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Review of HVDC control in weak AC grids

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ABSTRACT

Interconnection of High Voltage Direct Current (HVDC) transmission systems to a weak AC grid has been a challenge in recent years. The main target of this paper is to provide a comprehensive review of the "converter control" approaches for: (1) the Line Commutated Converter (LCC)-based HVDC and (2) the forced commutated converter-based HVDC systems in weak AC grids. The control architecture for each HVDC technology (forced commutated and line commutated) is included. The stability limitations associated with HVDC systems, including LCC-HVDC, Voltage Source Converter (VSC)-based HVDC, and the Current Source Converter (CSC)-based HVDC, are elaborated. Moreover, the most recent control approaches for possible integration of LCC-HVDC and VSC-HVDC to very weak AC grids are introduced. Finally, the reliability modeling for each HVDC technology in weak AC grid integration is included for corrective and preventive reliability analysis.

1. Introduction

1.1. Problem formulation

High Voltage Direct Current (HVDC) transmission is the best option to deliver generated power to long distances. The best application would be offshore wind farms where the wind turbines are installed far away from the shore to take advantage of high wind energy potential. The transmitted DC power is then converted to AC onshore station in order to interconnect to the main AC grid [1–4].

It is worth mentioning that HVDC lines connected to AC grids through long transmission lines are usually weak with low Short Circuit Ratio (SCR) and low effective DC inertia constant. Furthermore, with the advent of renewable energy resources, wind power has become one of the most suitable sources for power generation. However, areas with sufficient wind resources are geographically far from the consumers where the power grid is relatively weak (low SCR). The lower the SCR, the weaker the AC grid, which generates many problems such as voltage drop, voltage flicker, harmonic distortion, and frequency deviation [5–9]. Also, when an HVDC system is connected to a weak AC grid, oscillations and interactions may be experienced. Depending on the type of HVDC, these interactions will differ. The interactions and instabilities in this case are due to:

- Interactions between HVDC controllers and AC system [6],
- Failure in synchronization of HVDC converters with the AC system [7],
- Resonances between the inverter DC side capacitor and the AC system components [9],
- Commutation failures in the HVDC converter, etc. [10].

Several studies have focused on analyzing and troubleshooting the above problems related to interconnection of the HVDC systems and weak AC grids, which will be reviewed in this paper.

1.2. Literature review

There are two types of HVDC systems:

- Line Commutated Converter HVDC (LCC-HVDC) [11],
- Forced commutated converter-based HVDC [12].

The LCC-HVDC technology is the best option associated with high power capacities around 10,000 MW for a bipole configuration [13]. Forced commutated converter-based HVDC is the second type of HVDC transmission which is normally applied for medium power levels up to 1000 MW [13,14]. However, since the advent of Modular Multi-level Converters (MMCs), high power application of VSCs has become a reality [15]. For power transmission lines, the following two different types of converters have been established so far: (1) LCCs, which are Current Source Converters (CSCs) using Thyristor switches, and (2) Voltage Source Converters (VSCs), which use IGBT switches [14]. Other combinations and power electronic switches such as forced commutated converter-based CSCs are possible, but are not common at the

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moment for power transmission applications [16,17]. Compared to the forced commutated HVDC, higher power and voltage can be offered by LCC-HVDC which can increase the capacity of the entire system and decrease the total loss [18,19]. Depending on the type of the HVDC converter, the instabilities due to the weak AC grid connection will differ. The main focus of this article is to review: (1) the interactions caused by different types of HVDC converters and (2) the most recent approaches to overcome the dynamic instability of the HVDC transmission systems in weak AC grid connections.

The LCC-HVDC is a widespread technology around the world, but the reactive power absorption of LCC-HVDC is always a problem when interconnection to weak AC systems is required [20–23]. Therefore, the LCC-HVDC requires reactive power support from the AC grid in order to commutate reliably; thus, when connected to weak AC grids, it cannot operate stably and reliably. A reactive power compensation method is proposed in [20] which maximizes shunt capacitor size in AC systems so that the number of shunt capacitors is minimized. A small signal model of a multi-infeed HVDC transmission system containing LCCs and VSCs is developed in [21], where the converters are included in the Effective Short Circuit Ratio (ESCR) calculations. It was shown that with commonly used control strategies for LCCs and VSCs, the predicted maximum power transfer can only be achieved by reducing the controller gains. Another study analyzed the effect of low ESCR and the effective DC inertia constant on the stability of the interconnection of DFIG-based wind farms with LCC-HVDC [22]. Some studies suggested the application of the Flexible AC Transmission System (FACTS) when LCC-HVDC is connected to a weak AC grid to support the reactive power of the LCC-HVDC [24–27]. For example, a shunt FACTS has been implemented for the Baltic Cable HVDC link between Germany and Sweden to improve the power transfer level [26]. Due to the fact that the main cause of failure in LCC-HVDC connection to a weak AC grid is the commutation failure, Burr et al. [28] has tested different technologies for improving the commutation failure for LCC-HVDC systems. A commutation index has been defined and tested for various compensation structures. In another case, a dynamic reactive compensation algorithm was presented in [29] to calculate the amount of reactive power needed to be compensated when LCC-HVDC is connected to a weak AC grid. Nevertheless, a compensation device by FACTS is still necessary to compensate for the calculated amount of reactive power. An analysis approach was introduced in [22] to study the frequency dynamics for interconnection of the Doubly Fed Induction Generator (DFIG)-based wind farm, with an LCC-HVDC for very weak AC systems; but a solution has not been provided. A methodology was proposed in [30] for stabilization of LCCs connected to weak AC grids using a self-generated signal from a local oscillator for the converter's main inner control loop. However, this method has a major drawback; it is more challenging to suppress over-currents during network disturbances. Because FACTS are expensive and they require high maintenance, Li et al. [31] suggested a new reactive power balance strategy near the converter bridges which provides an additional commutation voltage and suppresses the harmonic currents near the harmonic source. This filtering method has enabled the reliable commutation of LCC-HVDC in weak AC grid connections.

VSC-based HVDC (VSC-HVDC) is the most commonly used approach in medium and long length DC transmission systems due to its flexibility, reliability, and independent active and reactive power control capability [17,32,33]. The vector control of VSC-HVDC enables the independent control of the active and reactive power while it limits the converter current in fault conditions. The main sources of these dynamic instabilities for VSC-HVDC have been reported as:

- Inner current controller loop interacts with the system and generates low-frequency resonances [34],
- Dynamics of Phase-Locked Loop (PLL) can result in instabilities [35–37],
- Resonances between the line inductance and the DC-bus voltage [34,38],
- Interactions of outer control loops in VSC [34],
- Impact of the constant power load on VSC dynamics when connected to a weak AC grid [35,39,38].

A few papers have focused on modeling and analyzing the effect of different VSC-HVDC control loops in weak AC grid interconnections [40–44]. For example, Wang et al. [41] investigated the impact of VSC-HVDC AC voltage controller gain on the stability of a VSC-HVDC system interconnected to a weak AC grid. As an another example, in [43], a small signal model was derived for a VSC-HVDC system connected to a weak AC grid and the Nyquist stability analysis was carried out to investigate the effect of the distributed parameter DC cable and π-section DC cable. Detailed investigation of PLL parameters on instability of VSC-HVDC has been reported in [35,45–48]. It was shown that PLL gains affect the maximum power transfer capability and theoretical power transfer limit can be achieved if the PLL gains are small. Impact of the PLL parameters on stability of VSC-HVDC in weak AC grid connections has also been investigated in [35,46]. A modified PLL approach named as Impedance-Conditioned (IC) PLL has been introduced in [47] in order to synchronize a VSC-HVDC to weak AC grids. The proposed method can successfully remove the barriers of traditional PLLs, but only works when the VSC-HVDC is controlling the alternating voltage. There has been a significant improvement in control of VSC-HVDC in the weak AC grid connection as explained in [49,50]. For example, Egea-Alvarez et al. [49] investigated the capability curve analysis of a VSC-HVDC connected to a weak AC grid, but did not provide a solution. The possibility of the offshore wind farm integration to a weak AC grid using VSC-HVDC has been investigated in [50], but the designed controller needs to be switched to the classical vector control when faults happen which is not optimized. Similar to [50], a frequency control based approach is introduced in [51] to control a VSC-HVDC system in weak AC grid connections. This design method requires switching to the classical vector control during a fault, which makes the design very complicated. A power compensation control scheme was also introduced in [52] to address the shortcoming of VSC-HVDC in weak AC grid connections. The proposed method modified the outer-loop control of the VSC in order to compensate for the required power transfer. As this method modifies the outer-loop, it operates properly only if the converter is controlling the active power. An advanced vector control method was introduced in [53] in order to overcome the barriers of VSC-HVDC, especially when connected to a very weak AC grid. The designed controller can robustly handle the interactions between the active power and voltage control. However, the design requires a gain scheduling technique, whose tuning adds to the complexity of the design.

Virtual inertia is another technique that can be used especially in the case of VSC-HVDC connected to offshore wind farms [54–57]. As high level of wind energy penetration makes the main grid inertia-less, a virtual inertia can be supplemented to the system using HVDC control. For instance in [55], a coordinated control strategy is proposed which applies the electrical energy stored in DC capacitors of HVDC converters and the kinetic energy of wind turbine rotors to emulate the inertia of synchronous generators in weak AC grids. This method, however, is only limited to the offshore wind farm integration of VSC-HVDC.

Some other researchers have explored synchronizing the HVDC system to the main grid without a PLL and called it synchronverter [58–63]. The idea was firstly introduced in [58,59] where an inverter control method was proposed to mimic the behavior of a synchronous generator. Compared to the dynamic model of a synchronous generator, the mechanical power exchanged with the prime mover in synchronous machine is replaced with the power exchanged with the DC bus in synchronverter. Among existing literature on synchronverters, only [60] considered a weak AC grid integration, which was a pure simulation based research and therefore, detailed analysis and validation is