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A novel assessment index of LCC-HVDC system impact on short-term voltage stability of the receiving-end AC system

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ABSTRACT

This paper proposes a novel index to quantitatively assess the impact of line commutated converter HVDC (LCC-HVDC) system on short-term voltage stability (STVS) of the receiving-end AC system. The major factor in a LCC-HVDC system to impact STVS is revealed and an analytic method is presented to depict the major factor. On this basis, an assessment index is proposed to quantify the LCC-HVDC system impact on STVS. Compared with short-circuit ratio based indices which only reflect the effects of voltage supporting strength of the receiving-end AC system, the proposed assessment index further takes into account the effects of HVDC system, induction motors, and transmission grid topology. The performance of the proposed assessment index has been validated in a simplified AC/DC system and a real large-scale power system, China Southern Grid.

1. Introduction

Being technically and economically advantageous, LCC-HVDC is expected to remain prevalent for bulk power delivery through long distance transmission and asynchronous interconnection in the foreseeable future [1]. When the commutating voltage of LCC-HVDC converters dips due to an AC system fault, a commutation failure will occur at the inverter of LCC-HVDC [2], which gives rise to transients in the active and reactive power of a LCC-HVDC system, and thus threatens the stability of the receiving-end AC system [3].

As a completely different HVDC transmission technology from LCC-HVDC, voltage source converter HVDC (VSC-HVDC) is prevalent for offshore wind power transmission. Using the insulated gate bipolar transistor (IGBT) and pulse width modulation (PWM) technology, VSC-HVDC has no commutation failure and possesses the decoupled control capability of real and reactive power, which has little negative effect on the stability of the receiving-end AC system [4,5]. On the other hand, compared with LCC-HVDC, VSC-HVDC lags in efficiency and power capacity and its application in remote and bulk power transmission is uncompetitive. Therefore, impacts of LCC-HVDC system on the stability of the receiving-end AC system catch much more concern.

Many efforts have been devoted to studying the impact of LCC-HVDC active power transients on rotor angle stability for years [6–10], but very few attention was paid to the impact of LCC-HVDC reactive power transients (RPTs) on short-term voltage stability (STVS) of the receiving-end AC system [11–13]. STVS issues are usually caused by unfavorable fast-acting load components, which lead to dynamic imbalance between the reactive power source and the reactive power load. In AC system, the greatly increased reactive power absorbed by induction motors (IMs) after a serious AC system fault is one of the most important factors leading to a STVS problem. In an AC/DC hybrid system, the STVS problem is exacerbated by the unfavorable "load" characteristics of LCC-HVDC system. With the increase of LCC-HVDC transmission scale and load density, the impact of LCC-HVDC system on STVS has attracted more attention and becomes an important restriction factor on the planning of transmission rating, terminal location and control strategy of HVDC system [14–16]. Due to the scale of modern power systems, it is necessary to derive fast, effective and reliable indices for the assessment of LCC-HVDC system impact on STVS. At present, short-circuit ratio (SCR), effective short-circuit ratio (ESCR), and multi-infeed effective short-circuit ratio (MIESCR) [17,18] are widely used to evaluate the impact of LCC-HVDC system on STVS by measuring the voltage supporting strength of the receiving-end AC system relative to the capacity of HVDC system.

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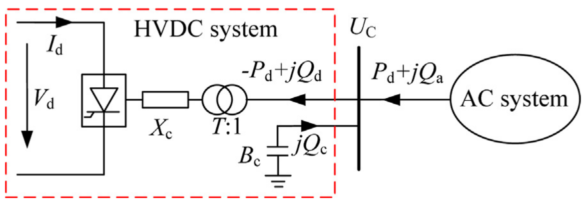

Fig. 1. Schematic diagram of an AC/DC power system.

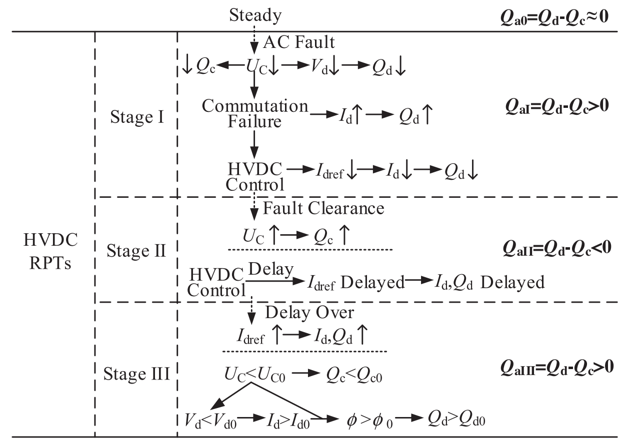

Fig. 2. LCC-HVDC RPTs following the AC system fault.

A high value of SCR or MIESCR means a small impact of LCC-HVDC system on STVS [19]. However, SCR related indices are with limited applications, because transient characteristics of LCC-HVDC system and dynamic loads are not considered [20].

This paper proposes a novel index for assessing the impact of LCC-HVDC system on STVS, further taking into account the effects of LCC-HVDC reactive power, dynamic loads and transmission grid topology in addition to the voltage supporting strength. The impact of LCC-HVDC RPTs on STVS is first investigated to reveal the major factor in a LCC-HVDC system to impact STVS, and an analytic method is presented to depict the major factor. Based on the process of LCC-HVDC system to impact STVS, the assessment index is proposed.

The rest of the paper is organized as follows. Section 2 analyzes LCC-HVDC RPTs in the case of HVDC commutation failure and reveals the impact of LCC-HVDC system on STVS. Section 3 proposes a novel assessment index. Section 4 presents a case study in a simplified AC/DC system. Section 5 validates the assessment index in China Southern Grid (CSG). Section 6 concludes the paper.

2. Impact of LCC-HVDC system on STVS

2.1. LCC-HVDC RPTs following the AC system fault

An AC/DC power system can be divided by the converter AC bus into two parts: an AC system and a HVDC system, as shown in Fig. 1.

The quasi-steady state model of the AC/DC power system is given as follows:

$$\begin{cases} V_d = N\left(\dfrac{3\sqrt{2}}{\pi}TU_C\cos\gamma - \dfrac{3}{\pi}I_dX_c\right) \\ \phi = \arccos\left(\cos\gamma - \dfrac{I_dX_c}{\sqrt{2}TU_C}\right) \\ P_d = V_dI_d \\ Q_d = P_d\tan\phi \\ Q_c = B_cU_C^2 \\ Q_a = Q_d - Q_c \end{cases} \quad (1)$$

where U_C is the voltage of the converter AC bus, V_d and I_d are the DC voltage and the DC current, respectively, T is the turns ratio of the converter transformer, X_c is the commutating reactance, N is the number of bridges in series, ϕ is the power factor angle, γ is the extinction angle, P_d is the DC active power and Q_d is the converter reactive power, Q_c is the output of capacitor banks and filters and B_c is the equivalent susceptance, and Q_a is the HVDC reactive power, i.e., the reactive power exchanging between the HVDC system and the AC system.

In the steady-state operation, Q_a approximates to zero. When a fault occurs in the AC system, V_d, I_d and γ change sharply within a very short time-frame (generally several milliseconds) along with the sag of U_C, which causes a drastic change in Q_d. In order to balance the change in Q_d, a var compensator should be switched on or off. However, it takes typically several seconds for the var compensator to act. In order to balance the change in Q_d in time, reactive power is absorbed from or injected into the receiving-end AC system, leading to a transient in Q_a.

LCC-HVDC RPTs are summarized in Fig. 2. It illustrates that after a fault occurring in the receiving-end AC system, LCC-HVDC RPTs mainly go through three stages identified by the direction of Q_a:

(1) **Stage I: Fault**. During the fault, U_C sags to a low value, which results in a HVDC commutation failure and a decrement in Q_d (although the increased I_d may result a small increment in Q_d). After that, in order to prevent the voltage instability, the function of voltage dependent current order limit (VDCOL) in the HVDC control is activated to further reduce Q_d. On the other hand, the low value of U_C reduces output of the var compensators, and the decrement in Q_c is greater than that in Q_d. Therefore, the HVDC system absorbs reactive power from the receiving-end AC system.
(2) **Stage II: Short-term Recovery**. When the fault is cleared, Q_c starts to increase along with the recovery of U_C. However, the I_d recovery is delayed due to the VDCOL to prevent oscillations and instability, which leads to the Q_d recovery delay. Consequently, Q_c is greater than Q_d, and the HVDC system injects reactive power into the receiving-end AC system.
(3) **Stage III: Long-term Recovery**. During this period, VDCOL is deactivated, I_d starts to increase and U_C is recovering. However, U_C is still less than U_{C0}, so V_d is less than V_{d0} and I_d is greater than I_{d0}. According to (1), ϕ is greater than ϕ_0 and Q_d is greater than Q_c. Therefore, the HVDC system absorbs reactive power from the receiving-end AC system. Under the condition of critical STVS, this stage usually lasts for a long time.

2.2. Impact of LCC-HVDC RPTs on STVS

In an AC system, one of the most important influence factors leading to the STVS problem is the reactive power/voltage characteristics of IMs. Following faults, stall-prone IMs consume a great amount of reactive power and cause other nearby IMs to stall, leading to a cluster effect in reactive power demand of IMs around the fault location [21]. As a result, the imbalance of reactive power deteriorates and the AC voltage level declines, which eventually results in a short-term voltage instability (STVIS) problem of the AC system.

When a LCC-HVDC system is terminated in the AC system, HVDC RPTs compose another important influence factor in STVS of the AC/DC hybrid system. As mentioned above, after an AC system fault, the role of Q_a for the receiving-end AC system alternates between "reactive power source" and "reactive power load", and thus the