International Journal of Electric Power and Energy Studies
ISSN: 3006-2004 (Print), ISSN: 3006-0826 (Online) | Volume 4, Number 2, Year 2025
DOI: https://doi.org/10.62051/ijepes.v4n2.02
Journal homepage: https://wepub.org/index.php/IJEPES/index

Theoretical Research on Fault Transient Analysis of AC-DC Hybrid Distribution Networks

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ABSTRACT

After a large number of distributed power sources are connected to the traditional distribution network, it faces problems such as unstable voltage, uneven current load, and large power fluctuations, which directly affect the stability and reliability of the system. In order to effectively address these issues, both academia and industry have proposed the concept of hybrid AC/DC power distribution networks. The AC/DC hybrid distribution network combines the advantages of AC/DC transmission to achieve more efficient energy transmission and more flexible power flow regulation, thereby improving the stability and reliability of the power grid. Due to the high inrush and fast transmission characteristics of DC fault currents in hybrid AC/DC distribution networks, the need for protection is urgent. Therefore, it is essential to analyze the fault characteristics of a hybrid AC/DC distribution network. Taking the four-terminal flexible DC hybrid distribution network as the research object, the fault characteristics and their influences at each stage are analyzed.

KEYWORDS

AC/DC Hybrid Distribution Network; Fault Characteristic Analysis; Equivalent Modeling.

1. INTRODUCTION

With the development of power systems, a large number of distributed generations (DG) have been integrated into traditional distribution networks, bringing a series of issues to these networks. Firstly, the uncontrollability and intermittency of DG can lead to increased instability and imbalance in the power grid, affecting its safe operation. Secondly, the operational model of traditional distribution networks cannot effectively adapt to the large-scale integration of DG, which may lead to uncontrolled parameters such as voltage and frequency. Additionally, the integration of DG may cause overload and overvoltage problems in the distribution network, worsening the aging and damage of grid equipment. In response to these issues, academia and industry have proposed the concept of mixed AC/DC distribution networks. As a new type of power distribution system, mixed AC/DC distribution networks have attracted significant attention and play an important role in meeting energy demand growth, renewable energy applications, and the efficient operation of power systems.

In the area of fault equivalent modeling, the focus is mainly on establishing fault equivalent circuit models that take into account the control characteristics of converters, as well as researching fault current calculation methods under different types of faults. In terms of fault transient characteristic analysis, the main attention is given to the rise rate, peak value, and decay characteristics of fault current, as well as the impact of faults on system voltage and power. However, existing research still has some shortcomings, such as insufficient depth in the study of equivalent models under complex fault scenarios, inadequate consideration of coupling levels, and a lack of comprehensive analysis of factors influencing fault transient characteristics.This paper addresses the above issues by conducting theoretical research on the transient analysis of AC/DC hybrid faults. It establishes a fault equivalent model that considers the control characteristics of converters and system parameters.

2. FAULT ANALYSIS OF AC/DC HYBRID DISTRIBUTION NETWORKS

2.1. Analysis of Unipolar Grounded Short-circuit Faults

Positive ground short circuit is one of the common types of faults in power systems, and the fault principle and characteristics are basically the same as those of negative ground short circuit[1]. Therefore, taking the positive ground short circuit as an example, the impact and countermeasures of the unipolar ground short circuit fault are analyzed in depth, and the equivalent circuit is refer with: Figure 1.

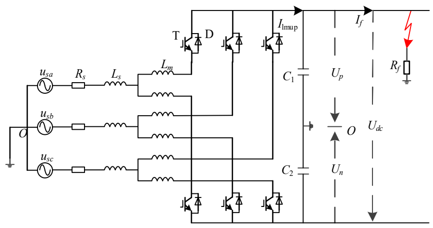

Figure 1. Equivalent circuit of a positive short-circuit to ground

In Figure 1 the u_{sa}, u_{sb}, u_{sc} are the AC side three-phase voltages. R_s and L_s are AC side phase resistance and phase inductance, respectively; U_p and U_n are the voltage of the positive and negative bus to the ground, respectively;L_m is VSC bridge arm reactor; R_f is the ground resistance; C_1 and C_2 are DC bus regulator capacitors, and C_1=C_2=C.

After the fault occurs, the positive and negative voltages of the bus on the DC side of VSC are as follows:

$$U_p = I_f R_f \, . \tag{1}$$

$$U_n = -U_{dc} + I_f R_f \, . \tag{2}$$

Where U_{dc} and I_f are the voltage and fault current between the poles on the DC side of VSC.

In the initial stage of the fault, the fault path causes the system to have a short-circuit current to ground, which changes the voltage and current distribution of the system. Due to the presence of a ground fault point, the current can rise rapidly and magnitude enormously, potentially causing damage to system equipment and devices[2]. The current on the IGBT connected to the grounding point increases dramatically, and the VSC quickly locks the IGBT according to its own protection mechanism to prevent the current from expanding abnormally further. The equivalent circuit of the VSC and DAB inverter after locking is refer with: Figure 2and Figure 3.

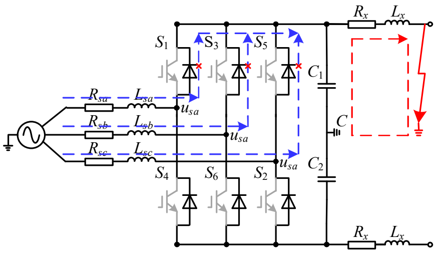

Figure 2. Positive pole ground fault VSC equivalent circuit

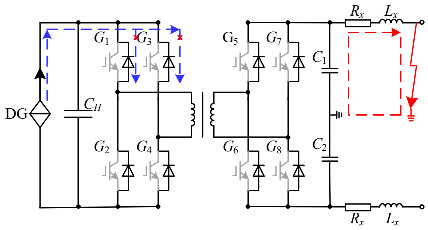

Figure 3. Positive pole ground fault DAB converter equivalent circuit

As can be seen from Figure 2 and Figure 3, after the converter is locked, the feed current is cut off, and the fault current mainly comes from the discharge of the regulated capacitor, and the fault equivalent loop is shown in Figure 4.

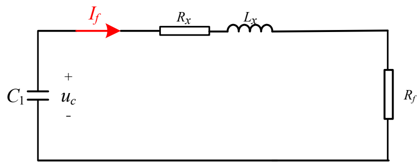

Figure 4. Faulted DC capacitor fault during the discharge phase of the positive electrode to ground

The discharge process of capacitor C_1 can be described as:

$$L_x C_1 \frac{d^2 u_c}{dt^2} + R_1 C_1 \frac{du_c}{dt} + u_c = 0 \tag{3}$$

2.2. Analysis of Extremely Short Circuit Faults

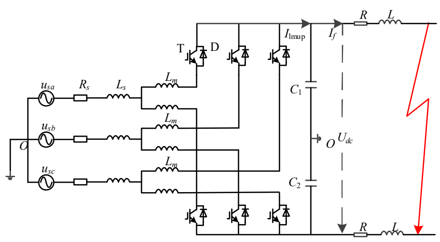

Figure 5. Equivalent circuit diagram of the interpole short-circuit fault of a DC line

Inter-pole short-circuit faults are the most serious fault scenarios in DC power grids, occurring between two electrodes in a circuit, resulting in large currents in the circuit, causing voltage instability and circuit damage[3]. When a short circuit between the positive and negative poles occurs in a DC line, the equivalent circuit is refer with: Figure 5.

After the occurrence of inter-pole short-circuit faults, various power electronic devices in the system play different roles, resulting in the change of current and voltage showing obvious phased characteristics in time, that is, three stages: regulated capacitor discharge, diode freewheeling and steady state[4].

Regulated capacitor discharge stage,The capacitor on the DC side instantly releases a large amount of electric energy, releases the stored electrical energy to the fault point, the capacitor voltage drops sharply, and the fault current of the DC line rises rapidly[5]. The fault equivalent circuit is refer with: Figure 6.

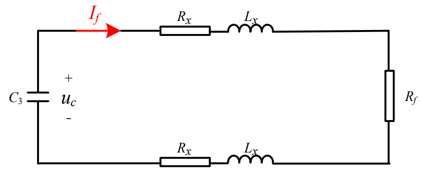

Figure 6. Equivalent circuit of DC capacitor during discharge phase due to interpole short-circuit fault

The fault current expression is:

$$\frac{d^2 I_f(t)}{dt} + \frac{R}{L}\frac{dI_f(t)}{dt} + \frac{I_f(t)}{LC_3} = 0 \tag{4}$$

Diode freewheeling stage,After the capacitor discharge on the current side is completed, the inter-pole short circuit fault enters the diode freewheeling stage. The DC bus voltage drops to 0V, the VSC diode is turned on, and the AC side is equivalent to a three-phase short-circuit fault[6]. The diode is subjected to high currents and continues to turn on, so that the fault current is not interrupted. The fault equivalent circuit is refer with: Figure 7.

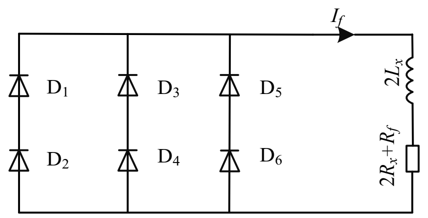

Figure 7. Diode freewheeling equivalent circuit

Steady-state phase,When the DC distribution line is in a steady state, the current is maintained at a relatively stable level[7]. Although the fault persists, the system continues to operate normally, is refer with: Figure 8.

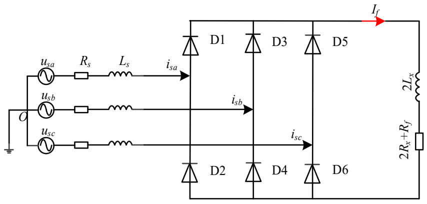

Figure 8. Equivalent circuit diagram in the steady-state phase

3. SUMMARY

To sum up, the three stages of inter-pole short-circuit faults are summarized. Voltage regulator capacitor discharge stage: when the inter-pole short-circuit fault occurs, the DC side capacitor quickly releases its stored charge, generating a large current with a short duration; Diode freewheeling stage: After the capacitor discharge is over, the VSC diode starts freewheeling to limit the direction of the current and prevent excessive current from damaging other devices. Steady-state stage: When the free current of the diode ends, the fault line enters a steady state, and the current and voltage will reach a relatively stable state. Each component of the system is stabilized according to its characteristics until the fault is troubleshot or other measures are taken.The transient process in the initial stage of the positive ground fault is an overdamping process. Due to the capacitor discharge on the DC side, the fault current flowing through the VSC upper arm increases, and the energy stored by the capacitor decreases. When the capacitor discharge is finished, the circuit begins to enter the steady-state phase, in which the system can operate normally for a short time.

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