Research on fault ride-through control strategy for DC microgrid with high-proportion renewable generation

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Abstract. DC microgrids with high-proportion renewable generation have been popular in the new era of the energy revolution. To improve the fault ride-through capability of DC microgrid, a fault ride-through scheme based on battery storage is proposed. A feed-forward term based on a nonlinear disturbance observer is introduced, and a fault ride-through control strategy based on battery storage under the improved droop control is designed for DC microgrid, which can effectively suppress the DC voltage fluctuations, shorten the voltage recovery time, thereby realizing the fault ride-through of DC microgrid under short-circuit fault in the DC branch. Finally, a model of DC microgrid with high-proportion renewable generation is established in Simulink, and simulation results verify the proposed scheme and the designed fault ride-through control strategy.

1. Introduction

With the large-scale development of renewable energy, the installed capacity of renewable generation is increasing. By 2019, the cumulative installed capacity of China's renewable generation is already 414.77 million kilowatts, which means renewable generation has played an important role in the grid. Traditionally, AC/DC converter is often required in the intermediate process to utilize renewable generation, which is unfavourable to the energy efficiency [1]. Therefore, with the increasing renewable generation and DC load, DC microgrid which organizes DC source, energy storage device and load in DC mode will become an important way [2].

The renewable generation is random and volatile, which results in the high uncertainty of power [3]. It will make some adverse effects on the power quality, especially for the voltage [4]. Meanwhile, the renewable generation connected to the DC microgrid mainly depends on the stable DC bus voltage. When a short-circuit fault or ground fault occurs on the grid side of the system, the fault will indirectly affect the DC bus voltage, which is harmful to the stable operation of the system. Besides, the DC fault will have a direct impact on the DC bus voltage. As a result, research on the fault ride-through control strategy under the DC fault is important to ensure the grid connection of the renewable generation.

Some research on the fault ride-through control strategy of systems has been done. In [5], the author studies the multi-mode operation of the three-phase photovoltaic power generation system with low voltage ride-through capability, and discusses the self-protection problem of the system under grid failure in [6]. In [7], based on a fuzzy neural network, a reactive power controller is proposed to provide fault ride-through capability for the renewable generation system. In [8], a fault ride-through control technology based on space vector Fourier transform is proposed under the unbalanced grid
faults. In [9], a new differential current-based rapid fault detection scheme is proposed for DC microgrid. In [10], an optimal PI controller for DVR is designed to improve the system performance during faulty conditions.

The above research on fault ride-through of the system mainly focuses on the improvement of the control strategy of three-phase grid-connected inverters when the main grid fails. For DC microgrids with renewable generation, the research focuses on fault detection and relay protection. On the whole, there are still few studies on the design of control strategies to make the system operate stably and then to achieve fault ride-through when the DC side fails.

In this paper, a fault ride-through scheme based on battery storage is proposed. This method can quickly detect the DC bus voltage disturbance caused by the DC fault, enhance the control capability of the battery storage when a fault occurs in the grid, thereby achieving fault ride-through of the DC microgrid. In section 2, the system structure is chosen and detailed model of the system is established. In section 3, the fault ride-through control strategy based on the battery storage is proposed. And in section 4, the effectiveness of the proposed fault-ride through scheme is verified by simulation.

2. System structure and modelling
Considering the generality, a radial topology DC microgrid is selected, as is shown in Figure 1. In the DC microgrid, the power electronic transformer (PET) establishes the voltage level with a 750V DC bus. Meanwhile, renewable power generation (REP), energy storage (ES) and DC loads are connected to the DC bus. Before controlling the system, it is essential to establish the model of microgrid.

![Figure 1. Topology of DC microgrid.](image)

2.1. Power electronic transformer
In the microgrid system, the three-level PET topology is commonly used. The object of this paper is the DC microgrid based on PET access, so only the topologies of the first two stages of PET are given, as shown in Figure 2.

![Figure 2. Topology of power electronic transformer.](image)
In Figure 2, the first stage is a cascaded H-bridge structure, which can perform higher voltage input and realizes rectification. The second stage is a dual active bridge structure to achieve DC voltage conversion and electrical isolation. The control of the PET can make the DC bus operate at DC 750V. The control strategy of the PET can be found in reference [11].

2.2. Renewable power
Photovoltaic (PV) is selected as a representative of REP. It can be directly connected to the DC microgrid after voltage conversion. The modeling includes photovoltaic modeling and control realization of the converter. The commonly used PV cell model can be described as

$$I = I_{ph} - I_{sc}e^{-\frac{V + IR_s}{V_{oc}} - \frac{V + IR_s}{R_{sh}}}$$  (1)

where $V$, $I$ are the output voltage and current of the cell, $I_{ph}$ is the photocurrent, $R_{sh}$, $R_s$ are the parallel resistor and the series resistance. $I_{sc}$ is the saturation current, $q$ is the charge on an electron, $A$ is the diode quality factor, $T$ is the temperature and $k=1.38e^{-23}$.

PV is connected to the DC microgrid through the boost converter, which operates at the maximum power point. And maximum power point tracking is achieved by the incremental conductance method[12].

2.3. Energy storage
The battery is used as the energy storage in the DC microgrid. And for the battery, voltage and state of charge (SOC) are defined as two important parameters [13]. The general equivalent model of the battery is made of a controlled voltage source $E$ and a series resistor $R$.

The relationship between the controlled source voltage and the battery voltage is shown in equation (2), where $V_{bat}$, $i$ are battery voltage and current respectively. Equation (3) defines controlled voltage source when the battery discharges. And equation (4) defines controlled voltage source when the battery charges. The other parameters in the equations can be found in [13].

$$V_{bat} = E - Ri$$  (2)

$$E = E_0 - K \frac{Q}{Q - Q_{th}} (Q_{th} + i') + Ae^{i - Q_{th}}$$  (3)

$$E = E_0 - K \frac{Q}{Q - Q_{th}} i' - K \frac{Q}{Q - Q_{th}} Q_{th} + Ae^{i - Q_{th}}$$  (4)

3. Fault ride-through control strategy
Fault ride-through refers to the fact that when the system fails, the DC microgrid can remain connected for a period of time without entering island operation, which can avoid the mode-switch during the system operation. Meanwhile, the DC bus voltage stability is an important indicator to the power balance of the DC microgrid, which helps to realize the fault ride-through. To some degree, the stable control of the DC bus is the key to realize the fault ride-through of the DC microgrid.

When a short circuit fault occurs in a branch of the DC microgrid, the short circuit is equivalent to connecting a very small resistor in parallel. The DC current increases and the DC output power is regarded as constant, so the DC bus voltage will drop. If only the PET is used to control the DC bus voltage, the voltage adjustment is slow. By adopting improved droop control, this article proposes a fault ride-through scheme based on battery storage, which can quickly track the disturbance and reduce its negative effect. In the transient process, the DC bus voltage can be restored faster and fault ride-through of the DC microgrid can be realized.

The improved droop control of the battery is achieved by introducing an additional term to its original droop controller, as is shown in Figure 3.
In Figure 3, \( i_{\text{bat}} \) and \( u_{\text{bat}} \) are the reference and actual value of the DC bus voltage respectively, \( i_b \) is the output current of the battery storage, \( U_{\text{ref}} \) is the reference voltage value of the battery. \( i_{\text{bat}}, i_{\text{ref}} \) are the reference value and actual value of the battery current respectively, \( r \) is the droop coefficient, \( \bar{I}_o \) is the equivalent load current observed by nonlinear disturbance observer (NDO), and \( x \) is state variable. In the following section, how to design the NDO and feedforward function \( G_d(s) \) will be introduced.

### 3.1. NDO of the DC microgrid

In order to simplify the analysis and design process, the power of the PET, renewable generation and constant power load can be considered as a whole part. And the total current of this whole part and the constant resistance load is defined as \( I_o \), which means the equivalent load current of the system.

Based on the above simplification, the DC microgrid system can be described by equation (5).

\[
\begin{align*}
\frac{du_{\text{bat}}}{dt} &= \frac{i_{\text{bat}} - i_b}{C}, \\
\frac{di_b}{dt} &= \left\{ \begin{array}{ll}
-u_b + d_i u_{\text{bat}}, & \text{Buck} \\
-u_b - (1 - d_i) u_{\text{bat}}, & \text{Boost}
\end{array} \right. \\
u_b i_b &= u_{\text{bat}} i_{\text{bat}}
\end{align*}
\]

(5)

where \( u_b \) is the battery storage port voltage, \( d_i \) and \( d_2 \) are the control output under different mode. After choosing the state variables as \( x = [u_{\text{bat}} \ i_b]^T \), the system described by (5) can be given as

\[
\begin{align*}
\dot{x} &= g_1(x)d + g_2(x)w(t) + f(x) \\
y &= x_1
\end{align*}
\]

(6)

where

\[
\begin{align*}
g_1(x) &= \begin{bmatrix} 0 & x_1 / L \end{bmatrix}^T, \\
g_2(x) &= \begin{bmatrix} -1 / C & 0 \end{bmatrix}^T
\end{align*}
\]

\[
\begin{align*}
d_1 &= \begin{bmatrix} d_i \end{bmatrix}, \\
d_2 &= \begin{bmatrix} d_i \end{bmatrix}
\end{align*}
\]

\[
f(x) = \begin{bmatrix} \frac{u_b x_2}{C x_1} - \frac{u_b}{L} \end{bmatrix}^T, \text{Buck} \\
\frac{u_b x_2}{C x_1} - \frac{x_1}{L} + \frac{u_b}{L} \end{bmatrix}^T, \text{Boost}
\]

needed to be estimated, and \( y = x_1 \) is the output of the system.

For such a nonlinear system described by (6), a NDO can be designed as

\[
\begin{align*}
\dot{\bar{w}} &= z + p(x) \\
\dot{z} &= -\bar{L}(x) g_2(x) z - \bar{L}(x) g_1(x) p(x) - \bar{L}(x) f(x) - \bar{L}(x) g_2(x) d
\end{align*}
\]

(7)

where \( \bar{w} \) is the estimation obtained by the NDO, \( z \) is an intermediate state, \( p(x) \) is the observer function, and \( \bar{L}(x) = \frac{dp(x)}{dx} = [d_i \ d_i] \) is the gain of the NDO.

According to (6) and (7), the error equation can be derived as

\[
\frac{de(t)}{dt} + \bar{L}(x) g_2(x) e(t) = 0
\]

(8)
where \( e(t) = w(t) - \bar{w}(t) \). If the gain of the NDO is chosen to satisfy \( I(x)g_e(x) > 0 \), the observer will satisfy the condition of convergence. As a result, the estimation \( \bar{w}(t) \) of the NDO can effectively fit the disturbance \( w(t) \). Also, from equation (8), it’s easy to the time constant of the NDO, which can be written as \( T = 1/I(x)g_e(x) \).

From (7), it can be known that if \( I(x)g_e(x)=0 \), the influence of the control input \( d \) can be eliminated. Considering the above convergence analysis, \( I(x)g_e(x) > 0 \) also need to be satisfied. Based on these two conditions, \( l_1<0 \), \( l_2=0 \) can be a reasonable choice for the gain of the NDO. As a result, the designed NDO for the system can be simplified as

\[
\begin{align*}
\dot{z} & = C \frac{z + l_1 u_{dc}}{C} + \frac{l_2 u_{dc}}{C} \dot{i}_u + \frac{i_u}{u_{dc}} \\
T \zeta & = z + l_1 u_{dc}
\end{align*}
\] (9)

Knowing that \( l_1<0 \), \( l_2=0 \) and \( g_e(x) = [-1/C \ 0]^T \), the time constant of the NDO can be calculated as \( T = -C/l_1 \). Therefore, we can get the relationship between the estimated disturbance current and the actual disturbance current. And it can be defined as

\[
\bar{I}_o(s) = \frac{1}{1 + T_{ob}s} i_o(s)
\] (10)

where \( T_{ob} = T = -C/l_1 \).

3.2. Feedforward function \( G_{if}(s) \)

From (10), we can know that the estimation of the NDO will lag behind the actual disturbance in the DC microgrid. This lag may cause an impact on the DC bus voltage when the disturbance current is large. In order to enhance the dynamic performance of the controller, the feedforward function \( G_{if}(s) \) needs to be considered and designed.

After adopting the improved droop control, the DC bus voltage response can be described by

\[
u_{dc}(s) = \frac{G_{ap}(s)G_{pi}(s)k}{sC + G_{ap}(s)G_{pi}(s)k} U_{dc}(s) - \frac{1}{sC + G_{ap}(s)G_{pi}(s)k} i_o(s) + \frac{kG_{ap}(s)G_{if}(s)}{sC + G_{ap}(s)G_{pi}(s)k} \bar{I}(s)
\] (11)

where \( r \) is the gain of droop control, \( G_{ap}(s) \) and \( G_{pi}(s) = \frac{U_{in}(k_p s + k_i)}{Ls^2 + k_p U_{in} s + k_i U_{dc}} \) are the commonly used control function for the voltage and current respectively.

From equation (11), we can know if the equation (12) is satisfied, the influence of the equivalent load current on the DC bus voltage can be eliminated.

\[
\frac{1}{sC + G_{ap}(s)G_{pi}(s)k} i_o(s) = \frac{kG_{ap}(s)G_{if}(s)}{sC + G_{ap}(s)G_{pi}(s)k} \bar{I}(s)
\] (12)

Then substitute (10) into (12), \( G_{if}(s) \) can be written as

\[
G_{if}(s) = \frac{1 + T_{ob}s}{G_{ap}(s)k} = \frac{1}{k} \left( 1 + T_{ob}s \right) \left[ \frac{Ls^2}{U_{dc}(k_p s + k_i)} \right]
\] (13)

Let \( G_{i}(s) = \frac{Ls^2}{U_{dc}(k_p s + k_i)} \), since the corner frequency of this transfer function is much lower than the rate of the disturbance current, \( G_{i}(s) \) can be simplified as
Substituting equation (14) into (13), it’s easy to obtain

\[ G_{li}(s) = \frac{-Ls}{U_{dc}(k_p s + k_i)} \approx \frac{L}{U_{dc} k_p} \]

After simple calculation, we can judge that the quadratic order term is far less than the primary term in \( G_{li}(s) \). Therefore, equation (15) can be further simplified as

\[ G_{li}(s) \approx \frac{-C/l_i + L/(U_{dc} k_p)}{k} s + 1 \]

To conclude, the finally obtained feedforward function \( G_{li}(s) \) of the system is a linear function.

4. Simulation results

The failure operation of the DC microgrid is simulated to verify the effectiveness of the fault ride-through scheme. In this paper, the simulation of the system is divided into two parts: the battery storage does not participate in the voltage control and it participates in the voltage control. In Table 1, main parameters for the microgrid simulation are listed.

| Parameter       | Description                  | Value   |
|-----------------|------------------------------|---------|
| \( P_{PET \, nom} \) | Nominal capacity of the PET | 1MW     |
| \( P_{bat \, nom} \) | Nominal capacity of the battery | 450 kWh |
| \( P_{PV \, nom} \) | Nominal power of the PV | 500kW   |
| \( U_{dc \, nom} \) | Nominal value of DC bus voltage | 750V   |
| \( C \)            | Capacitance of DC bus       | 6000µF  |
| \( L \)            | Inductor in battery storage unit | 0.5mH  |
| \( l_i \)          | Gain of the NDO             | -2      |

4.1. DC fault simulation without battery storage

At 1.5s, a short circuit fault occurs at the branch near the DC load, and the fault is removed after 10ms. The simulation results of the system are shown in Figure 4.

**Figure 4.** Simulation results when battery storage is not used for voltage control.

Figure 4(a) shows that when a short-circuit fault occurs at 1.5s, the voltage at the DC bus drops from 750V to about 630V. When the DC short-circuit fault is removed at 1.51s, the DC bus voltage begins to recover under the control of the PET. However, due to the slow response of the voltage control of the PET, the time required for the DC bus voltage to recover to the rated value is about 530ms. Such a transient process makes a challenge to the continuous grid-connected operation of
photovoltaics. It can be seen from Figure 4(b) that the fluctuation process of the DC load current is also longer due to the DC bus voltage change, which is also disadvantageous for load operation with power quality requirements. Therefore, it is necessary to further add battery control to improve the transient performance and enhance the operation reliability.

4.2. DC fault simulation with battery storage

Under the same fault as in section 4.1, the simulation result under the effect of improved battery storage control is shown in Figure 5.

Figure 5(a) shows that when the fault occurs at 1.5s, the voltage at the DC bus drops to about 670V, which is about 40V less than the voltage drop without battery storage control. When the fault is removed, the DC bus voltage begins to recover under the common control of the PET and the battery storage. Its recovery time is about 340ms, which is 190ms less than when there is no battery storage control. Figure 5(b) shows that after adding the battery storage control, the transient process of the DC load current changes from 580ms to less than 380ms. Figure 5(c) shows that the battery storage can quickly respond to changes in the DC bus voltage, increase the output current, and provide power support for the DC microgrid when the voltage drops. In summary, the improved control of the battery storage can not only effectively suppress the voltage drop during faults, but also speed up the transient response of the DC voltage and reduce the recovery time.

![Simulation results when battery storage is used for voltage control.](image)

5. Conclusions

This paper determines the structure of the DC microgrid with high-proportion renewable generation, and establishes the mathematical model of the DC microgrid. When the short-fault occurs at the DC...
branch of the DC microgrid, a fault ride-through scheme based on battery storage unit is proposed. Based on NDO, a feedforward term is introduced to improve the control ability of the battery storage. The fault ride-through scheme based on the battery storage can effectively reduce the DC bus voltage drop during the failure, shorten the DC bus voltage recovery time, and realize the fault ride-through of the DC microgrid. In the future, transient performance of the DC fault ride-through need to be explored under more conditions, which will be helpful to the reliable operation of the grid with large-scale renewable generation.

Acknowledgements

This work is supported by technical project of the State Grid Corporation of China(5204XQ20000F).

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