A Method of Detecting Commutation Failure in Multi-infeed HVDC Systems Based on Critical Failure Impedance Boundary

Guoqing Li, Song Zhang, Tao Jiang, Houhe Chen, Xue Li
Department of Electrical Engineering
Northeast Electric Power University
Jilin, JL, 132012 China
{lgq; tjiang; szhang; chenhouhe; xli}@nedu.edu.cn

***Abstract*—A fast distinguish method to discriminate the critical commutation failure region of multi-infeed HVDC system is proposed in this paper. Based on the nodal impedance matrix and nodal voltage interaction factor (VIF), the extinction angles of convert stations under the single-phase or three-phase to ground fault happening at any bus in AC system is first calculated. If the calculated extinction angle with regard to a certain bus is greater than the critical extinction angle, the single-phase or three-phase to ground fault at that bus will cause commutation failure of the HVDC system. The critical failure impedance boundaries on topology diagram can be therefore delimited by examining every bus in the AC system. The simulation results of a two-infeed HVDC test system verifies the effectiveness and accuracy of the proposed method which detects the commutation failure of multi-infeed HVDC system based on critical failure impedance boundaries.**

***Index Terms*-- Commutation failure, critical failure impedance boundary, effective short circuit ratio, extinction angle, multi-infeed HVDC system.**

I. INTRODUCTION

In multi-infeed HVDC systems, AC system failure may cause the commutation failure at the convert station near the fault location, or even the commutation failure of the multi-DC transmission lines at the same time or in succession. If commutation function is not recovered timely, disastrous consequence of wide-range power outage will arise, and the secure and stable operation of the power grid would be threatened. However, not all of the AC system faults can trigger commutation failure of DC system. With the fast construction and deployment of DC transmission systems, it is important to establish an accurate and fast scheme to detect commutation failure, reduce or avoid simultaneous commutation fault of multi-DC transmission system

A great deal of research and operation experience have proved that when there is a fault in the AC system, the decrease of the extinction angle of the inverter is the primary cause of commutation failure of converter valve group [1-3]. Literature [4] proposes a method of detecting commutation failure of multi-infeed HVDC system based on critical multi-infeed interaction factor. This approach detects the commutation failure of HVDC system when three-phase faults happen on other DC commutation buses. However, it cannot detect commutation failure caused by faults at the non-commutation bus. Literature [5] raises the conception of critical fault impedance boundary on the basis of nodal impedance matrix, with which the area of AC system buses where faults can cause DC commutation failure is identified quickly. However, critical fault impedance boundary of commutation failure with regard to. unsymmetrical fault in the AC system is not analyzed.

This work derives the mathematical equation to calculate the extinction angle of the inverter at the moment of AC system faults by exploring the relation between the extinction angle and the nodal impedance matrix. Using the critical extinction angle as criterion, it is able to respectively identify the critical fault impedance boundary of multi-infeed DC system on the topological graph of network structure when three-phase short circuit ground fault or single-phase short circuit ground fault occur to AC system. The short circuit fault at the node lying within the critical fault impedance boundary is more likely to cause the commutation failure of DC system while the fault at the node outside the boundary will not cause commutation failure. The proposed method is able to quickly identify the critical fault impedance boundary and therefore graphically identify the AC system area where faults can cause the commutation failure of DC system.

II. COMMUTATION FAILURE CRITERIA

A. *Commutation Failure Mechanism*

After the end of commutation process, if the converter valve which has just quitted current conduction fails to restore interdicting ability in a period, when the voltage added on the converter valve is positive, the current conducts again. At this situation, the internal short circuit occurs in the converter, this is called commutation failure. In multi-infeed AC/DC

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systems, AC system disturbance is the main cause of DC commutation failure [6]. If only AC system faults are considered, commutation bus voltage drop is the major cause of commutation failure and the essential reason is that the extinction angle is smaller than the inherent limit extinction angle of the valve.

In power system analysis, to the question of commutation failure, we should not only investigate its mechanism, the method that can quickly and accurately judge whether it is happened is also of importance. Morerover, to the multi-infeed HVDC system, we should pay attention to whether more than one subsystem has commutation failure.

B. Three-phase Short Circuit Fault Commutation Failure Criterion

Multi-infeed interaction factor (MIIF) is an indicator of the strength of interaction between converter stations in multi-infeed HVDC transmission system [7-8]. Multi-infeed interaction factor $MIIF_{ji}$ is defined by (1) and is essentially the voltage drop ratio at Bus *j* following a 1% voltage reduction at the AC busbar of converter *i* caused by a three-phase balanced inductive fault

$$M_{IIFji}=\frac{\Delta U_j}{1\% U_{i0}}=\left|\frac{Z_{ij}}{Z_{ii}}\right| \tag{1}$$

where U_{i0} is the RMS value of the line voltage of Bus *i* before the fault, and ΔU_j is the voltage drop of Bus *j*. Similar to the definition of MIIF, voltage interaction factor (VIF), VIF_{ji}, is defined as the voltage change rate of converter Bus j following a 1% voltage reduction at the Bus i of the AC system caused by a three-phase balanced inductive fault.

$$V_{IFji}=\frac{\Delta U_j}{1\% U_{i0}}=\left|\frac{Z_{ij}}{Z_{ii}}\right| \tag{2}$$

where Z_{ii} is the auto-impedance of Bus *i*, Z_{ij} is the mutual impedance between Bus *i* and converter Bus *j*, and U_{i0} and ΔU_j have the same meaning as in (1).

When three-phase to ground metallic short circuit fault occurs at commutation Bus *i*, bus voltage U_{i0} drops to 0, and the voltage drop of converter Bus *j* is

$$\Delta U_j = V_{IFji} U_{i0}\frac{U_{jN}}{U_{iN}} \tag{3}$$

where U_{iN} and U_{jN} are the rated voltages of Bus *i* and Bus *j* respectively.

Thus, the voltage of converter Bus j is

$$U_j = U_{j0}-\Delta U_j = U_{j0}-V_{IFji}U_{i0}\frac{U_{jN}}{U_{iN}} \tag{4}$$

When the system is symmetric, the inverter extinction angle [9] can be expressed as in (5).

$$\gamma=\arccos\left(\frac{\sqrt{2}nI_d X_L}{U_L}+\cos\beta\right) \tag{5}$$

where *n* indicates the transformer tap ratio, I_d is the DC current, X_L is commutation reactance, U_L is the RMS value of the line voltage of the converter bus, and β is the advance trigger angle.

Substitute (4) into (5), the extinction angle of inverter *j* can be expressed as

$$\gamma_j=\arccos\left[\frac{\sqrt{2}n_j I_d X_{Lj}}{U_{j0}-V_{IFji}U_{i0}\frac{U_{jN}}{U_{iN}}}+\cos\beta_j\right] \tag{6}$$

For simplicity, two assumptions are made in this paper: 1) the AC voltages of the converter buses are perfect sinusoid, i.e. the harmonics are filtered; 2) reactance of the AC system is negligible. Under these two assumptions, the commutation reactance is approximately the short-circuit reactance of the converter transformer and can be expressed as follows.

$$X_{Lj}=\left(X_{Kj}\%\right)\frac{U_{jN}/\left(\sqrt{3}n_j\right)}{\sqrt{2}I_{dj}/\sqrt{3}}=\left(X_{Kj}\%\right)\frac{U_{jN}}{\sqrt{2}n_j I_{dj}} \tag{7}$$

Substitute (7) into (6), the extinction angle of inverter *j* when three-phase to ground short-circuit fault happens at commutation node *i* is

$$\gamma_j=\arccos\left[\frac{(X_{kj\%})U_{jN}}{U_{j0}-\frac{Z_{ij}}{Z_{ii}}U_{i0}\frac{U_{jN}}{U_{iN}}}+\cos\beta_j\right] \tag{8}$$

γ_{min} is the minimum extinction angle of the converter. The deionized response time of high power thyristor is around 400μs. If series element error is considered, the corresponding extinction angle $\gamma_{min} = 10°$. When three-phase to ground metallic short-circuit fault happens at commutation node i, commutation failure will happen at converter j when $\gamma_j \leq \gamma_{min}$. This serves as a criterion for detecting the three-phase short circuit fault commutation failure.

C. Single-phase Short-circuit Fault Commutation Failure Criterion

When asymmetric faults occur in the AC system, the magnitudes and angles of the commutation voltages will be changed and the extinction angles between converter valves of the inverter will be further affected, which could trigger DC system commutation failure. The criterion for commutation failure caused by single-phase short-circuit fault can be analyzed in a similar way as that for three-phase fault.

When phase *A* to ground fault happens at Bus *j*, according to symmetrical component method, the three-phase voltage of converter Bus *i* is

$$\begin{cases}\dot{U}_{ia}=\dot{U}_{i(1)}+\dot{U}_{i(2)}+\dot{U}_{i(0)}\\ \dot{U}_{ib}=\alpha^2\dot{U}_{i(1)}+\alpha\dot{U}_{i(2)}+\dot{U}_{i(0)}\\ \dot{U}_{ic}=\alpha\dot{U}_{i(1)}+\alpha^2\dot{U}_{i(2)}+\dot{U}_{i(0)}\end{cases} \tag{9}$$

$U_{i(1)}$, $U_{i(2)}$ and $U_{i(0)}$ are the positive-sequence, negative-sequence and zero-sequence voltage components respectively.

$$\begin{cases}\dot{U}_{i(1)}=1+\Delta\dot{U}_{i(1)}\\ \dot{U}_{i(2)}=0+\Delta\dot{U}_{i(2)}\\ \dot{U}_{i(0)}=0+\Delta\dot{U}_{i(0)}\end{cases} \tag{10}$$

According to the physical meaning of impedance matrix elements of the positive-sequence, negative-sequence, and zero-sequence nodes, we have: