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Seamless Mode Transfer Control Strategy of Two-stage Energy Storage Converter under Time-sharing Operation Mode

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***Abstract*-- The technology of energy storage has attracted more and more attention, where the two-stage energy storage converter is flexible and can be utilized to realize power quality improvement in grid-connected mode and provide emergency power supply in off-grid mode. Under the most of existing control strategies, the battery must keep working in both modes to balance the power flow, leading to battery life reduction. To solve above-mentioned problem, a time-sharing operation mode is proposed in this paper. However, it is difficult for converter to achieve a seamless transfer between grid-connected and off-grid mode, because both the front-stage DC/DC converter and the battery are in a standby state. Therefore, an improved mode transfer strategy under time-sharing operation mode is further proposed to solve this issue. Finally, a prototype of the energy storage converter is developed, and the effectiveness of the control strategy is verified by simulation and experiment results.**

***Index Terms*—Time-sharing operation mode, two-stage converter, energy storage technology, seamless mode transfer.**

I. INTRODUCTION

In recent years, the research on technology of energy storage has attracted more and more attention. Generally, energy storage medium is connected to the power grid or load interfaced by power electronic converter [1]. Compared with the traditional single-stage converter, two-stage converter enjoys a wide range of input voltage and output voltage, leading to high flexibility [2][3]. The wide input voltage range makes it convenient for capacity expansion of energy storage medium. On the other hand, the multi-function energy storage converter can be utilized to realize power quality improvement in grid-connected mode and serve as emergency power supply in off-grid mode [4]. Therefore, two-stage energy storage converter has a higher application value and the research on control strategy of it is significative.

Many existing researchers have focused on the power quality improvement and emergency power supply using energy converter. Z. Wang et.al in [5] proposes a control strategy for two-stage photovoltaic (PV) converter to achieve an emergency power supply in off-grid mode. The mode switch strategy of PV inverter is further proposed in [6] to achieve a seamless transfer between grid-connected mode and off-grid mode. But its application is limited by the fluctuation and intermittent of PV generation. X. Liu et.al have introduced the control principles of a multi-function energy storage converter in both grid-connected and off-grid operation mode, under a single-stage topology [7]. In [8], grid-connection application of energy storage converter integrating with battery and supercapacitor is introduced to realize the power quality improvement. The energy storage converter serves as an uninterruptible power supply (UPS) in [9] and its control strategy is designed. These researches in [5]-[9] have indicated the extensive application of energy storage converter.

However, under the most of existing control strategies, the battery must keep working in both grid-connected and off-grid modes to balance the power flow, which leads to battery life reduction. To solve this issue, a time-sharing operation mode is proposed in this paper. Under the operation mode, only the inverter works to achieve power quality control, which greatly reduces the working time of the battery and improves the efficiency of grid-connected operation. In grid-connected mode, both the front-stage DC/DC converter and the battery are in a standby state, which leads to difficulty in seamless mode transfer between grid-connected and off-grid mode.

The seamless mode transfer from grid-connected mode to off-grid mode must be ensured for normal operation of critical load. The control strategy for seamless mode transfer can be mainly divided into direct method and indirect method. Under direct method, the control loop is changed directly to realize the mode transfer [10]. While that under indirect method, saturation and desaturation of controller are utilized to achiever a seamless mode transfer [11] [12]. Direct method is easy to simple and intuitive, but the oscillation may occur during the transfer. On the contrary, indirect method is smoother because the direct change between control loop is avoided. But it's sensitive to parameter design.

Therefore, to ensure both the seamless mode transfer and energy storage life increase, an improved mode transfer strategy under time-sharing operation mode is further proposed to solve above mentioned issue. The rest of the paper is organized as follows. In section Ⅱ, the time-sharing operation mode and its difficulty brought in seamless mode transfer is introduced. Based on transient analysis, the improved mode transfer strategy based on feed-forward control is proposed in section Ⅲ. Finally, simulation and experimental results are provided in section Ⅳ and conclusion is remarked in section Ⅴ.

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II. Topology and Analysis of Time-sharing Operation Mode

In this part, the topology of two-stage energy converter is firstly introduced. Based on the two-stage topology, the time-sharing operation mode is proposed to reduce the working time of battery and improve its lifetime.

A. Topology of Two-stage Energy Storage Converter

The topology of two-stage energy storage converter is shown as Fig.1. An interleaved three-level bidirectional buck-boost circuit makes up the front-stage DC/DC converter, which helps reduce the current ripple effectively. The neutral point clamped (NPC) three-level inverter is selected as the DC/AC part. The application of three-level topology highly increases the power density of the converter. A DC-bus composed of large capacitors C_{p1} and C_{p2} is linked between DC/DC converter and DC/AC inverter. The energy storage converter is connected to the power grid by a built-in static transfer switch (STS). In the condition of power outage, the STS is turned off and the energy storage converter is transferred from grid-connected mode to off-grid mode.

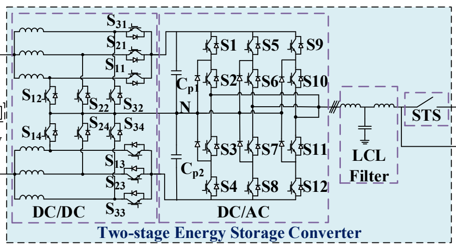


Fig. 1. Topology of two-stage energy converter

B. Analysis of Time-sharing Operation Mode

As introduced before, to reduce the working time of battery and increase its service life, a time-sharing operation mode is proposed in this paper, which is illustrated in Fig.2.

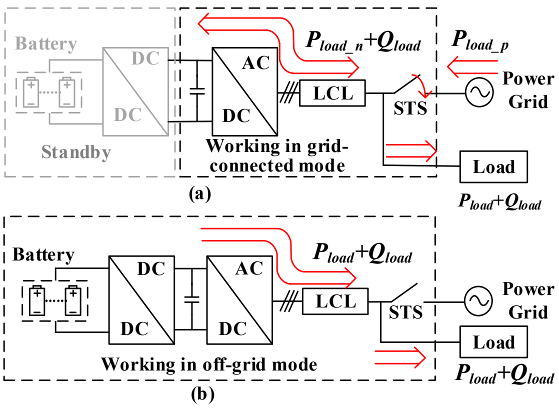


Fig. 2. Working state of time-sharing mode

The working principle of time-sharing operation mode is introduced as follow. As shown in Fig.2 (a), in grid-connected mode, only the inverter works to achieve power quality control, such as reactive power and unbalanced power compensation. In this case, the PWM pulses of DC/DC converter are locked and the battery is in standby mode. What's more, the active power of load is supplied by power grid. Once power outage occurs accidently, the STS is turned off, and the DC/DC converter and battery start to work, shown in Fig.2 (b). The load active power is provided by battery. In actual working conditions, the time length of power outage is far shorter than that of power grid working normally. Therefore, condition (b) in Fig.2 less often happens and the working time of battery is substantially reduced, leading to increase of its service life and reduction of maintenance cost. On the one hand, the power loss of DC/DC converter is effectively avoided compared with the traditional control strategy of two-stage energy storage converter.

However, time-sharing operation mode has brought some trouble to the transfer between grid-connected mode and off-grid mode, because of the reasons listed as follows:

a) In grid-connected mode, the DC-bus voltage is controlled by NPC inverter, while in off-grid mode, the DC-bus voltage is controlled by DC/DC converter because the inverter is supposed to realize AC voltage control. The DC-bus voltage controller has changed between the transfer process, and the transient regulation process caused by new controller may result in DC-bus voltage drop and furtherly influence the AC voltage.

b) In grid-connected mode, the battery is in standby state. Once transferred to off-grid mode, the battery current will suddenly increase until the load power demand is satisfied. The ascent rate of battery current will significantly affect the recovery speed of DC-bus voltage, which is the key to realize seamless mode transfer.

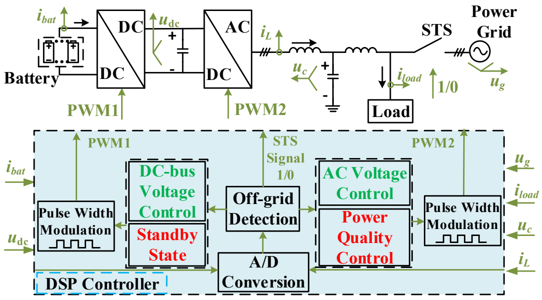
III. Control Strategy Design

To solve the problem on seamless mode transfer caused by time-sharing operation mode, which has been presented in section II, an enhanced seamless mode transfer strategy based on feedforward control is proposed in this paper. Under the proposed control strategy, the front-stage DC/DC converter and battery can reach the steady state smoothly and quickly to meet the power demands and a seamless transfer between grid-connected and off-grid mode can be achieved.

The control strategy for two-stage energy converter is composed of two parts. The first part is the basic power quality control in grid-connected mode and emergency power supply in off-grid mode. The other part is enhanced mode transfer strategy proposed in this paper. In this section, the control strategy design process will be provided in detail.

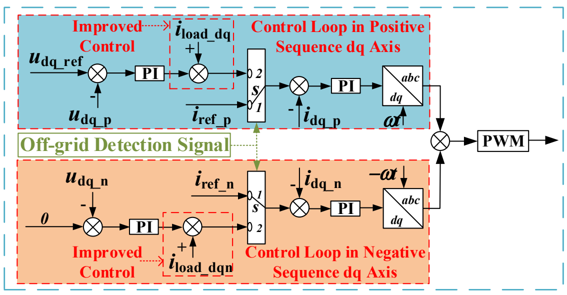
A. Overall Control Structure

The overall control structure of two-stage is shown as Fig.3, where $\boldsymbol{i}_{bat}$ is the battery current, $\boldsymbol{u}_{dc}$ is DC-bus voltage, $\boldsymbol{i}_{L}$ is three-phase current of filter inductor, $\boldsymbol{u}_{c}$ is three-phase voltage of filter capacitor, $\boldsymbol{i}_{load}$ is the load current, and $\boldsymbol{u}_{g}$ is three-phase voltage of power grid, respectively. The above sensed signals are sent to digital signal processing (DSP) controller to apply the proposed control strategy, where the green part is the control strategy in off-grid mode while the red part is that in grid-connected mode. Finally, three set of signals are generated to the converter, of which are PWM pulses for DC/DC converter, PWM pulses for DC/AC inverter, and the level signal to control the STS, respectively.

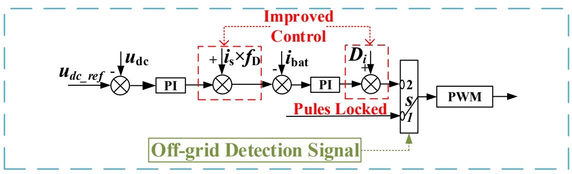


B. Basic Control Strategy of Converter

The specific control structure of seamless mode transfer under time-sharing operation mode is shown as Fig.4. The feedforward part in red dotted box is newly added for enhanced control, which will be introduced in part C, while the other part is the basic control strategy and it will be recommended in this section.



(a) Enhanced control structure of DC/AC inverter



(b) Enhanced control structure of DC/DC converter

Fig.4. Specific control structure of the converter

As demonstrated in Fig.4, $\boldsymbol{i}_{dq}$ is the component of $\boldsymbol{i}_L$ in dq axis, $\boldsymbol{u}_{dq}$ is that of $\boldsymbol{u}_c$ in dq axis, the subscript **_p** and **_n** represents the positive sequence and negative sequence, and the subscript **ref** indicates the reference value of the control loop, respectively. In grid-connected mode, the switch **s** is at point one. While power outage occurs, the switch **s** is turned to point two and the converter works in off-grid mode. Obviously, the off-grid detection signal is the key to realize a precise mode transfer. There're many existing methods to achieve off-grid detection or islanded detection [13]. Since it's beyond the scope of this paper, the detailed off-grid detection method selection and design process are ignored.

In grid-connected mode, the mode switch **s** is turned to point one. In this case, a single current control loop is utilized in DC/AC inverter and the proportional and integral (PI) controller is used in dq axis to achieve error-free performance. The reference value of q axis in positive sequence and that of dq axis is generated by sensed load current i_{load}, using positive-negative sequence separation method [14]. The corresponding component of i_{load} is set as the reference value in control loop to realize unbalance and reactive power compensation, which results in power quality improvement. In time-sharing operation mode, the front-stage DC/DC and battery are not working, and the inverter also undertakes the task of DC-bus voltage control. Therefore, the reference value of d axis in positive sequence $\boldsymbol{i}_{ref\_p\_d}$ is obtained by voltage control loop, shown as Fig.5.

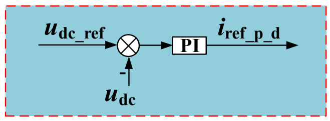


Fig.5. DC-bus voltage control structure

In off-grid mode, the mode switch **s** is turned to point two. In this case, the dual control loop is utilized in DC/AC inverter, composed of outer voltage loop and inner current loop, to achieve the three-phase voltage control. The reference value of dq axis in negative sequence is set to zero, ensuring the voltage quality in unbalanced condition. DC/DC converter starts working and unlocks the PWM pulses. The dual control loop is also used in DC/DC converter to provide DC-bus voltage control, shown as Fig.4 (b).

C. Analysis of Transfer Issues under Time-Sharing Mode

As mentioned in section Ⅱ, time-sharing mode can reduce the working time of battery and effectively improve its lifetime. Nevertheless, it has brought some trouble on mode transfer, which will be analyzed in this part.

First, the mode transfer process of inverter is analyzed, taking q axis in positive sequence as an example. In off-grid mode, the reference value of current control loop is obtained by the output of voltage loop:

$$i_{ref\_q} = \Delta u G_{PI}(s) \tag{1}$$

$$\Delta u = u_{ref\_q} - u_{d\_q} \tag{2}$$

$$G_{PI}(s) = k_p + \frac{k_i}{s} \tag{3}$$

where $\boldsymbol{i}_{ref\_q}$ is the reference value of current loop in q axis under off-grid mode, $\mathbf{G}_{PI}\mathbf{(s)}$ is the transfer function of PI controller, $\boldsymbol{k}_p$ is the proportional coefficient, $\boldsymbol{k}_i$ is integral coefficient, $\boldsymbol{u}_{ref\_q}$ is reference value of voltage and $\boldsymbol{u}_{d\_q}$ is feedback volage, respectively.

In DSP controller, the control algorithm is implemented in discrete form, and (1) is expressed as:

$$i_{ref\_q\_1} = i_{ref\_q\_0} + k_p(\Delta u_{\_1} - \Delta u_{\_0}) + k_i T_s \Delta u_{\_1} \tag{4}$$

where the subscript **_1** represents the value of current operation period, **_0** is memory value of last operation period, and $\mathbf{T}_s$ is the operation period of the controller. At the end of each operation cycle, the memory value is updated with the calculated value at the current time, and then the next operation cycle is started. The memory value of the first operation period in the control algorithm is 0.

In grid-connected mode, the reference value is i_{load_q}, while transferred to off-grid mode, the reference value is generated from zero until reaching the steady state value, shown as (4). This indicates a step change of reference value and a dynamic regulation process, which causes the unsmooth mode transfer. The other control loop works in the similar way.

On the other hand, as for DC-DC convert, the mode transfer process is analyzed subsequently. According to Fig.4, the following equation can be obtained:

$$i_{ref\_bat} = \Delta u_{dc}(k_{pv} + \frac{k_{iv}}{s}) \quad (5)$$

$$\Delta u_{dc} = u_{dc\_ref} - u_{dc} \quad (6)$$

$$D = \Delta i_{bat}(k_{pi} + \frac{k_{ii}}{s}) \quad (7)$$

$$\Delta i_{bat} = i_{ref\_bat} - i_{bat} \quad (8)$$

where $\boldsymbol{i}_{\mathbf{ref\_bat}}$ is the reference value of inner current loop, $\boldsymbol{u}_{\mathbf{dc\_ref}}$ is reference value of DC-bus voltage, $\boldsymbol{k}_{\mathbf{pv}}$ and $\boldsymbol{k}_{\mathbf{iv}}$ are the proportional and integral coefficient of voltage controller, $\boldsymbol{k}_{\mathbf{pi}}$ and $\boldsymbol{k}_{\mathbf{ii}}$ are those of current controller, and D is the duty cycle sent to PWM modulation module, respectively.

The discrete expression of (5) and (7) is shown as:

$$i_{ref\_bat\_1} = i_{ref\_bat\_0} + k_{pv}(\Delta u_{dc\_1} - \Delta u_{dc\_0}) + k_{iv}T_s\Delta u_{dc\_1} \quad (9)$$

$$D_{\_1} = D_{\_0} + k_{pi}(\Delta i_{bat\_1} - \Delta i_{bat\_0}) + k_{ii}T_s\Delta i_{bat\_1} \quad (10)$$

Under time-sharing operation mode, the PWM pulse of DC/DC converter is locked in grid-connected mode, which result in equation (11):

$$i_{ref\_bat} = 0, \quad D = 0 \quad (11)$$

The restore rate of DC-bus voltage is determined by the settling time that $\boldsymbol{i}_{\mathbf{ref\_bat}}$ and **D** cost to reach the steady state, which further influences the mode transfer in AC side. Time-sharing operation mode causes that D has to increase from zero and thus the recovery speed of DC-bus voltage is reduced, leading to the unsmooth mode transfer.

D. Enhanced Seamless Mode Transfer Strategy

As analyzed in part C, the settling time of $i_{\mathrm{ref\_q}}$, $i_{\mathrm{ref\_bat}}$ and D is the key to realizing the seamless mode transfer. According to (4), (9) and (10), three solutions to reduce the settling time can be acquired:

a) reduce the operation period of controller, which is Ts.

b) increase the proportional and integral coefficient of the PI controller.

c) properly design the initial value in first calculation period, which is represented by $\boldsymbol{i}_{\mathbf{ref\_q\_0}}$, $\boldsymbol{i}_{\mathbf{ref\_bat\_0}}$ and $\mathbf{D_{\_0}}$.

In DSP controller, the operation period $\mathbf{T_s}$ is usually a constant value, which is determined by the switching frequency of power electronic devices and DSP controller itself. As for parameters of PI controller, the overshoot and stability issues will occur with the increase of proportional gain, while increase of integral gain may result in an accumulation of errors. The proper parameter design is inseparable from accurate modeling.

Therefore, the third solution idea is utilized in this paper. Based on this idea, the feedforward control is used. The key principle of the enhanced seamless mode transfer strategy is designing proper feedforward value in control loop. Thus, the dynamic response of the controller can be significantly improved to achieve a seamless mode transfer. The specific design process is introduced as follow.

The design of DC/AC inverter strategy is also analyzed, taking q axis in positive sequence as an example. According to Fig.4 (a), in off-grid mode, the reference value of inner current loop is the output value of the outer voltage loop. In off-grid mode, the load power is totally supplied by the converter, which means the steady-state value of the reference value in inner current loop is the same as the corresponding load current, shown as:

$$u_{out\_p} = i_{ref\_p} = i_{load\_p} \quad (12)$$

$$u_{out\_n} = i_{ref\_n} = i_{load\_n} \quad (13)$$

where $\boldsymbol{u}_{\mathbf{out}}$ is the output value of outer voltage loop, $\boldsymbol{i}_{\mathbf{ref}}$ is the reference value of inner current loop, and the subscript **_p** and **_n** represents positive and negative sequence component, respectively. Therefore, the feedforward value of controller in inverter can be easily designed, which is the same as the corresponding load current component, shown as the red dotted box in Fig.4 (a). By adopting the proposed strategy, the first operation cycle of the DSP controller can be rewritten as:

$$i_{ref\_q\_1} = i_{load\_q} + k_p(\Delta u_{\_1} - \Delta u_{\_0}) + k_i T_s \Delta u_{\_1} \quad (14)$$

As for parameter design in DC/DC converter, it's also related to the steady-state value of the control loop. In both grid-connected and off-grid modes, the load voltage is almost the same. And load active power $\boldsymbol{P}_{\mathbf{s}}$ can be calculated in grid-connected mode as (15), where $\boldsymbol{u}_{\mathbf{gd}}$ is the grid voltage in d axis and $\boldsymbol{i}_{\mathbf{load\_d}}$ is load current in d axis. Then, the steady-state battery current in off-grid mode can be estimated as (16), where $\boldsymbol{u}_{\mathbf{bat}}$ is the battery voltage.

$$P_s = 1.5u_{gd}i_{load\_d} \quad (15)$$

$$i_s = P_s / u_{bat} \quad (16)$$

However, $\boldsymbol{i}_{\mathbf{s}}$ is not suitable as feedforward value directly, not just because of the estimation error, but also the overshoot it may cause in voltage control loop. Therefore, the final feedforward value is obtained as $\boldsymbol{i}_{\mathbf{s}}$ multiplied by a coefficient $\boldsymbol{f}_{\mathbf{D}}$, shown as the red dotted box in Fig.4 (b). Considering feedforward effect and overshoot suppression, $\boldsymbol{f}_{\mathbf{D}}$ is selected between 0.5-0.75. Therefore, (9) is rewritten as (17) with the enhanced control strategy.

$$i_{ref\_bat\_1} = i_s \times f_D + k_{pv}(\Delta u_{dc\_1} - \Delta u_{dc\_0}) + k_{iv}T_s\Delta u_{dc\_1} \quad (17)$$

Furthermore, a feedforward value of duty cycle is introduced to speed up the regulation process of DC-bus voltage. In off-grid mode, the DC/DC converter works in boost mode, and the relationship between the input voltage $\boldsymbol{u}_{\mathbf{in}}$ and output voltage $\boldsymbol{u}_{\mathbf{out}}$ is shown as (18), where $\mathbf{D_0}$ is the duty cycle of DC/DC converter. Accordingly, the steady-state value of duty cycle can be obtained in (19). Take $\mathbf{D_i}$ as the feedforward value of the current control loop, also shown as the red dotted box in Fig.4 (b).

$$u_{out} = u_{in} / 1 - D_0 \quad (18)$$

$$D_i = 1 - u_{in}/u_{out} = 1 - u_{bat}/u_{dc\_ref} \quad (19)$$

Thus, (10) can be rewritten as:

$$D_{\_1} = D_i + k_{pi}(\Delta i_{bat\_1} - \Delta i_{bat\_0}) + k_{ii}T_s\Delta i_{bat\_1} \quad (20)$$

To sum up, by adding a feedforward control shown as (14), (17) and (20), both the dynamic response of DC/AC inverter and DC/DC converter has been improved, and a seamless mode transfer will be achieved.

IV. SIMULATION AND EXPERIMENTAL VERIFICATION

To verify the effectiveness and feasibility of the proposed control strategy, a simulation model is built in MATLAB/Simulink. Furthermore, prototype is developed to provide experimental results. The key parameters are shown in TABLE I and the experimental platform is shown as Fig.6.

TABLE I
KEY PARAMETERS OF SIMULATION AND EXPERIMENT

Name	Value	Name	Value
Battery output voltage	35V	DC-bus voltage	100V
RMS value of grid voltage	50V	DC-bus capacitor	5.7 mF
Three-phase load resistance	5 Ω	Switching frequency	20 kHz
Three-phase load resistance	5 Ω	Filter capacitor	20 uF
Filter inductor near converter	0.8 mH	Filter inductor near grid	22uH

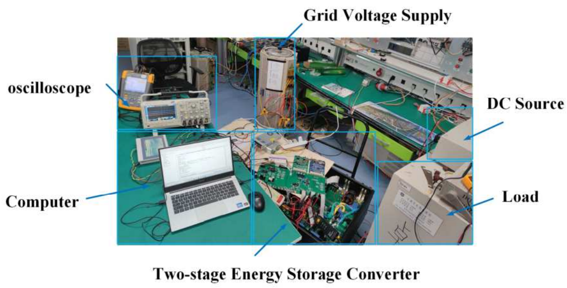


Fig.6. Experimental platform

A. Simulation Results

The simulation results are provided as Fig.7 and the detailed analysis is as follows:

a) The mode transfer with traditional control is shown as Fig.7 (a) and (b). The power outage occurs at 0.1s, and the converter transfers to off-grid mode. The battery current starts to rise after 20ms and DC-bus voltage drops to around 85V. They reach to steady state at 0.5s, which causes an unsmooth transfer in AC side. There's a substantial fall in AC side voltage and it reaches steady state in around five grid cycles. Obviously, under time-sharing operation mode, the performance of traditional strategy is poor.

b) The mode transfer with enhanced control is shown as Fig.7 (c) and (d). By applying enhanced strategy, battery current rises immediately once power outage occurs and the DC-bus volage drop has been significantly decreased. As for AC-side, the load voltage keeps stable in mode transfer process without any voltage drop. A seamless mode transfer is well achieved under the enhanced strategy.

The simulation results have verified the effective improvement in mode transfer with enhanced strategy.

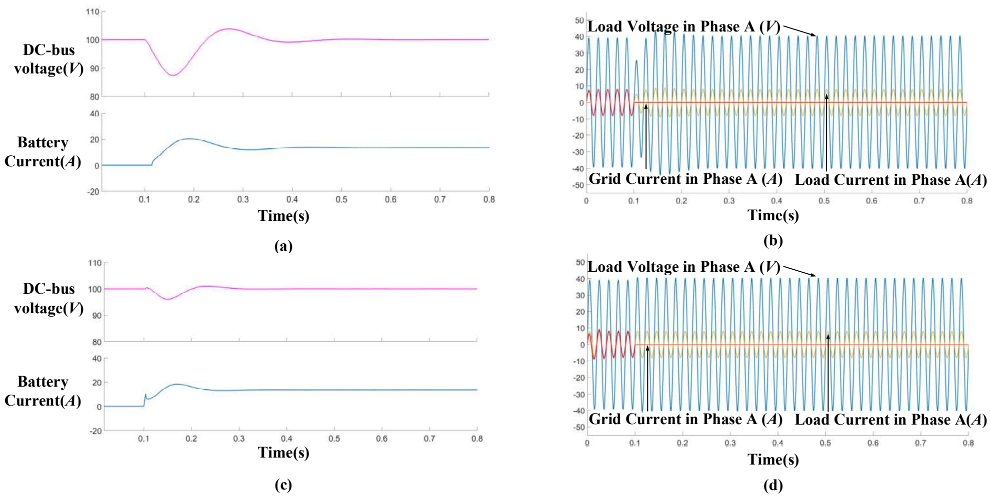


Fig.7. Simulation results: (a)(b) with traditional control, waveform during mode transfer in DC and AC side (c)(d) with improved control, waveform during mode transfer in DC and AC side

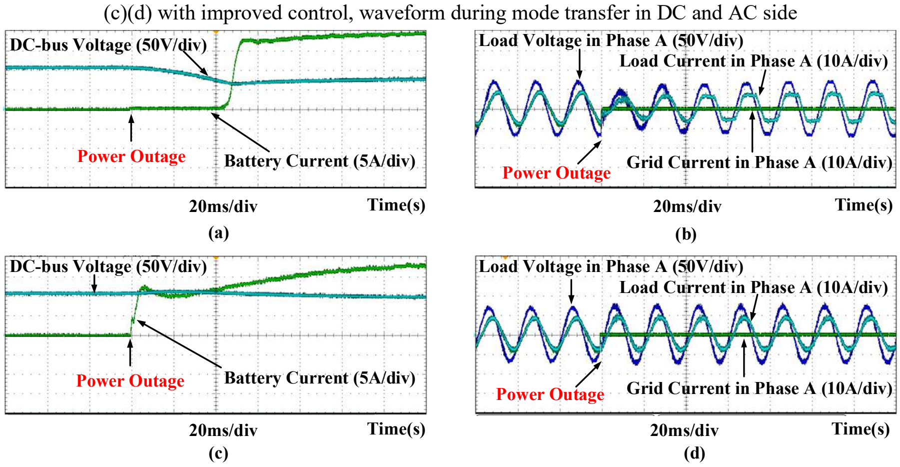


Fig.8. Experimental results: (a)(b) with traditional control, waveform during mode transfer in DC and AC side (c)(d) with improved control, waveform during mode transfer in DC and AC side

B. Experimental Results

For further verification, the experimental results are shown in Fig.8.

a) The mode transfer with traditional control is shown as Fig.8 (a) and (b). When power outage occurs, the DC-bus voltage drops to 60V and has not recovered after 1.4s. The battery current begins to increase after around 40ms, which causes the continuous DC-bus voltage drop. In AC side, the load voltage drops obviously and recovers to the steady-state value after around 40ms. What's more, the DC-bus voltage drop causes the AC voltage distortion.

b) The results with improved control are shown as Fig.8 (c) and (d). During the mode transfer process, the DC-bus voltage keeps stable and the battery current responses rapidly. What's more, there's not overshoot of battery current, which indicates the proper selection of $\boldsymbol{f}_{\mathbf{D}}$. In AC side, the load voltage and current keep almost unchanged during mode transfer and the power outage causes no impact on the load. A seamless mode transfer is achieved under the improved control strategy and the performance of energy storage converter has been significantly improved.

The experimental results match well with simulation results.

V. CONCLUSION

The highly flexible two-stage energy storage converter is easy to expand, which can be utilized to realize power quality control in grid-connected mode and serve as emergency power supply in off-grid mode. However, under the most of existing control strategies, the battery must keep working in both modes to balance the power flow, leading to battery life reduction.

To solve above-mentioned problem and enhance the practical value of two-stage energy storage converter, a time-sharing operation mode is proposed in this paper to improve the battery life and reduce the power loss of converter. Aiming at the mode transfer issue brought by this mode, an enhanced control strategy based on feedforward value design is introduced. Under the proposed strategy, the performance of two-stage storage converter in mode transfer process is significantly improved. The simulation and experiment results have verified the effectiveness and feasibility of the proposed strategy.

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