results are shown in Fig. 10.

It can be seen from Fig. 10 that DESUs work in traditional droop control at 3 s in the discharge state of the energy storage unit, and the recommended droop control begins to work after 3 s. The system linearly increases load in 4 s–5 s, as can be seen from (a) and (b). Although output power of DESU and SOC are not balanced at this time, the linear increase of load does not affect the rate and effect of balancing. Each DESU can adaptively adjust its own output power ratio. During 6 s–7 s, output power of DESUs are gradually balanced, and a larger proportion of linear load changes do not affect the working state of DESUs. In order to verify effectiveness of the strategy under the condition of linear load removal, all increased loads are linearly removed in 8 s–9 s. It can be seen from Fig. 10 that DESUs can respond efficiently, and system voltage can always be stabilized near the rated voltage.

C. Photovoltaic Change and Local Load Mutation

In order to test the practical application effect of the proposed control strategy, this Case is based on the real-time digital experiment platform of RTDS and DSP, which verifies effectiveness and stability of the proposed control strategy under change of light intensity and local load. Initial SOC of DESUs are set to 80%. During 0 s–3 s, output power of PV module is stable at 100 kW and DESUs are in stable discharge mode to support stable operation of microgrid. When light intensity is increased at 6 s, output power of the PV module is increased by 1200 KW, and local load of 900KW is put

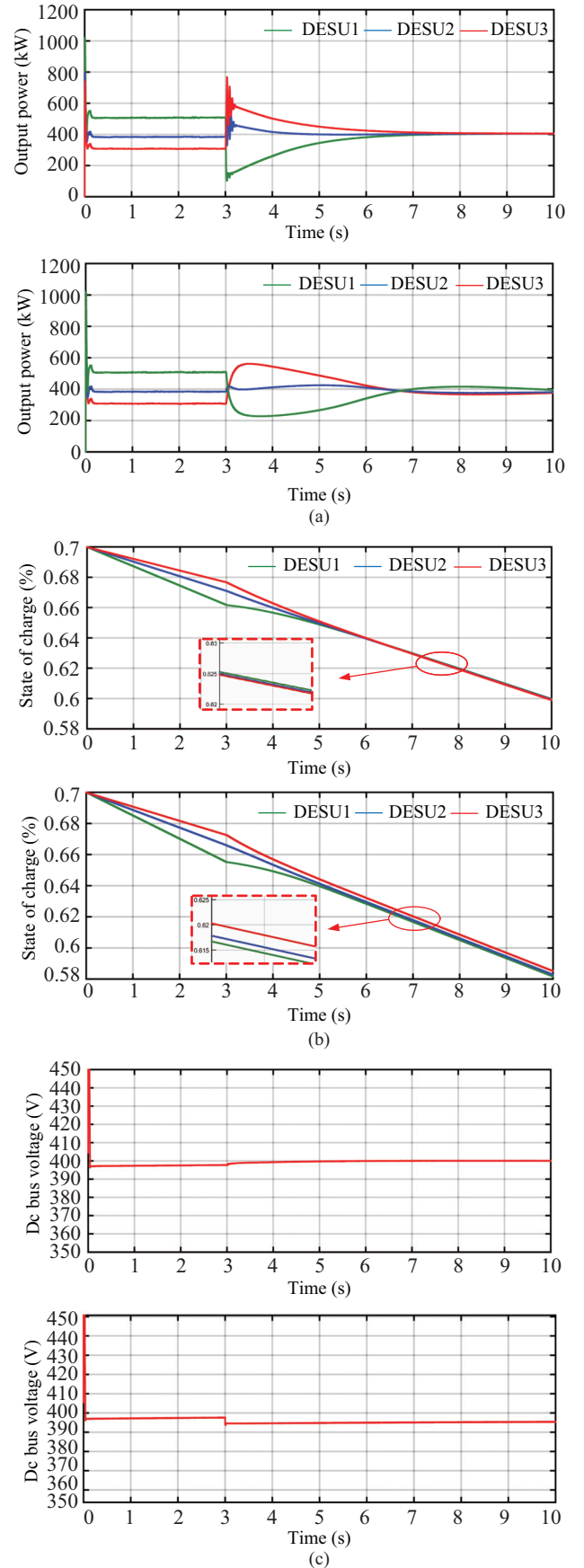


Fig. 9. The control effect of this paper is compared with that of [22] under stable discharge. (a) Output power. (b) State of charge. (c) DC bus voltage.

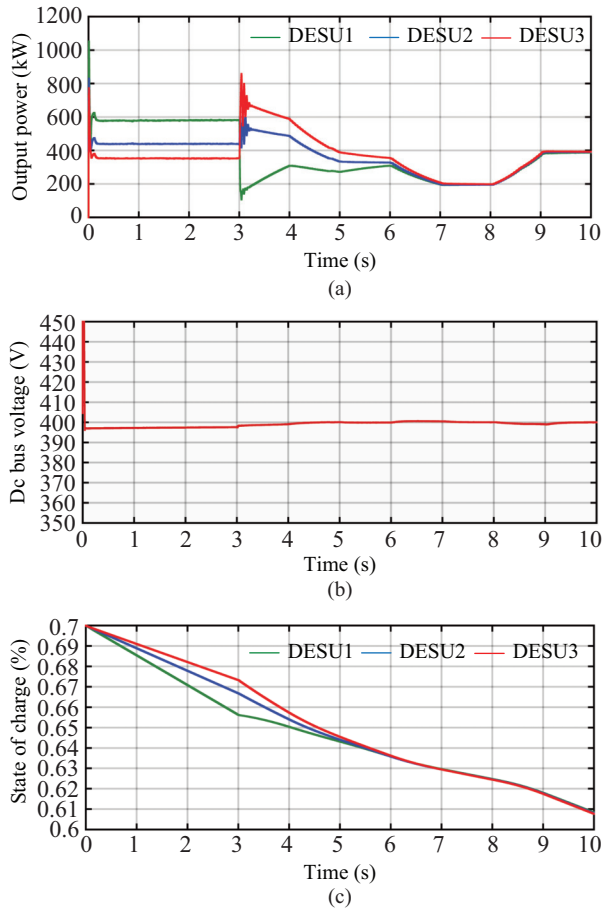


Fig. 10. Adaptive improved droop control under linear load variation. (a) Output power. (b) State of charge. (c) DC bus voltage.

into use at 9 s. Experimental results of RTDS are shown in Fig. 11.

It can be seen from Fig. 11(a) and (b) that before 6 s, due to low light intensity and insufficient output power of PV, DESUs are in the state of discharge to provide support for the system. After 6 s, because power provided by the PV module can meet power requirements of the system, DESUs change from discharge state to charging state. After 9 s, due to large input of local load, power demand of the system increased rapidly, and DESUs switched to stable discharge mode. As can be seen from Fig. 11(c), when load changes, DC bus voltage can be adjusted quickly and is stable around the rated value.

D. Communication Failure

This case is based on RTDS and DSP interconnection experimental platform to verify the effect of the proposed strategy in case of communication failure. Before 3 s, the system runs in traditional droop control, 3 s–7.5 s switches to adaptive droop control based on communication, communication channel is closed at 7.5 s to simulate communication failure, and 9 s system is switched to an improved strategy that does not depend on communication. RTDS experimental results are shown in Fig. 12.

As can be seen from Fig. 12(a) and (b), if 7.5 s fault is not dealt with, more and more DESU output power and SOC deviation will appear again under the influence of mismatched

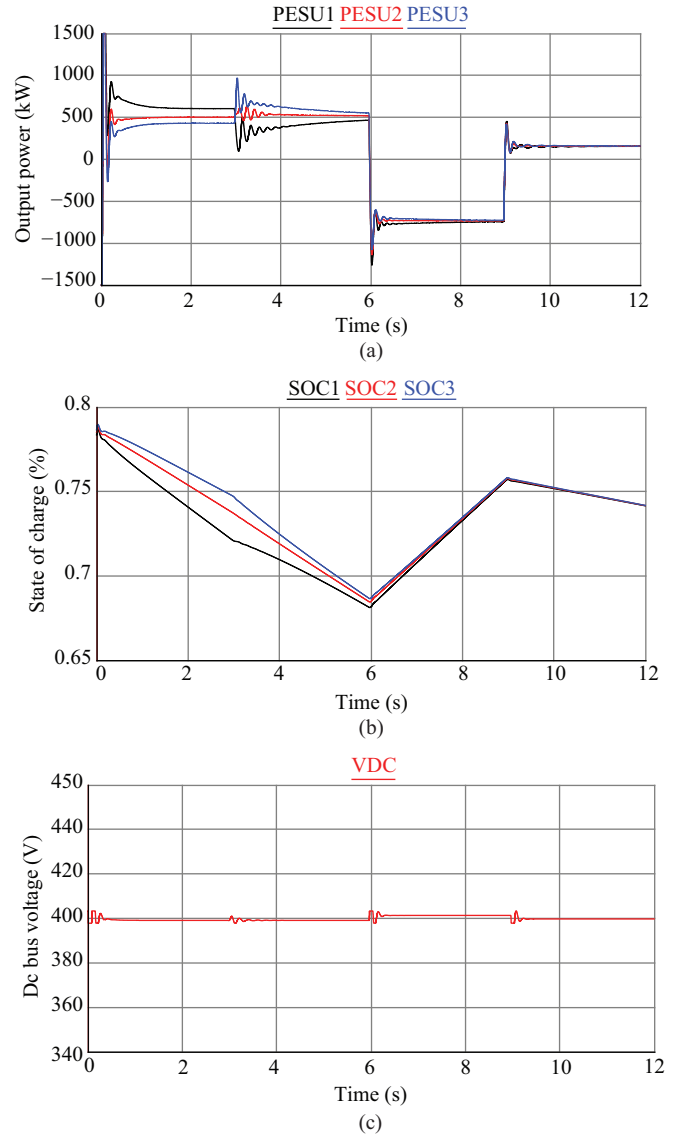


Fig. 11. Adaptive improved droop control strategy under sudden change of light intensity and local load. (a) Output power. (b) State of charge. (c) DC bus voltage.

line impedance. After 9 s switching to improved droop mode not based on communication proposed in this paper, DESU output power and SOC deviation caused by mismatched line group of 7.5 s–9 s are quickly eliminated, and the system always operates stably in the switching process, and there is no obvious power and voltage fluctuation. As can be seen from Fig. 12(c), the improved droop control strategy not based on communication proposed in this paper will only cause a voltage drop of about 2 V, which fully meets system operation requirements, so this strategy is very suitable as a backup measure in case of communication failure.

V. CONCLUSION

An improved control method is proposed that can adaptively adjust droop coefficient. The method combined with dynamic consistency algorithm can obtain SOC correction of each sampling period, which may eliminate the influence of mismatched

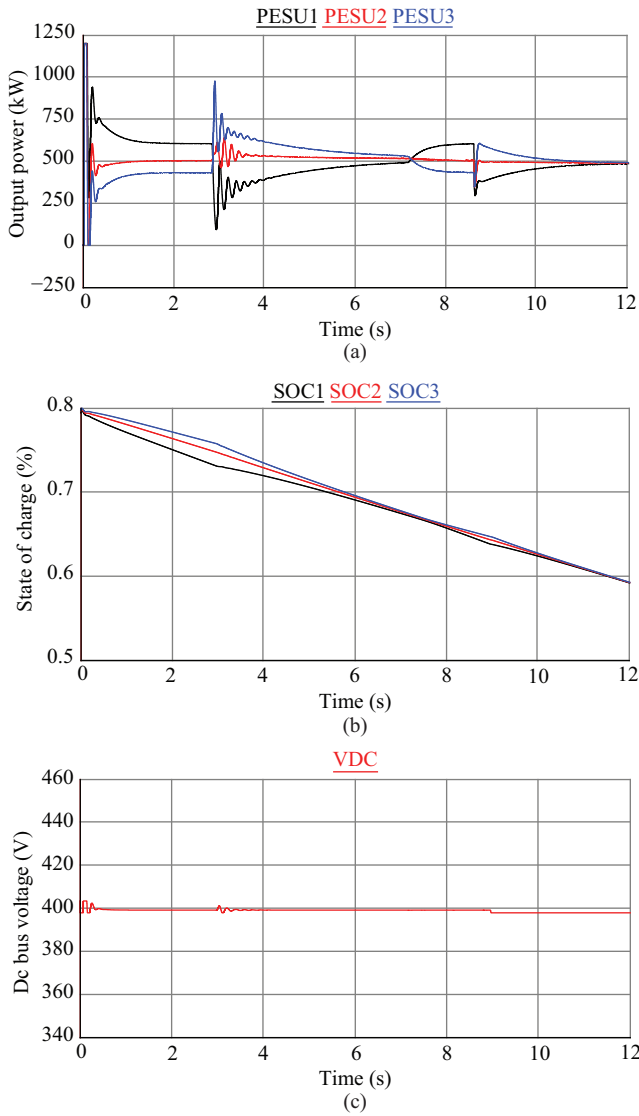


Fig. 12. Adaptive improved droop Control Strategy under Communication failure. (a) Output power. (b) State of charge. (c) DC bus voltage.

line impedance on output power distribution of energy storage units in DC microgrid system.

In this paper, possibility of communication failure is also considered. In order to ensure stable operation of the DC microgrid system, based on the Metropolis acceptance criterion, a non-communication backup control is proposed, which is not dependent on communication, and corresponding smooth switching strategy between modes is designed to achieve smooth switching of control modes under different communication conditions. Finally, effectiveness of the scheme is verified by Matlab/Simulink simulation and RTDS experiment.

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