Collaborative control strategy of power electronic transformer and fault current limiter in DC microgrid

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Abstract: With rapid development of DC microgrid (DCMG), the protection against short circuit fault on the whole DC system has gained widespread concern. This paper proposes an approach which uses power electronic transformer (PET) and fault current limiters (FCLs) to improve the impact of short circuit current in DCMG. PET in the fault line can work in the fault current limiting mode to limit short circuit current in this line. PET adjusts the input power from AC grid to DC grid to keep the DC voltage stability in the DCMG. A complete model of PET and DCMG is developed and the collaborative control strategy of PET and FCL is analysed. The simulation results confirm that the proposed control strategy based on the collaborative operation of PET and FCL can enhance the ability to ride through the short circuit fault of each part of DCMG system.

1 Introduction

With the rapid development of distributed energy resources (DERs) and DC loads, DCMG capacity increases quickly. The short circuit fault is the worst situation in operation for DCMG, which would cause over-current flow through devices and damage the devices. Then the bus voltage in DCMG fluctuates because of over-current flow. In a worst case, the normal operation of the whole DCMG system is broken off and the widespread blackout occurs. In this situation, research on limiting short circuit fault current becomes meaningful work in enhancing fault tolerant ability of DCMG system.

Fault current limiter (FCL), as a short circuit current limiting device, has lots of advantages compared with other short circuit current limiting devices. FCL does not affect the power grid system when system runs normally. When short circuit fault occurs in a branch, FCL can limit the short circuit current quickly and effectively by operating on the fault current limiting mode. Then, FCL can cut off the branch immediately if short circuit current cannot be limited. In [1], a microgrid protection scheme was proposed by optimally sizing FCLs. The study in [2] put forward over-current protection strategies for distribution systems with DERs and FCLs. In [3], a concept of using power electronic protections on microgrid to avoid the over-current fault was proposed.

FCL is able to provide effective protection for devices in the fault branch. While the system power fluctuation caused by the fault cannot be resolved through FCL, the system output power increases when short circuit current fault occurs. Also, the output power reduces to zero when fault branch is removed by FCL. Output power variation in fault branch causes DC bus voltage fluctuation. Thus, it is important to reduce the impact on output power fluctuations.

Due to the flexible regulation ability of active and reactive power, quick protection ability, relatively smaller size, and so on [4]. Power electronic transformer (PET) has been considered as the promising scheme in the AC/DC hybrid distribution systems with the purpose of enhancing the devices access ability of the distribution grid or microgrid. However, the existed research ignores the flexible regulation ability of PET on system power control. With the rapid development of PET in AC/DC hybrid micro-grid, the research on DC short circuit fault in the DCMG with the integration of PET and FCL becomes a significant work. Through the use of PET in adjusting input power, the deviation of the system input and output power during the fault reduces and DC bus voltage fluctuation can be suppressed.

This study proposes an approach which uses both PET and FCLs to eliminate the influence of short circuit current in DCMG. When a short circuit fault occurs in a device, FCL in the fault line can be activated quickly and change into fault current limiting operation automatically to reduce short circuit current in this line. Meanwhile, PET adjusts the input power from AC grid to DC grid promptly. Finally, the goal of reducing the incidence of the short circuit current fault on the whole system can be achieved. The simulation results in this paper validate that the proposed control strategy based on the collaborative operation of PET and FCL can limit the impact of the whole DCMG system effectively.

2 System configuration of DC microgrid

AC/DC hybrid microgrid model is presented in Fig. 1. Reference [5], radioactive topology of DCMG is chosen in this paper. The advantage of radioactive topology is that the design of the grid structure is uncomplicated and the fault identification is accurate. AC grid, AC microgrid and high voltage/low voltage (HV/LV) DCMG are connected by PET, in which the back to back three-stage structure is chosen. PET achieves HVAC/HVDC/LVDC/ LVAC conversion by the control of rectifier, H-bridge (on both sides of high frequency transformer) and inverter. This paper focuses on the study of DCMG (both HV and LV DCMG) and rectifier (to regulate high DCMG voltage) and H-bridge (to regulate low DCMG voltage).

HVDC microgrid is connected to power grid system through HVDC bus, and LVDC microgrid is connected to power grid system through LVDC bus. Radioactive topology is applied in both HVDC and LVDC microgrid. Each DEG and DC load with a FCL in series is connected by each branch. With the purpose of enhancing both the steady state performance and the dynamic

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performance in the system, sliding mode variable control (SMC) is applied to rectifier due to the tiny parameter dependencies, simple implementation, quick dynamic response, etc. Meanwhile, the closed-loop voltage control is applied to H-bridge to adjust the voltage in LVDC.

3 Operation of FCL on short circuit fault

The FCL model in [6] is chosen in this paper as shown in Fig. 2. FCL operation is divided into three stages as the following:

3.1 Normal operation

In normal operation, DC bus voltage maintains stability while solid state switch (SSS) in FCL keeps turning on. Thus, FCL does not have influence in DCMG at this time.

3.2 Fault current limiting operation

After the fault occurs and the short circuit current rises to a set level, the fault branch is putted into fault current limiting operation. SSS in FCL turns on and off at a high-speed. FCL works like a variable resistance to limit short circuit current increase by adjusting the ratio on the turn-on and turn-off time. If the short circuit current can be limited effectively in this operation, DCMG keeps running in this operation until the fault is resolved and then changes into normal operation. Otherwise, FCL changes into circuit breaker operation.

3.3 Circuit breaker operation

In this operation, SSS in FCL turns off so that faulty device is isolated, and then the current in the fault branch reduces to zero quickly. SSS remains off until the fault is resolved. Also then this branch changes into normal operation.

Output power of fault branch can also be analyzed with the model of FCL. By the adjustment of PET, there will be no DC bus voltage fluctuations when a fault occurs. Thus, the increment of output power is almost proportional to the increment of branch current. On the one hand, short circuit current still has a significant increase after the fault occurs though FCL can limit short circuit current. The fault branch output power also increased correspondingly. On the other hand, branch current is reduced to zero after FCL removes the fault branch. The fault branch output power also reduces to zero correspondingly. Therefore, FCL cannot keep up the output power stably when the fault occurs.

With the purpose of reducing the impact of the output power fluctuation in a fault situation, PET is used to connect AC/DC hybrid microgrid and power grid.

4 Control strategy of PET

With the control of rectifier and H-bridge, the adjustment of the input power of HVDC and LVDC microgrid is achieved by PET. In the traditional control of PET, PI closed loop control is used in rectifier while open loop control is used in H-bridge. Both PI closed loop control in rectifier and open loop control in H-bridge lacks of the momentary power regulation ability due to the limited control bandwidth. This paper employs SMC strategy in rectifier and closed loop voltage control in H-bridge to keep input power almost equal to output power.

4.1 Control strategy of rectifier

Basic principle of SMC can be obtained from reference [7]. SMC is used in the control of rectifier to enhance the dynamic response ability when a short circuit current fault occurs. The control structure is given in Fig. 3. SMC is a class of special non-linear control essentially. Several predetermined ‘sliding mode’ are given with the state of control variable (such as the deviation and derivatives of the deviation, etc) in SMC. Then the system is commanded to move forward on predetermined ‘sliding mode’. In this paper, high-order sliding mode is used to apply for the rectifier control.

In [8], the mathematical model of the grid side converter in the synchronous rotating \(d, q\) coordinate system can be obtained as

\[
\begin{align*}
L_i_{d}g_{d} &= -R_i_{d}g_{d} + \omega_1 L_i_{q}g_{q} + u_{gd} - v_{gd} \\
L_i_{q}g_{q} &= -R_i_{q}g_{q} - \omega_1 L_i_{q}g_{q} + u_{gq} - v_{gq} \\
C &u = 2U_{gd}i_{gd} - 2\sqrt{2}u_i_L \\
\end{align*}
\]

In the formula: \(u_{gd}, v_{gd}\) are the \(d\)-axis grid voltage and \(q\)-axis grid voltage; \(i_{gd}, i_{gq}\) are the \(d\)-axis input current and \(q\)-axis input current; \(V_{gd}, V_{gq}\) are the \(d\)-axis output voltage and \(q\)-axis output voltage.
short circuit faults. Based on [7], exponential law is used in SMC as follows:

\[ s = -n_1 s - n_2 \text{sgn}(s) \]  

In the formula

\[ n_1 > 0, \quad n_2 > 0 \]  

To increase the system dynamic response to accommodate possible short circuit faults. Based on [7], this study proposes a variable coefficient exponential law in SMC as follows:

\[ s = -k_1 \cdot e^{k_3 \sqrt{v^2 - v^g}} \cdot s - k_2 \text{sgn}(s) \]  

In the formula

\[ k_1 > 0, \quad k_2 > 0, \quad k_3 > 0 \]  

The voltage loop control law can be derived as

\[ i_{\text{eq}} = i_{\text{dq}} + i_{\text{dn}} \]  

In the formula

\[ \begin{cases}  
  i_{\text{dq}} = \frac{\sqrt{v^2}}{U_1} i_s 
  
  i_{\text{dn}} = -\frac{C}{2a_1 U_1} \int_0^t \left( -k_1 \cdot e^{k_3 \sqrt{v^2 - v^g}} \cdot s_1 - k_2 \text{sgn}(s_1) - e_1 \right) d\tau 
\end{cases} \]  

\[ i_s \] is the current of high voltage DC bus; \( U_1 \) is \( d \)-axis voltage when \( q \)-axis is assumed to zero; \( s_1 \) is sliding surface; \( e_1 \) is the deviation of given value and actual value of DC bus voltage’s square; \( a_1 \) are adjustable parameters which are greater than zero.

Similar to the voltage loop control analysis, the \( d \)-axis current control based on SMC can be expressed as

\[ v_{\text{eq}} = v_{\text{dq}} + v_{\text{dn}} \]  

In the formula

\[ \begin{cases}  
  v_{\text{dq}} = -i_{\text{dq}} L - Ri_{\text{dq}} + \alpha i_{\text{dq}} L + U_1 
  
  v_{\text{dn}} = -\frac{L}{a_2 s} \int_0^t \left( -k_4 \cdot e^{k_8 \sqrt{v^2 - v^g}} \cdot s_2 - k_6 \text{sgn}(s_2) - e_2 \right) d\tau 
\end{cases} \]  

\( s_2 \) is sliding surface; \( e_2 \) is the deviation of given value and actual value of \( d \)-axis current; \( a_2, k_4, k_6, k_8 \) are adjustable parameters which are greater than zero.

The \( q \)-axis current control based on SMC can be expressed as

\[ v_{\text{eq}} = v_{\text{dq}} + v_{\text{dn}} \]  

In the formula

\[ \begin{cases}  
  v_{\text{dq}} = \frac{-i_{\text{dq}} L - R i_{\text{dq}} + \alpha i_{\text{dq}} L + U_1}{2a_1 U_1} \int_0^t \left( -k_1 \cdot e^{k_3 \sqrt{v^2 - v^g}} \cdot s_1 - k_2 \text{sgn}(s_1) - e_1 \right) d\tau 
  
  v_{\text{dn}} = -\frac{L}{a_2 s} \int_0^t \left( -k_4 \cdot e^{k_8 \sqrt{v^2 - v^g}} \cdot s_2 - k_6 \text{sgn}(s_2) - e_2 \right) d\tau 
\end{cases} \]  

\( s_3 \) is sliding surface; \( e_3 \) is the deviation of given value and actual value of \( q \)-axis current; \( a_3, k_7, k_8, k_9 \) are adjustable parameters which are greater than zero.

4.2 Control strategy of H-bridge on both sides of high frequency transformer

The closed loop Voltage control is used in the control of H-bridge on both sides of high frequency transformer to increase dynamic response when a short circuit current fault occurs. The control structure is shown in Fig. 4.

5 Simulation results

The simulation model was constructed by the model in Fig. 1. Output power of AC/MG is set to 3 MW. There is a DER (2 MW input) and a DC load (3 MW output) connected to HVDC microgrid. There are two DERs (both 0.5 MW input) and two DC loads (both 0.5 MW output) connected to LVDC microgrid. AC voltage of grid side is 10 kV, DC voltage of high DC bus is 20 kV. DC voltage of low DC bus is 1 kV. The fault circuit simulation results are obtained by Matlab/simulink.

5.1 Fault branch with FCL

The fault branch current after fault occurs is shown in Figs. 5 and 6, in which short circuit fault occurs at 0.6 s in HVDC load. The short circuit current \( I_f \) increases immediately after short circuit fault occur. Also, \( I_f \) growth rate slows down under the action of FCL. At about 0.63 s, \( I_f \) increases to peak current 900 A. Then the SSS in FCL is turned off and \( I_f \) decreases to be zero at about 0.67 s.
Output power $P_f$ in fault branch is given in Fig. 7. The output power waveform is basically the same as the fault current waveform. $P_f$ increases immediately after short circuit fault occurs. Also, $P_f$ growth rate slows down under the action of FCL. At about 0.63 s, $P_f$ up to peak power, and then $P_f$ decreases to be zero at about 0.67 s.

5.2 HVDC bus voltage with different control

Figs. 7 and 8 show the HVDC voltage with the PI closed loop control and SMC respectively, in which short circuit fault occurs at 0.6 s in HVDC load. If traditional PI control is used in rectifier, HVDC bus voltage $U_1$ drops over 800 V (4%) when the failure occurred. After the faulty branch is cut off, $U_1$ rapid rebounds since the output power is reduced. $U_1$ reaches a peak voltage which is higher than original voltage 400 V(2%) at 0.69 s. $U_1$ returns to the steady state voltage at about 1.00 s with traditional PI control. If SMC is used in rectifier, as shown in Fig. 8, HVDC bus voltage $U_2$ drops <150 V (0.75%) when the fault occurs. After the faulty branch is cut off, $U_2$ reaches a peak voltage which is higher than original voltage 100 V (1%) at 0.67 s. $U_2$ returns rapidly to the steady state voltage at about 0.8 s with SMC. It can be shown that SMC is better than PI control when short circuit fault occurs.

5.3 LVDC bus voltage with different control

Figs. 9 and 10 show the LVDC voltage with the PI closed loop control and SMC, respectively, in which short circuit fault occurs at 0.6 s in LVDC load. If opened loop control (fixed duty cycle) is used in H-bridge, LVDC bus voltage $U_3$ drop immediately when failure occurred. After the faulty branch is cut off, $U_3$ rapid rebounds since the output power is reduced. $U_3$ is 30 V(3%) higher than the steady state operation point. If closed loop control is used in H-bridge, the bus voltage $U_4$ is 10 V(1%) higher than the steady state operation point. It can be found that closed loop control is better than opened loop control when short circuit fault occurs.

6 Conclusion

With theoretical analysis and simulation analysis, the collaborative control strategy of PET and FCL proposed in this paper can effectively reduce the impact of short circuit current fault on the whole DCMG system. With this control strategy, the faulty branch can be cut off quickly, and meanwhile, both HVDC and LVDC bus voltage fluctuation decrease significantly.

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8 References

[1] Majumder R., Ghosh A., Ledwich G., et al.: ‘Power management and power flow control with back-to-back converters in a utility connected microgrid’, IEEE Trans. Power Syst., 2010, 25, (2), pp. 821–834

[2] Tang W.J., Yang H.T., Tsai C.C., et al.: ‘Overcurrent protection strategies for distribution system with distributed energy resources and fault current limiters’. 2016 IEEE Int. Conf. on Power System Technology, 2016, pp. 1–6

[3] Nayak G., Nath S.: ‘Effect of power electronic protections of inverters on protection of micro-grids’. 2016 IEEE 6th Int. Conf. on Power Systems (ICPS), 2016, pp. 1–6

[4] Strzelecki R., Roasto I., Romero-Cadaval E.: ‘Design of a simple modular active power electronic transformer’. IECON 2014 – 40th Annual Conf. of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 1410–1415

[5] Jia L., Zhu Y., Wang Y.: ‘Architecture design for new AC–DC hybrid micro-grid’. 2015 IEEE First Int. Conf. on DC Microgrids (ICDCM), 2015, pp. 113–118

[6] Zhuang J.W., Zhang X.F., Yang F., et al.: ‘Design and analysis of a new type DC fault current limiter’, J. Nav. Univ. Eng., 2005, 17, (4)

[7] Chen B., Feng Y., Zhou M.H.: ‘Terminal sliding-mode control scheme for grid-side PWM converter of DFIG-based wind power system’. IECON 2013 – 39th Annual Conf. of the IEEE Industrial Electronics Society, 2013, pp. 8014–8018

[8] Venkat J., Shukla A., Kulkarni S.V.: ‘A novel dq-vector based control for the three phase active rectifier in a power electronic transformer’. 2013 Annual IEEE India Conf. (INDICON), 2013, pp. 1–6