Stability analysis of DC microgrid considering the action characteristics of relay protection

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Abstract. The stability of microgrid is the key issue of microgrid operation control. This paper focuses on the transient stability after the correct operation of relay protection. In this paper, 400V DC microgrid with photovoltaic and energy storage system is taken as the research object. Research on the fault characteristics of voltage and current after the system is subjected to short-circuit, it is proposed to introduce current differential protection. With bus voltage as the only indicator, whether the transient stability is improved after the protection system operates correctly. The DC microgrid is modeled and simulated based on MATLAB/Simulink to confirm the validity of the proposed statement. The simulation results show that the fault can be correctly located, accurately isolated and timely removed by the protection system after the short-circuit fault occurs, bus voltage is restored to maintain stable operation of the system.

1. Introduction
With the international energy crisis and the increasingly intensified environment, DG (Distribution Generation) based on renewable energy, can greatly alleviate the pressure of environment and energy, which has attracted attention at home and abroad, and has made rapid progress. However, due to the randomness and uncontrollability of distributed generation, microgrid technology has emerged. It is a small power generation, distribution and utilization system which is composed of distributed generation, energy storage system, energy conversion device, monitoring and protection device, load and so on [1]. It can be divided into DC microgrid, AC microgrid and AC/DC hybrid microgrid. The existing research mainly focuses on the AC microgrids. In the current era, DC loads such as electric vehicles and information equipment in urban distribution networks are increasing rapidly. Compared with the AC microgrid, the DC microgrid has the characteristics of high conversion efficiency, small line loss. Therefore, as a way of networking with higher operation efficiency, lower comprehensive cost and less space, DC microgrid has been paid more and more attention.

Since there is no reactive power flow in the DC microgrid, the DC bus voltage is the only indicator to measure the safe and stable operation of the DC microgrid [2]. By controlling the voltage stability in the DC microgrid, the stable operation of microgrid can be controlled. If the dc bus voltage is unstable, the steady operation of load will be threatened, even lead to the false tripping of protection system, and even affect the normal operation of power network in serious cases [3]. The stability of DC microgrid includes static stability and transient stability. In recent years, the static stability problem of microgrid has been extensively studied [4]. However, in contrast with static stability of the microgrid, the research on transient stability of the microgrid is still limited. Static stability analysis methods include eigenvalue analysis based on state space equation and impedance analysis based on impedance model. In [5], based on the stability problem of DC microgrid, the average model of various converter
and their control systems in DC microgrid is established by state space method, which is linearized at the equilibrium point, and static stability analysis of the DC microgrid is performed on this basis. By establishing small signal model, the stability of DC microgrid is analysed using Middlebrook impedance ratio criterion [6] in [7]. Transient stability analysis methods are mainly divided into the time domain simulation and Lyapunov direct method. Based on the Popov absolute stability criterion [8-9], the dissipative system theory [10] and other methods based on Lyapunov energy function, it has been studied in the transient stability analysis of microgrid.

At present, there is no research on whether the correct action of the protection strategy can improve the transient stability of the microgrid when internal faults occur in the system. In this paper, the DC microgrid is taken as the research object. The DC microgrid shown in figure 1 is built in MATLAB/Simulink to analyse the fault characteristics of the system when a short-circuit fault occurs. When the protection is correct, the influence of the system transient stability is analysed, and the correctness of the conclusion is verified by MATLAB/Simulink simulation.

2. Characteristics of short-circuit fault

2.1 Fault types of DC microgrid

According to the faults location, the faults of the DC microgrid can be divided into two types: bus faults and feeder faults; according to the type, it is divided into pole to pole faults(mainly short-circuit) and single pole to ground faults, among them, the bus pole to pole faults are the most harmful. Therefore, the busbar protection should be the highest level of the protection scheme [11]. In the event of a feeder fault, it is only necessary to disconnect the faulty line from the microgrid. This paper mainly studies the case of pole to pole short-circuit faults.

2.2 Pole to pole faults characteristics analysis

2.2.1 Bus faults. As shown in figure 1, photovoltaic is used as the main distributed generation, which is connected to the bus through DC/DC line. There are two types of bus fault F1 and feeder fault F2. Fault F1 will affect all sources and loads connected to the bus. Since the sources are connected in parallel, they can be treated separately. Taking the energy storage system as an example, the battery

![Figure 1. DC microgrid with PV and battery](image-url)
can be connected to the DC bus through a cable. When a bus bipolar short-circuit fault occurs, the equivalent fault diagram is shown in figure 2:

![Figure 2. Equivalent circuit for bus fault](image)

Part of the fault current is provided by the battery $U_{batt}$, and part of it comes from the rapid discharge of the capacitor. The total impedance of the energy storage system is the sum of the internal battery impedance ($R_{batt}$ and $L_{batt}$) and the cable impedance ($R_L$ and $L_L$) (the cable capacitance can be ignored during pole to pole short-circuit fault) [12], so the fault current provided by the battery can be calculated as:

$$i_b(t) = \frac{U_{batt}}{R_{batt} + R_L} [1 - \exp(-\frac{t}{\tau_{batt}})]$$  \hspace{1cm} (1)

Where $\tau_{batt} = \frac{L_{batt}}{R_{batt} + R_L}$, the design of the battery determines how long it can supply a short-circuit current without causing internal damage [13]. The DC/DC converter is directly connected to the bus and, hence, has a low impedance, mainly consisting of the series impedance of the capacitors $R_c$ and $L_c$, where the latter can be neglected. Fault F1 will cause the capacitors to discharge, which results in a current with high amplitude and low rise time, but with limited duration. The capacitor fault current can be calculated as:

$$i_c(t) = \frac{U_{dc}}{R_{eq}} \exp\left(-\frac{t}{\tau_c}\right)$$  \hspace{1cm} (2)

Where $R_{eq} = 2R_c, C_{eq} = 2C_c, \tau_c = C_{eq}U_{dc}R_{eq}$ is the DC bus voltage. When the bus has a bipolar short-circuit fault, the fault current $i_f(t)$ comes from the above two parts:

$$i_f(t) = K_Ai_b(t) + i_c(t)$$  \hspace{1cm} (3)

Because of the current limiting effect of the circuit control module in the energy storage system, the current limiting coefficient $K_A$[14] is introduced. $K_A$ depends on the voltage level of the DC microgrid and the equivalent resistance of the fault feeder, with a value of 0.01 $\sim$ 0.02. Therefore, the short-circuit current provided by the battery can be ignored. So $i_f(t)$ can be calculated as:

$$i_f(t) \approx i_c(t) = \frac{U_{dc}}{R_{eq}} \exp\left(-\frac{t}{\tau_c}\right)$$  \hspace{1cm} (4)

2.2.2 Feeder faults. When a bipolar short-circuit fault occurs on the DC microgrid feeder, the fault F2 and distributed generation form a new low impedance circuit. Taking AC/DC converter in
grid-connected power supply for example, the system will go through three stages in a short time after the fault occurs.

The first stage is the capacitor discharge phase, at which time the system is equivalent to an RLC second-order circuit, the equivalent circuit diagram is shown in figure 3. The converter is blocked at the moment of short-circuit fault, the DC capacitor is discharged to the fault point quickly, the fault current rises rapidly, and the fault voltage drops to 0 quickly. The discharge current of the DC capacitor is much larger than the AC side of the large power network, so the AC current is ignored at this time. Available from Kirchhoff's law:

\[
\begin{align*}
    u_c &= L \frac{di}{dt} + Ri_L \\
    \frac{du_{dc}}{dt} &= -\frac{1}{C} i_L
\end{align*}
\]

Finishing is available:

\[
LC \frac{d^2 u_{dc}}{dt^2} + RC \frac{du_{dc}}{dt} + u_{dc} = 0
\]

Where \( u_{dc} \) is the DC capacitor voltage, considering that the short-circuit in the system is mostly metallic short-circuit fault and the transition resistance is small. So the capacitor discharge process is an underdamped oscillation process, that is, \( R < \frac{L}{\sqrt{C}} \). It is assumed that the pole to pole short-circuit fault occurs at the time of \( t_0 \), the initial condition is \( u_{dc}(t_0) = U_0, i_L(t_0) = I_0 \). Because the circuit oscillates and discharges, the second-order RLC circuit will have an oscillating fault current with the following values:

\[
i_L(t) = \frac{U_0}{\omega L} e^{-\frac{\delta t}{L}} \sin(\omega t)
\]

The second stage is the diode freewheeling phase. When the DC capacitor voltage is reduced to 0, the inductor is discharged, and the fault current continuously flows through the inverse parallel diode, the circuit is equivalent to the first-order circuit.

The third stage is the uncontrolled rectification phase. Due to the conduction of the freewheeling diode, the fault current exhibits an uncontrolled rectification characteristic, so that the short-circuit current cannot be naturally attenuated.

3. Protection system design

The traditional protection methods mainly include: three-stage overcurrent protection, distance protection and differential protection. Due to the small capacity of the DC microgrid and the short transmission line, the three-stage overcurrent protection is based on overcurrent protection, however, in instantaneous overcurrent protection, the short line below 25km may have no protection range. Therefore, the choice of three-stage overcurrent protection does not meet the selectivity and fastness of protection; distributed generation in microgrid will increase the uncertainty of internal power flow in microgrid due to its uncertain output. Therefore, the use of directional components may lead to protection false or failure to trip. Based on the above aspects and fault characteristics, the current differential protection is selected as the main protection of the DC microgrid. Its selectivity is guaranteed according to Kirchhoff’s current law, that is, the sum of the currents leading to the fault point is equal to zero. It is suitable for DC microgrid with small capacity and short line.

The principle of line current differential protection of DC microgrid system is as follows: the direction from the bus to the protected line is positive. When the system is running normally or an external fault occurs, the current input to the DC bus is equal to the output current, and the differential current is equal to zero; when a DC bus internal short-circuit fault occurs, the input current and the output current are not equal, and can reach tens or even dozens of the setting value of the differential protection. The magnitude of the input current and the output current are detected, the absolute value of the sum is compared with the protection setting current. If it is greater than the current setting value, it can be determined that an internal short-circuit fault occurs, and the protection at both ends sends the permission signal to the opposite. So that the protection device is tripped and the fault line is cut off.

Define the differential current \( I_{diff} \) as:

\[
I_{diff} = -\sum_{i=1}^{n} I_i
\]
Where \( n \) is the number of lines connected to the bus, and \( I_i \) is the current flowing through the article line.

The current differential protection criterion is:

\[
I_{\text{diff}} = | - \sum_{i=1}^{n} |I_i| > I_{\text{set}}
\]  

(9)

The setting principle is to avoid the sum of the absolute values of the maximum measurement errors of the measuring components in normal and external faults.

As mentioned above, current differential protection is a fast protection principle with absolute selectivity, and the short-circuit current of the bus short-circuit fault is generally much larger than the differential current setting value, so the sensitivity is higher.

Another characteristic of the short-circuit fault is that the bus voltage is reduced, and under-voltage protection can be used. However, since the voltage drops sharply of short-circuit, even drops to 0, if the under-voltage protection is used as the main protection, there may be an action dead zone. So under voltage protection can be used as backup protection. When the current differential protection is failure to trip, the under voltage protection can be operated to ensure the damage of the peak current to the power electronic components.

4. Stability and simulation analysis

4.1 DC bus voltage stability

It is unlikely to traditional AC systems, traditional AC power is mainly generated by synchronous generators, and its stability is a problem in which synchronized synchronous generators are kept in sync. For DC systems, the power balance of the system is guaranteed, and the DC microgrid is kept stable. So the voltage becomes the only indicator reflecting the power balance of the system. The voltage stability of a DC microgrid can be defined as the ability to maintain the DC bus voltage within a certain range (voltage fluctuations do not exceed ±5% of the rated value) when the system is disturbed [15]. When the DC microgrid is suffered to large disturbances, if the DC microgrid is oscillated to transition to a new steady state operation, the microgrid system is considered to be transiently stable; if the difference between the DC bus voltage and the original rated value or the steady-state value increases and diverges, the microgrid system is considered to be transient unstable.

In this paper, the fault characteristics of the voltage and current when the system is subjected to the bipolar short-circuit faults are analysed. After the current differential protection, if the protection is correctly operated, the voltage is restored to a stable state. Then it can be considered that the addition of the protection system can restore the unstable DC microgrid to a stable state, and the indicator of restoring stability is that the bus voltage is restored to its original value after being disturbed.

4.2 Analysis of bipolar short-circuit faults in different positions

It is constructed the simulation model of DC microgrid with photovoltaic and battery that based on the MATLAB/Simulink simulation software as shown in figure1. Where the line resistance is 0.1Ω/km, the line capacitance is 0.2mH/km, the line inductance is 0.23μF/km, the filter capacitance is 30mF, the bus voltage is 400V and the bus length is 0.6km.

The following simulation is made for the pole to pole short-circuit fault of bus and feeder. The simulation time is 3s, and figure4 is the bus voltage and current in normal operation.
The bipolar short-circuit fault is set when the simulation time is 1s, and the bus and feeder voltage and current are as shown in the following figure 5:

![Voltage and current during bus and feeder faults](image)

(a) Bus voltage during bus fault  
(b) Current during bus fault  
(c) Voltage during feeder fault  
(d) Current during feeder fault

**Figure 5.** Voltage and current during bus and feeder faults

It can be seen from the above waveform diagram that the amount of change in the fault voltage and current is different when the fault is at different positions, and the change of voltage and current is greater when the bus fault. When the fault occurs on the bus, the bus fault voltage drops rapidly to 0, and then stabilizes at 200V, the current rises sharply, reaching tens or even dozens of times before the fault; the feeder fault will be recovered after 0.5s, and the fault current is several times the current before the fault. It can be seen that the bipolar short-circuit occurring on the bus has a greater influence on the system, which verifies that the protection of the bus mentioned above is the highest level of the protection scheme.

### 4.3 System operating characteristics when adding current differential protection

Figure 6 shows the current at both ends of the DC line before and after the external fault and the internal fault. It can be seen from the figure that before and after the external fault, the current values at both ends of the line are equivalent reversed, which satisfies the above-mentioned: In the specified positive direction, when the DC line has an external fault, the differential current is 0. When the internal fault occurs, the current is in the same direction in the specified positive direction.

![Terminal currents during external fault and internal fault](image)

(a) Terminal currents during external fault  
(b) Terminal currents during internal fault

**Figure 6.** currents across the line during short-circuit fault

Figure 7 shows the differential current internal fault. The differential current setting $I_{set}$ in the protection control module can be set to 1200A. It can be seen from the simulation diagram that the differential current can reach the set value when the fault occurs for 6ms. The DC breaker in the simulation has a 2ms error in the action delay. Therefore, after 8ms of the fault occurs, the circuit breakers at both ends act and the fault circuit is cut off.
Figure 7. Differential current during internal short-circuit fault

Figure 8 shows that after the protection system is operating correctly, the circuit breaker cuts off the line at 8ms. Compared with the waveform diagram of the short-circuit fault voltage of the bus in figure 5(a), it can be seen that the low voltage phenomenon disappears, and the bus voltage is restored to the original 400V after a period of fluctuation. It meets the requirements of voltage stability and ensures the stable operation of the system. The correctness of the conclusion is verified.

Figure 8. Bus voltage with protection

5. Conclusion

In this paper, research on the fault characteristics of the DC microgrid voltage and current after bipolar short-circuit fault. On this basis, current differential protection is added as main protection and under voltage protection as backup protection. In the DC microgrid, since the flow of reactive power is not considered in the system, the voltage becomes the only indicator reflecting the power balance of the system. By controlling the voltage stability of the DC microgrid, it is possible to control the stable operation of the microgrid. Therefore, the correct action of the relay protection is used to judge the stability of the system, and the bus voltage is used as an indicator to determine whether the system can recover after the internal short-circuit fault. The simulation verification and analysis are carried out in MATLAB/Simulink. It is concluded that the correct action of relay protection can restore the system in a short time and has important application value for the stable operation of DC microgrid.

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