Control Strategy of Bi-directional Converter for Battery Energy Storage System

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Abstract - To ensure the stable operation of the system, a bi-directional converter is essential to distributed generation system. In this paper, a charge/discharge control strategy of single-stage power electronics topologies with three phase bi-directional converter was proposed. When working in grid-connected conditions, the external DC-link voltage loop control strategy was used for battery charge, and the external power control loop and the inner deadbeat control was used for battery discharge. When working in islanded conditions, the inner deadbeat control and the external voltage control loop was used for battery discharge. It is demonstrated that the proposed control strategy is effective for battery charge/discharge in islanded and grid-connected mode, and it is exhibits satisfactory transient response and robustness to load variations.

Keywords - Microgrid; Bi-directional Converter；Grid-connected；Islanded；Deadbeat control

I. INTRODUCTION

Recently, distributed generators are a fast-developing trend and will result in an increase in reliable and power quality [1],[2]. When lots of distributed generators are connecting to the grid, there may be many problems because of the fluctuations of the distributed generators. In order to improve the utilization of distributed generators, the conception of microgrid was proposed in [3]. A microgrid is a low voltage system that has different distributed generators, loads and energy storage unit. A microgrid can working in grid-connected mode under normal conditions and will transfer to islanded mode under network faults conditions [4],[5], so the power quality and supply reliability are increased.

To ensure the stable operation, a bi-directional converter which can inject and draw power from the grid is essential to the microgrid. When power is injected into or drawn from the energy storage unit, a bi-directional converter can meet the instantaneous power balancing between loads requirements and distributed generators in microgrid. The controller of the converter is responsible for keeping voltage and frequency within the given limits, so how to control the converter is the key technology for microgrid stable operation. Now there are numerous studies about the control method of the bi-directional converter [6],[7]. In [8], a charge/discharge control strategy for bi-directional converter was proposed. Compared to traditional control strategy, higher charge-discharge efficiency was obtained. In [9], a single phase bi-directional inverter was used in the microgrid which contains PV, wind generation and battery, the fluctuation of the solar or wind energy was balanced by the inverter. The double closed loop control of voltage and current was applied in the bi-directional converter system in [10],[11], and the fast dynamic response was gained. However, the steady error is inevitable when there is a load disturbance. In [12], a droop control method was proposed, and the seamless transform was gained between gird-connected mode and islanded mode, so the reliability of energy supplies was increase, but the small signal stability and robustness of the system is weak [13],[14]. So at the moment, droop control is merely experimental, a sudden breakthrough could pose some tricky questions.

This paper discusses the issues related to the control strategy of a three phase bi-directional converter, and a feasible control strategy based on deadbeat control was proposed, also the dynamic behavior of bi-directional converter was researched. This has been demonstrated using simulation results.

II. BI-DIRECTIONAL CONVERTER CONFIGURATIONS

The battery energy storage system is connected to the grid through a bi-directional converter, and the typical topology of the converter is shown in Fig. (1), the bi-directional converter is a voltage source PWM converter. As the input of the converter, a capacitor which is used to suppress the harmonic currents is in parallel with the battery. Through the PWM converter, the input of the DC voltage is converted into a three-phase, high frequency chopper voltage, and after a three-phase low-pass filter, a three-phase sinusoidal voltage is obtained. In order to avoid interference between the battery energy storage system and the grid, an isolation transformer is used.

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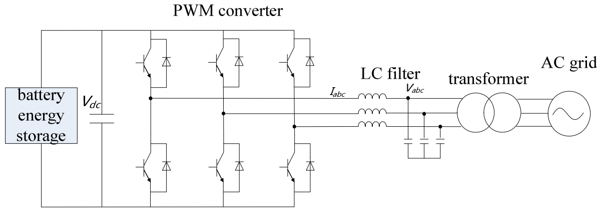


Fig.1 The block diagrams of bi-directional converter

When charging the battery energy storage system, the bi-directional converter is working in rectifier mode, the power will flow from grid to the DC side, and the energy will be stored in the battery. When the battery energy storage system discharging, the bi-directional converter is working in inverter mode, the power will flow from DC side to the grid, and the energy which was stored in the battery will be released.

III. CHARGE CONTROL OF BI-DIRECTIONAL CONVERTER

According to different requirements, the charge process is divided into two steps which are constant voltage charge and constant current charge when connected to grid, the converter works as a rectifier and the power flows from the grid to the battery energy storage system.

In constant voltage charging, for example, the dual-loop control is used, the external DC voltage control loop, which controls the output voltage of the converter, V_{dc} track the given reference voltage V_{dcref}. The error between the real DC bus voltage and the reference DC bus voltage is given to a proportional-integral controller. The output of the proportional-integral controller, $i_{d\text{-}ref}$ is used as d axes input of internal current loop. For the power factor is set as 1, the q axes input of internal current loop, $i_{q\text{-}ref}$ is set to 0. The inner current control loop, is responsible for fast dynamic adjustment of the current. The error between the real current and the reference current is also given to a proportional-integral controller, then the modulated signal m_d and m_q, are finally obtained. The control function of this control is given as equation (1).

$$\begin{cases} i_{d\_ref} = \left(K_{dp1} + \dfrac{K_{di1}}{S}\right)\left(V_{dcref} - V_{dc}\right) \\ i_{q\_ref} = 0 \\ m_d = \left(K_{dp2} + \dfrac{K_{di2}}{S}\right)\left(i_{d\_ref} - i_d\right) \\ m_q = \left(K_{qp2} + \dfrac{K_{qi2}}{S}\right)\left(i_{q\_ref} - i_q\right) \end{cases} \tag{1}$$

The parameters meaning of charge control is shown in table I.

TABLE I. THE PARAMETERS OF GRID-CONNECTED MODE CHARGE CONTROL

Parameters	The parameter meaning
V_{dc} ， V_{dcref}	DC bus voltage, the reference DC bus voltage
i_d ， $i_{d\text{-}ref}$	d axes current, the reference d axes current
i_q ， i_{q_ref}	q axes current, the reference q axes current
K_{dp1} ， K_{di1}	proportional and integral coefficient of external loop
K_{dp2}， K_{di2}	proportional and integral coefficient of d axes
K_{qp2}， K_{qi2}	proportional and integral coefficient of q axes

The block diagram for this control is shown in Fig.2

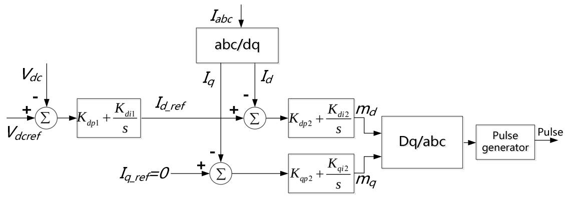


Fig.2 Block diagram of grid-connected mode charge control

Fig.3 shows the DC bus voltage when the converter is connected to a utility, the reference DC bus voltage is 500V, and the DC bus voltage will reach 500V at 0.04 second. The results of simulation show that the system has quicker response speed and higher steady precision.

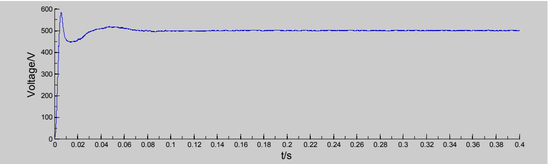


Fig.3 DC bus voltage of bi-directional converter in grid-connected mode charge control

It can be seen that, when connected to utility, the external voltage loop control strategy which controls the DC-link voltage can realized the constant voltage charge and constant current charge of the battery, and meet the needs of battery charge.

IV. DISCHARGE CONTROL OF BI-DIRECTIONAL CONVERTER

There are two types of process when the battery is discharged: the grid-connected mode discharge control and islanded mode discharge control.

A. *The grid-connected mode discharge control*

When in grid-connected mode discharge control process, the bi-directional converter is the grid-following unit. Based on the set points for reactive and real powers, the bi-directional converter will send corresponding reactive and real powers to the grid. The controller of the converter includes two different sections. One is an external power control loop which is realized by a common proportional integral controller. The output of the external real and reactive power regulator is used as d axes input and q axes input of internal current loop respectively. The control function of this control is given as equation (2), and the parameters meaning of grid-connected mode discharge control is shown in table II.

$$\begin{cases} i_{d\_ref} = \left(K_{dp1} + \dfrac{K_{di1}}{S}\right)\left(P_{ref} - P\right) \\ i_{q\_ref} = \left(K_{qp1} + \dfrac{K_{qi1}}{S}\right)\left(Q_{ref} - Q\right) \end{cases} \quad (2)$$

TABLE II. THE PARAMETERS OF GRID-CONNECTED MODE DISCHARGE CONTROL

Parameters	The parameter meaning
P，P_{ref}	real power, the reference real power
Q，$Q_{ref,}$	reactive power, the reference reactive power
i_d ，$i_{d\text{-}ref}$	d axes current, the reference d axes current
i_q ，i_{q_ref}	q axes current, the reference q axes current
K_{dp1} ，K_{di1}	proportional and integral coefficient of external real power loop
K_{qp1}，K_{qi1}	proportional and integral coefficient of external reactive power loop

After getting the set points for current, the commonly used method is the inner current control which is realized by a common PI controller, but there is steady state error between the reference current and measured current when the load disturbed. In this paper, the deadbeat control strategy is used in the inner current control.

The bi-directional converter variables on the d-q frame, $i_{d\text{-}ref}$, $i_{q\text{-}ref}$ are transformed to variables $i_{abc\text{-}ref}$ on the three stationary axes a, b, and c. For a sufficiently short PWM carrier period, T, the duty cycle of the converter are d_A，d_B，d_C , and $d_A+d_B+d_C=1.5$, then it is possible to calculate the transfer function of the deadbeat controller from equation(3) to equation(6).

$$\begin{cases} U_{an} - U_{bn} = -L\dfrac{di_a}{dt} + V_{AB} + L\dfrac{di_b}{dt} \\ U_{bn} - U_{cn} = -L\dfrac{di_b}{dt} + V_{BC} + L\dfrac{di_c}{dt} \\ U_{cn} - U_{an} = -L\dfrac{di_c}{dt} + V_{CA} + L\dfrac{di_a}{dt} \end{cases} \quad (3)$$

$$\begin{cases} \dfrac{di_a}{dt} = \dfrac{i_{aref} - i_a}{T} \\ \dfrac{di_b}{dt} = \dfrac{i_{bref} - i_b}{T} \\ \dfrac{di_c}{dt} = \dfrac{i_{cref} - i_c}{T} \end{cases} \quad (4)$$

Defining the variables *A*, *B* as

$$\begin{cases} A = \dfrac{L\left[\left(i_{aref} - i_a\right) - \left(i_{bref} - i_b\right)\right] + \left(U_{an} - U_{bn}\right)\bullet T}{U_{dc}\bullet T} \\ A = \dfrac{L\left[\left(i_{bref} - i_b\right) - \left(i_{cref} - i_c\right)\right] + \left(U_{bn} - U_c\right)\bullet T}{U_{dc}\bullet T} \end{cases} \quad (5)$$

Then the duty cycle of each phase is given as following equation (6)：

$$\begin{cases} d_A = \left(2A + B + 1.5\right)/3 \\ d_B = \left(-A + B + 1.5\right)/3 \\ d_C = \left(-A - 2B + 1.5\right)/3 \end{cases} \quad (6)$$

The inner deadbeat controller is presented in Fig. (4).

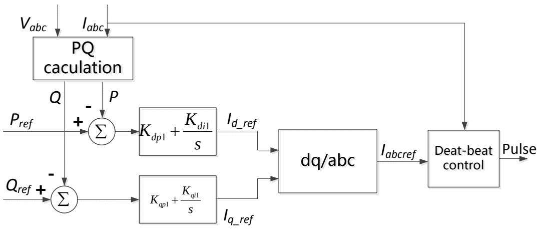
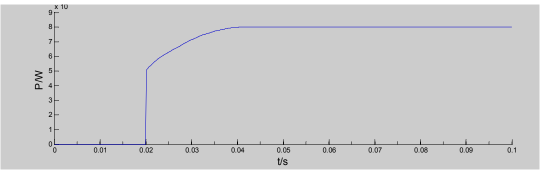


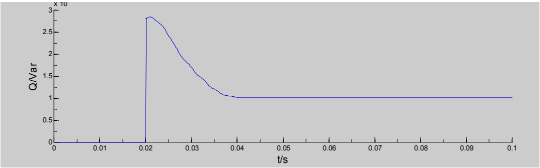
Fig.4 Block diagram of grid-connected mode discharge control

When working in the grid-connected mode discharge, the simulation waveforms is shown in Fig. 5. In this phase, the real power P_{ref} is setting to 80kW, the reactive power is setting to 10kVar. The three-phase loads are unbalanced load, P_a=30kW，P_b=30kW，P_c=50kW，Q_c=20kVar.

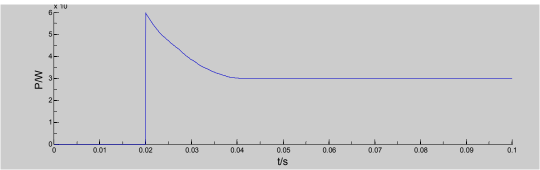
In a shortly response time (0.04s), the real and reactive power of the converter will reached the steady state(80kW，10kVar), and the steady state error is almost zero, as shown in Fig. (5-a), (5-b). For the totally three phase load is 110kW，20kvar， the utility power output will increase to 30kW，10kvar correspondingly, as shown in Fig. (5-c), (5-d). The real and reactive power output of the converter maintains constant, the unbalance power requirement will be supplied by the grid, as shown in Fig. (5-f).



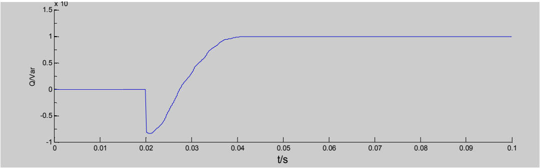
（a）Real power of the converter



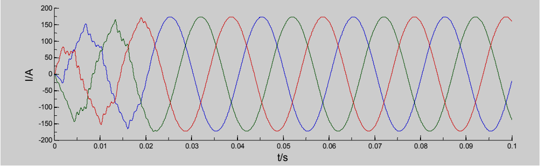
（b）Reactive power of the converter



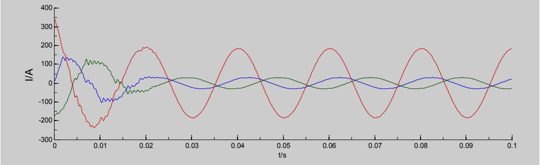
（c）Real power of the grid



（d）Reactive power of the grid



（e）Current of the converter



（f）Current of the grid

Fig.5 Grid-connected mode discharge of bi-directional converter

When the converter is working in grid-connected discharge mode, from the simulation waveforms in Fig.5, it may be observed that bi-directional converter which was controlled by external power control loop and the inner deadbeat control will send corresponding reactive and real powers to the utility based on the set points for reactive and real powers, and the fluctuation of the load will be balanced by the grid.

B. The islanded mode discharge control

When in islanded mode discharge control process, the bi-directional converter is the grid-forming unit and setting the voltage and frequency of the microgrid. The battery energy storage system works as a high quality AC voltage source, the V/f control of bi-directional converter is shown in Fig. (6).

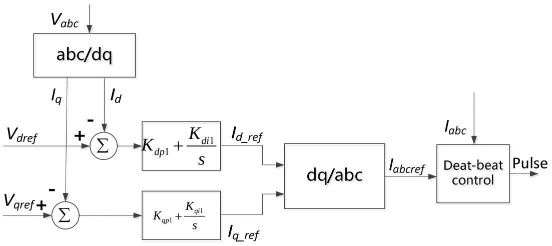


Fig.6 Block diagram of islanded mode discharge control

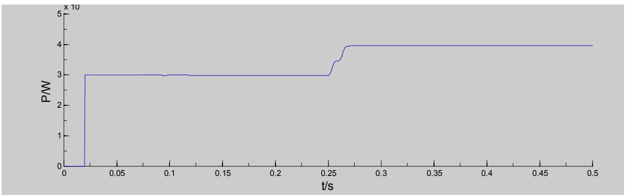
During islanded discharge mode, the V/f control is also achieved in d-q frame. The controller of the converter includes two different parts. One is an external voltage control loop which is achieved with a standard proportional-integral controller, but the reference voltage is setting according to the system requirements whose premise is the synthesizing voltage vectors magnitude are equal between three-phase and synchronous reference frame, and the phase angle of coordinates transformation is also given directly according to the output frequency. The control function of this control is given as equation (7).

$$\begin{cases} i_{d\_ref}=\left(K_{dp1}+\dfrac{K_{di1}}{s}\right)\left(V_{d\_ref}-V_d\right) \\ i_{q\_ref}=-\left(K_{qp1}+\dfrac{K_{qi1}}{s}\right)\left(V_{q\_ref}-V_q\right) \end{cases} \tag{7}$$

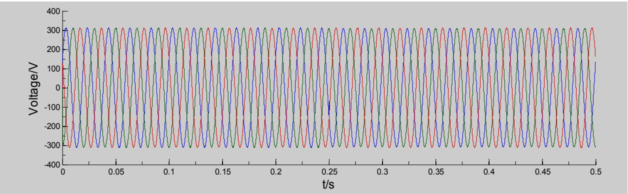
Compare to equation (6), the inner current control is also deadbeat control in islanded discharge control.

Fig.7 gives the islanded discharge mode operation curve of unbalanced load conditions. In 0-0.25s, three phase load is balanced, and each phase load is 10kW, so the total load is 30kW, as shown in Fig. (7-a). In this time, the bi-directional converter is setting the frequency and voltage of the microgrid. As shown in Fig. (7-b), the frequency and voltage of the system is 50Hz, 311V, also the three phase currents are balance, as shown in Fig. (7-c).

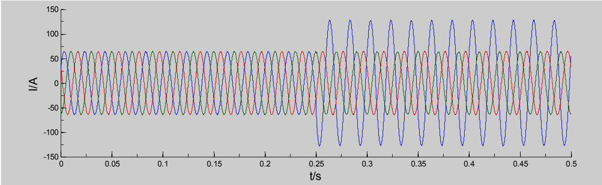
At 0.25s, there is a step change of the phase A load, from 10kW to 20kW. For the V/f control of the bi-directional converter, the battery power output of phase A will increase from 10kW to 20kW correspondingly. This means that the total three phase power will increase from 30kW to 40kW, as shown in Fig. (7-a). The output voltage of the converter remains unchanged, but the current of phase A will increase with the load, as shown in Fig. (7-b), (7-c).



（a）Real power of the converter

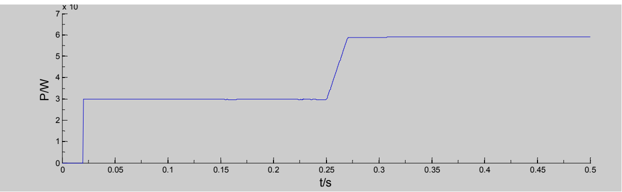


（b）Voltage of the converter

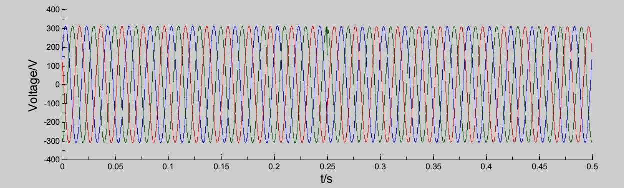


（c）Current of the converter

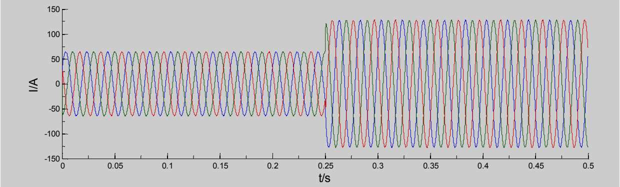
Fig.7 Islanded mode discharge of bi-directional converter in unbalanced load conditions



（a）Real power of the converter



（b）Voltage of the converter



（c）Current of the converter

Fig.8 Islanded mode discharge of bi-directional converter in sudden load change conditions

In 0-0.25s, the three phase balanced load is 30kW, so the output power of the converter is 30kW, as shown in Fig. (8-a). Both the voltage and current are balanced, as shown in Fig. (8-b), (8-c).

At 0.25s, the three phase load will increase from 30kW to 60kW suddenly. For the V/f control of the bi-directional converter, the output power of the battery will increase from 30kW to 60kW correspondingly, as shown in Fig. (8-a). The three phase voltage of the converter still remains unchanged, but the three phase current will increase with the load, as shown in Fig. (8-b), (8-c).

When the bi-directional converter is working in islanded discharge mode, from the real power, voltage and current simulation results in Fig. (7) and Fig. (8), it may be observed that the bi-directional converter which was controlled by external voltage control loop and the inner deadbeat control will maintain the voltage even there is a suddenly change of one phase or three phase load, and the current will fluctuate accordingly with the load.

V. CONCLUSION

In this paper, a control strategy for bi-directional converter in different mode was proposed. When working in grid-connected conditions, the external DC-link voltage loop control strategy was used for battery charge, and the external power control loop and the inner deadbeat control was used for battery discharge. When working in islanded conditions, the inner deadbeat control and the external voltage control loop was used for battery discharge. Simulation results show that the proposed control strategy was effective in islanded and grid-connected mode charge and discharge, also it was simple, exhibits satisfactory transient response and robustness to load variations.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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