Virtual DC Machine Control Strategy of Energy Storage Converter in DC Microgrid

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***Abstract*—The bus voltage of DC microgrid is the key indicator of the stable operation of the system. The energy storage units play an important role in maintaining the stability of DC bus voltage in DC microgrid. In this paper, a virtual DC machine (VDCM) control strategy of energy storage converter in DC microgrid is adopted, aiming to solve the problem that the DC bus voltage is vulnerable to disturbed by renewable energy or loads and cannot be well maintained. This control method simulates the characteristics of the DC machine and is a robust and flexible DC/DC converter control method, which can make the converter and the DC bus flexible connection, thus effectively restrain the DC bus voltage disturbance so as to enhance the stability of DC microgrid. A simulation model of DC microgrid with photovoltaic, energy storage unit and loads is established in MATLAB/Simulink. Simulation results show the feasibility and validity of the adopted control method.**

Keywords—DC microgrid; DC bus voltage; energy storage converter; virtual DC machine (VDCM) control

I. INTRODUCTION

DC microgrid is a small DC power system with distributed generations, loads, energy storage units, converters and monitoring and protection devices [1]-[4]. Compared to AC microgrid, DC microgrid has no phase synchronization, harmonics and reactive power problems, thus, DC microgrid has been considerable attention in recent years [5]-[7]. In DC microgrid, distributed generations, energy storage units and AC/DC loads are connected to common DC bus through power electronic converter. Therefore, the stability of the DC bus voltage and the balance of active power on the DC bus become an important indicator to judge whether the DC microgrid is stable. However, in DC microgrid, a large number of distributed renewable energy sources and the loads have obvious power random fluctuation, and the fluctuation of power especially the impact of short-time power will likely influence the DC bus voltage stability, easily lead to the collapse of DC microgrid system. Consequently, it is necessary to take effective control measures to maintain the stability of the DC bus voltage in DC microgrid.

There are two operation modes of DC microgrid, namely, grid-connected mode and isolated mode. In the grid-connected mode, the normal operation of AC power grid, the DC/AC bidirectional converter is used to control the stability of the DC bus voltage. In the isolated mode, controllable distributed generations or energy storage units are usually used to control the stability of the DC bus voltage. A virtual inertia control strategy was proposed in [8] for the poor voltage quality due to the low inertia of DC microgrid. The control strategy associates DC bus voltage with the instantaneous power regulation of grid and the droop coefficient regulation of the battery and also the speed regulation of permanent magnet synchronous generators (PMSG). The inertia of the system is enhanced due to the large virtual capacitance value of each converters when there is a disturbance. For the control of the DC bus voltage, a virtual DC generator control method for load DC/DC converter is presented in [9]. This control method can simulate the inertia characteristics of the rotating electric machine. The control method is used to eliminate the effects of the load's output and restore disturbed load side voltage softly while the device is put in or cut off from the DC bus. In [10], an AC/DC hybrid electric energy hub was proposed with a modular structure and isolation on the line-frequency AC side. Using the hub, the low voltage AC and DC distribution networks, renewable energy sources, energy storage devices and loads can be easily integrated into the utility system. A virtual-machine-based control strategy was presented for the energy hub to emulate the machine inertia and damping, improving its stability. In these papers, the model of virtual DC machine control strategy is presented for different research objects. However, the control model of these literatures has certain limitations, and cannot fully reflect the characteristics of the DC machine, and the working mechanism of the virtual DC machine control method and the principle of the stability of the DC bus voltage has not been analyzed deeply.

In order to solve the problem that the DC bus voltage is vulnerable to disturbed by renewable energy or loads and cannot be well maintained in DC microgrid, a virtual DC machine control strategy of energy storage converter is adopted. This control strategy simulates the characteristics of the DC machine and is a robust and flexible energy storage DC/DC converter control method, which can make the converter and the DC bus flexible connection, thus effectively restrain the DC bus voltage disturbance so as to enhance the stability of DC microgrid. The small signal model and the simulation model are established to analyze the working mechanism of the virtual DC machine control method and the principle of the stability of the DC bus voltage. Simulation and analysis results

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show the feasibility and effectiveness of the adopted control method.

The remaining sections of this paper are organized as follows: in section II, virtual DC machine (VDCM) control strategy is described in details. Small signal model and analysis is discussed in III. Simulation results are shown in IV. Finally, section V presents the conclusion.

II. Virtual DC Machine (VDCM) Control Strategy

A. *Virtual DC machine model*

In AC microgrid, virtual synchronous generator control strategy is adopted to simulate the external characteristic of the synchronous generator [11, 12], promote its flexible connection with the power grid, reduce the impact on the power grid, and enhance the stability of the power grid voltage and frequency. Similar to AC microgrid, virtual DC machine control strategy of energy storage converter in DC microgrid is adopted to simulate the external characteristic of the DC machine, promote the converter and the DC bus flexible connection, and effectively restrain the DC bus voltage disturbance so as to enhance the stability of the DC bus voltage.

Based on the characteristics of the DC machine, the model of virtual DC machine for energy storage converter is shown in Figure 1. A non-isolated bidirectional Buck-Boost converter is selected for the energy storage interface converter, which can be equivalent to a two port network, the fore-end is connected with a battery energy storage device, and the back-end is connected with the DC bus. The equivalent model of the DC machine has a corresponding relationship with the equivalent two port network of the energy storage interface converter. By simulating the characteristics of the DC machine, the system's inertia and the stability of the DC bus voltage can be effectively enhanced.

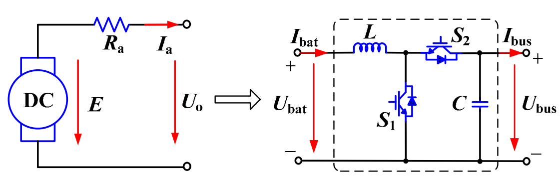


Fig. 1. Virtual DC machine model

The virtual DC machine model can be described by the mechanical rotation equation and armature equation of the DC machine [13]. The mechanical rotation equation is described as follows:

$$J\frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_N) \tag{1}$$

$$T_e = P_e / \omega \tag{2}$$

Where J is moment of inertia, D is damping coefficient, T_m and T_e are mechanical torque and electromagnetic torque of DC machine, respectively. ω is angular velocity, ω_N is rated angular velocity, P_e is electromagnetic power.

The armature equation of the DC machine is described as follows:

$$U_o = E - R_a I_a \tag{3}$$

$$E = C_T \Phi \omega \tag{4}$$

Where E is armature induced electromotive force (EMF), R_a is armature equivalent resistance, I_a is armature current, U_o is the output voltage of the DC machine, C_T is torque coefficient, Φ is flux per pole.

B. *Virtual DC machine control method*

The control structure of virtual DC machine control method for energy storage converter is shown in Figure 2. The power circuit part is the battery energy storage unit which is connected with the DC bus through bidirectional Buck-Boost converter. The control part consists of the DC bus voltage control, virtual DC machine control, current regulation control and PWM modulation.

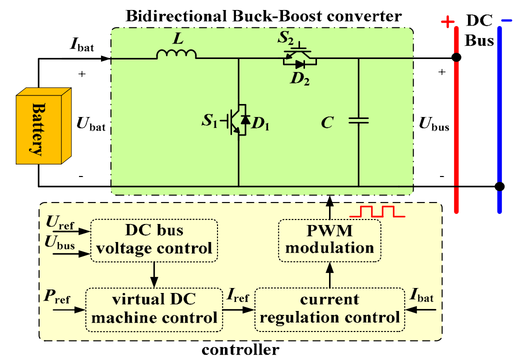


Fig. 2. The structure of control system

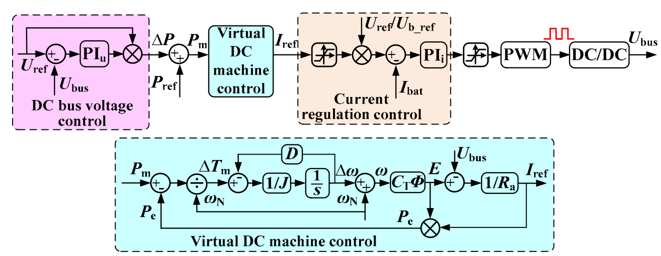


Fig. 3. Control block diagram of virtual DC machine

The control block diagram of virtual DC machine control strategy is shown in Figure 3, it is similar to the traditional voltage and current double-closed loop control to join the virtual DC machine control loop. In the DC bus voltage control part, the DC bus voltage feedback value U_{bus} and the DC bus voltage reference value U_{ref} are compared, using the voltage proportional integral (PI) controller to adjust the DC bus voltage and the mechanical power deviation, and add P_{ref} to mechanical power P_m. Where P_{ref} is the average power reference value of loads, namely, the loads power fluctuate around this value. In the virtual DC machine control part, according to mechanical rotation equation and armature equation of the DC machine to construct the control model, make its have similar to the characteristics of the DC machine moment of inertia and damping coefficient so as to improve the stability of the DC bus voltage. In the current regulation control part, in order to regulate and track the input current I_{bat}, the armature current reference value I_{ref} is converted to the input current reference value through the U_{ref}/U_{b_ref}. Where

U_{b_ref} is the output voltage reference value of the energy storage unit.

As a result of the adoption of virtual DC machine control method, the mechanical rotation equation can adjust the actual angular velocity ω, and then the armature equation can regulate the armature EMF E. Holding the stability of the armature EMF E can keep the stability of the output voltage U_o, namely, maintaining the stability of the DC bus voltage.

The transfer function of the virtual DC machine control can be derived from (1)-(4):

$$G(s) = \frac{R_a}{JR_a s + (C_T \Phi)^2 + DR_a} \tag{5}$$

According to the equation (5), the virtual DC machine control link is approximated as an inertial link. Based on the characteristic of inertia link, the control model of the virtual DC machine can be equivalent to a virtual capacitor on the DC bus side, as shown in Figure 4. The value of moment of inertia corresponds to the capacitance value of the virtual capacitor, the greater moment of inertia, the larger the capacitance value of the virtual capacitor. When the DC bus is disturbed, the virtual DC machine control strategy can effectively stabilize and buffer disturbance impact, and improve the inertia of system, and enhance the stability of the DC bus voltage.

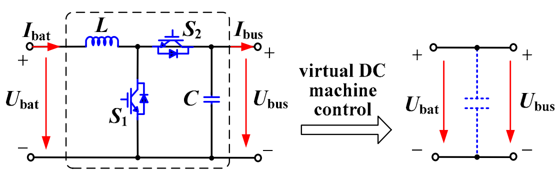


Fig. 4. Equivalent model of control method

III. SMALL SIGNAL MODEL AND ANALYSIS

In order to analyze the stability of the whole system which adopts virtual DC machine control method, the small signal model of bidirectional Buck-Boost converter and the small signal model of the control system are established. Based on the small signal model, the open-loop Bode diagram of the control system is drawn to analyze the influence of the related parameters on the stability of the control system. The small signal model of the bidirectional Buck-Boost converter is shown in Figure 5, and the small signal model of the control system is shown in Figure 6.

The following equations can be derived from Figure 5:

$$G_{iu}(s) = \frac{\hat{i}_L}{\hat{u}_{bat}} = \frac{sC}{s^2CL + sCR_L + d^2} \tag{6}$$

$$G_{ii}(s) = \frac{\hat{i}_L}{\hat{i}_{bus}} = \frac{d}{s^2CL + sCR_L + d^2} \tag{7}$$

$$G_{id}(s) = \frac{\hat{i}_L}{\hat{d}} = -\frac{sCU_{bus} + dI_L}{s^2CL + sCR_L + d^2} \tag{8}$$

$$G_{uu}(s) = \frac{\hat{u}_{bus}}{\hat{u}_{bat}} = \frac{d}{s^2CL + sCR_L + d^2} \tag{9}$$

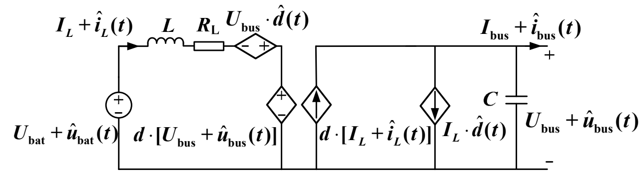


Fig. 5. Small signal model of bidirectional Buck-Boost converter

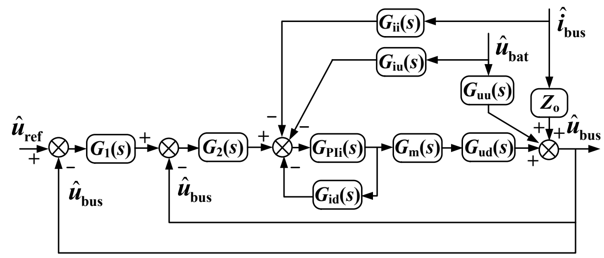


Fig. 6. Small signal model of the control system

$$G_{ud}(s) = \frac{\hat{u}_{bus}}{\hat{d}} = \frac{(sL + R_L)I_L - dU_{bus}}{s^2CL + sCR_L + d^2} \tag{10}$$

$$Z_o = \frac{\hat{u}_{bus}}{\hat{i}_{bus}} = -\frac{sL + R_L}{s^2CL + sCR_L + d^2} \tag{11}$$

Where R_L is equivalent resistance of inductor, C is capacitor, d is duty ratio. The other equations in Figure 6 are as follows:

$$G_{PIi} = \frac{sk_{pi} + k_{ii}}{s} \tag{12}$$

$$G_m = \frac{1}{V_m} \tag{13}$$

$$G_1(s) = \frac{U_{ref} C_T \Phi R_a (sk_{pu} + k_{iu})}{s\omega_N [JR_a s + (C_T \Phi)^2 + DR_a]} \tag{14}$$

$$G_2(s) = \frac{U_{ref}}{R_a U_{b\_ref}} \tag{15}$$

Where V_m is carrier peak, k_{pi} and k_{ii} are proportional coefficient and integral coefficient of PI current regulator, respectively. k_{pu} and k_{iu} are proportional coefficient and integral coefficient of PI voltage regulator, respectively. Equation (14) is the transfer function of the DC bus voltage deviation to the armature EMF difference ΔE. Equation (15) is the transfer function of the armature EMF difference ΔE to the input current. The open-loop transfer function of the control system can be derived from (6)-(15):

$$G_{uo}(s) = \frac{G_1(s)G_2(s)G_{PIi}(s)G_m(s)G_{ud}(s)}{1 + G_{PIi}(s)G_{id}(s) + G_2(s)G_{PIi}(s)G_m(s)G_{ud}(s)} \tag{16}$$

The open-loop Bode diagram of the control system is shown in Figure 7. As can be seen from Figure 7, the phase margin of the control system is 85.6 degrees, the amplitude margin is 24.6 dB, thus, the control system has a good stability. In order to analyze the influence of the moment of inertia J and damping coefficient D on the control system of the virtual DC machine control, the open-loop Bode diagrams of the control systems with different moment of inertia J and different damping coefficient D are drawn, respectively. As shown in Figure 8 (a) and (b), moment of inertia J mainly affects the

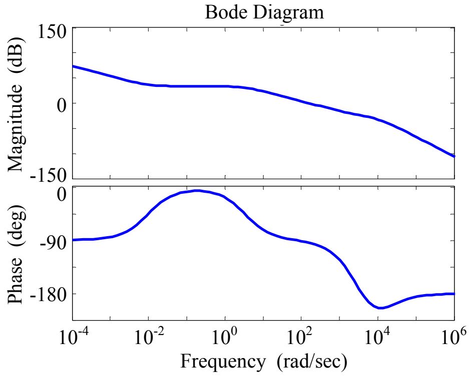
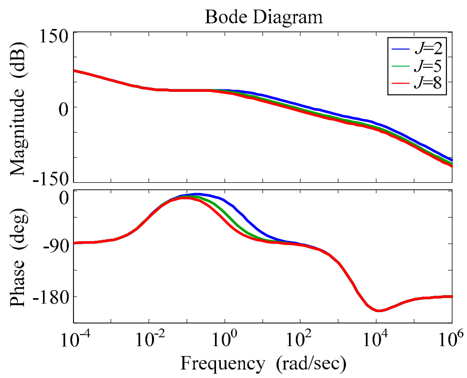
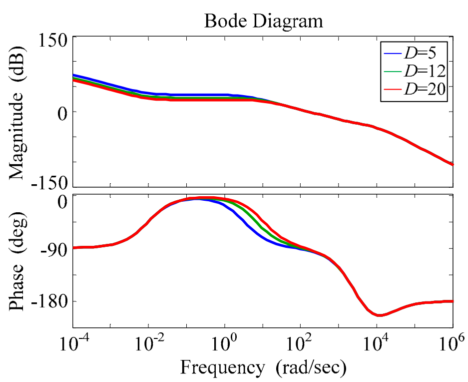


Fig. 7. Open-loop Bode diagram of the control system



(a) Open-loop Bode diagram of different J



(b) Open-loop Bode diagram of different D

Fig. 8. Open-loop Bode diagram of control system with different parameters

high frequency section, and with the increase of moment of inertia J, the amplitude margin of the control system is increased and the stability of the control system is improved. Because the increase of moment of inertia J makes the control system have a greater inertia. Thus, the impact of disturbance signal to the control system is buffered. Damping coefficient D mainly affects the low frequency section, and with the increase of damping coefficient D, the phase margin of the control system is increased and the stability is improved. Due to the increase of damping coefficient D, the suppression ability of the control system to disturbance signal is enhanced. As a result, the virtual DC machine control method can be used to buffer and restrain the disturbance of the control system, which can effectively improve the stability of the control system.

IV. SIMULATION RESULTS

In order to verify the feasibility and effectiveness of the virtual DC machine control strategy, a simulation model of DC microgrid with photovoltaic, energy storage unit and loads is established. The perturbation and observation method is used to realize maximum power point tracking (MPPT) control of photovoltaic power generation. The virtual DC machine control strategy is adopted for the energy storage unit to maintain the stability of the DC bus voltage. The related parameters of the control system are shown in Table I.

TABLE I. CONTROL SYSTEM PARAMETERS

Parameters	Symbol	Value
DC bus voltage	U_{bus}	400V
PV output voltage	U_{pv}	235V
PV output current	I_{pv}	21.25A
PV output power	P_{pv}	5kW
Initial state of charge (SOC) of energy storage	SOC	60%
Rated angular velocity	ω_N	100π rad/s
Power reference value	P_{ref}	2000W
Moment of inertia	J	8 kg·m^2
Damping coefficient	D	5
Torque coefficient	C_T	18.48
Flux per pole.	Φ	0.0698Wb
Equivalent resistance of armature circuit	R_a	1Ω

Figure 9 shows the simulation results of the photovoltaic power generation, it can be found that PV output voltage is 235V, PV output current is 21.25A, and PV output power is almost 5kW. The maximum power output of the photovoltaic can be realized by the maximum power point tracking control. The simulation results of the energy storage unit using the virtual DC machine control strategy are shown in Figure 10. As can be seen from Figure 10, when the load is put in or cut off from the bus, the energy storage unit can be self-adapted to carry out the charging and discharging, and the DC bus voltage is stable at 400V by adjusting the angular velocity ω and armature EMF E of the virtual DC machine.

Under the condition of power random fluctuation of the PV and the loads, the simulations of the virtual DC machine control strategy and the droop control with secondary voltage regulation is carried out in order to analyze its influence on the stability of the DC bus voltage. Figure 11 shows the simulation results of the DC bus voltage when the load power is random fluctuation. As can be seen from Figure 11, when the load power is random fluctuations at 1-4s, compared to the droop control with secondary voltage regulation, the disturbance amplitude of the DC bus voltage is smaller by adopting the virtual DC machine control strategy, and the stability of the DC bus voltage is better. Figure 12 shows the simulation results of the DC bus voltage when the PV output power random fluctuation caused by the variation of solar irradiance. When the solar irradiance is changed fast, the photovoltaic output power will be the corresponding fluctuations, which can cause the disturbance of the DC bus voltage. Compared to the droop control with secondary voltage regulation, the adoption of virtual DC machine control strategy, the disturbance of the DC bus voltage is very small, therefore, the stability is improved.

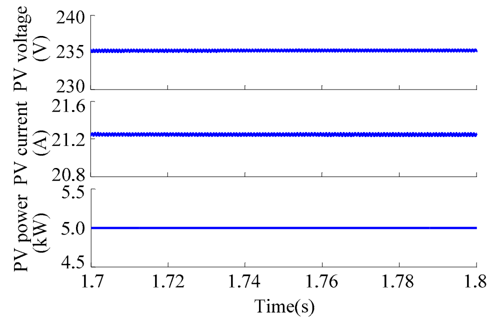


Fig. 9. Simulation results of photovoltaic power generation

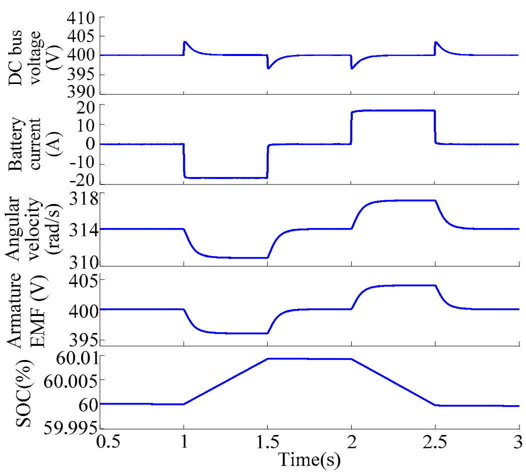


Fig. 10. Simulation results of the energy storage unit

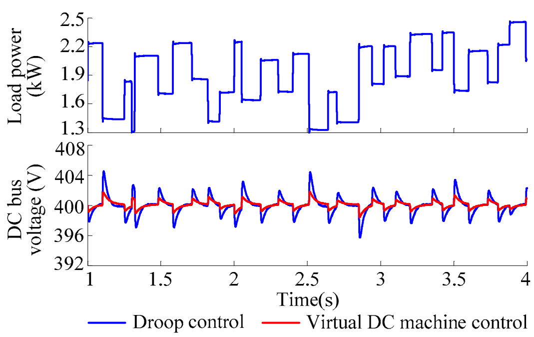


Fig. 11. Simulation results of loads power random fluctuation

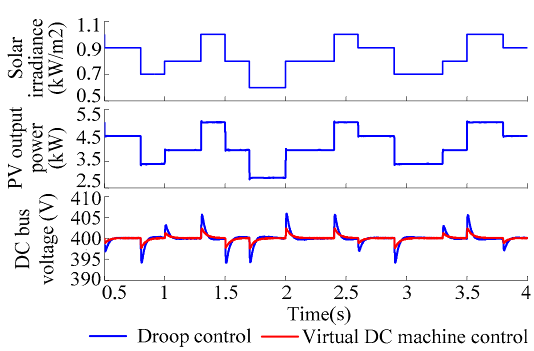


Fig. 12. Simulation results of PV output power random fluctuation

V. Conclusion

A virtual DC machine (VDCM) control strategy of energy storage converter in DC microgrid is adopted, aiming to solve the problem that DC bus voltage is vulnerable to disturbed by renewable energy or the loads and cannot be well maintained. The small signal model of the control system is established to analyze the stability of the whole system which adopts virtual DC machine control method. Based on the small signal model of the control system, the influences of moment of inertia J and damping coefficient D on the stability of the control system are discussed, and the influences of virtual DC machine control strategy and the droop control with secondary voltage regulation on the stability of the DC bus voltage are compared. The Simulation models based on MATLAB/Simulink are established. The simulation results show that virtual DC machine control strategy can effectively buffer the impact of power fluctuations on the DC bus voltage, and enhance the stability of the DC bus voltage. The feasibility and effectiveness of the adopted control method is verified by the simulation and analysis, which provides a robust and flexible control method for the stability control of the DC bus voltage.

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