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Hierarchical power control of multiterminal HVDC grids

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ABSTRACT

This article introduces a hierarchical power control structure for Multi-terminal High Voltage Direct Current (MT-HVDC) systems. The presented hierarchy is similar to the control structure used in classical AC transmission systems and is divided in primary, secondary and tertiary control actions. The voltage control in the MT-HVDC scheme acts in a way similar to the primary control action of generators in AC systems, while the secondary control action is performed by an outer power control loop. The design of the individual controllers and the interaction between these control loops is discussed in detail. Furthermore, the operational characteristics are described and the main operating points are identified. Scenarios including a power reference change and a grid side converter disconnection have been simulated in order to test and verify the proposed method. The main contribution of the paper is the development of a control methodology, providing a separation of the different control actions in different time domains, similar to what is already in use (and therefore known) within traditional power systems.

1. Introduction

The energy policy in Europe is based on three main pillars: sustainability, competitiveness and security of supply. This has led to the creation of a liberalized internal energy market, where a significant part of the energy supply is provided by renewable energy sources, mostly from solar and wind. Where the initial renewable power plants were quite small, their size has increased significantly over the years. The latest trend is the move towards offshore wind generation. In 2012 in Europe, 1166 MW of offshore wind power have been installed, representing about 11% of the new wind power installed in Europe [1]. The increase in renewable generation requires a fundamental upgrade of the energy infrastructure. Firstly to connect all the (new) renewable generation to the existing grid, secondly to reinforce the existing grid to accommodate the new generation and thirdly to compensate for the capacity factor which is much lower for renewables.

Nowadays, the dominant transmission technology is still classical AC transmission, but HVDC (High Voltage Direct Current) transmission is gaining much attention in the power sector. HVDC offers the advantage of straightforward long underground connections at high power ratings. As such, this technology is now used for onshore connections where using overhead lines is difficult, for instance due to permitting issues [2], as well as for offshore wind farm transmission [3]. The choice between different transmissions technologies is a technical-economical problem [4,5]. As such, a considerable part of the new transmission system investments is now done using HVDC. ENTSO-E predicts that in the next 10 years 1/5th of the required updates will be done in the form of HVDC [6]. This represents about 12,000 km of new HVDC transmission lines in Europe.

Most existing HVDC lines are point-to-point connections. A step further is the creation of HVDC grids [7,8]. Several projects and initiatives focus on the development of a Multi-terminal HVDC (MTDC) grid. Examples are the Supergrid or the DESERTEC projects [9,10]. The main concept of both projects is to create a pan-European system to integrate a large amount of renewable energy resources to the AC grid.

These MT-HVDC grids are made possible by the relatively new Voltage Source Converter (VSC) HVDC technology. Compared to Line Commuted Converter (LCC) HVDC, VSC HVDC converters use a common DC bus voltage allowing straightforward parallel connections, they permit independent control of active and reactive power [11]. Furthermore, VSC technology offers blackstart capabilities and comes at a reduced footprint [12].

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There are several challenges to be addressed in the development of the MT-HVDC grids. Protection and control of the MT-HVDC grid and the interaction with the AC system are some of the main issues to be solved and the reliable operation of DC grids requires DC breakers [7]. Although such breakers are not yet commercially available, prototypes have been presented [13].

Different ways to control the DC voltage in a DC grid have been described in literature, and there is a general tendency to favour droop based control methods (an overview of the different methods is given in [14]). From the point of view of power flow control, the droop control as such does not allow to fix the power that is injected by a converter due to constant variations in operation points. If the droop control action is in effect, for example, after a converter outage, the powers change according to the droop characteristics and do no longer reflect the pre-fault values. For this reason, outer control loops are required to control the droop set-points and thereby the converter powers. Some authors propose a centralized controller which sets optimized voltage references to the local controllers [15] using a fast communications system. Others propose to design the power controller based on droop regarding the power flow control in the steady state [16,17].

In [18] a hierarchical control scheme was presented. The present paper describes the proposed scheme in greater detail. The objective of the proposed control structure is to allow power flow control in the DC network while ensuring that the terminal voltages are maintained stable within appropriate limits. This is achieved by designing a hierarchical control structure where the power flow (high level) controller sets the references for the voltage (low level) control. The proposed structure is comparable to the classical AC control system and allows for an integrated management of the MT-HVDC regarding the DC voltage and the power flow control. The cascaded interaction between controllers, considering slow communications, makes the implementation of the proposed control feasible in a real system. Aspects such as the degraded operation or the power rescheduling after a contingency have been considered. First the DC voltage droop control is discussed. The resemblance with the AC primary control is shown. In the next step, the power control is introduced and discussed and its similarities with the AC secondary control mechanism are shown. Furthermore, the operating points and modes of the MT-HVDC are described. The proposed control structure also allows the introduction of a tertiary control mechanism, which is rather an optimization than a control in itself and therefore not dealt with in detail in this paper. Finally, simulation results for various scenarios show the validity of the proposed method to control the power flows.

2. Control structure description

2.1. Balancing generation and load

One of the fundamental controls in electric grids manages the balance between generation and load. Put differently, the balance between the injected and withdrawn power in a grid must remain equal. In AC systems, this balance is reflected in the value of the frequency. The power balance is maintained by the frequency control mechanism. This mechanism adjusts the power outputs of the generation (or possibly the load) to assure a constant frequency. Although different implementations exist throughout the world [19], the control reactions can be generally subdivided in three time domains with different specific actions in each[1] (Fig. 1).

The first control action is an automatic reaction of all activated generators after a deviation of the frequency from the nominal frequency. In a multi-zonal system, this results in a change of output power throughout the system. The power deviation is proportional to the frequency deviation (droop control). The primary control is activated in a very short time period (15–30 s) and acts to limit the frequency deviation. The set-point for the active power injections in the different generating units during the primary control action remains at the initial value. The primary control actions are available for only a limited time period (e.g. 15 min).

The secondary control action restores the original exchanges between different zones, causing the ACE (Area Control Error) to get back to zero. The secondary control action changes the active power set-points in the area with a power deficit or excess to match the original schedule. Due to the change in set-point in the affected zone by the secondary control, the previously committed primary reserves are no longer required, and in fact overcompensate the initial fault. This effect is again automatically cancelled by the primary control action which moves back to the original value in the entire system, thus releasing the previously activated primary reserves. The tertiary control action shifts the power from the secondary reserves, which are available on a short time basis to more long term power generation, and is often manually activated by the system operator as the result of a system optimization.

2.2. Balancing injections to and from the DC grid

The power exchange to and from the DC grid have to be balanced in a similar manner as the AC system. Where the AC system power balance is reflected in a constant frequency, the DC voltage perform a similar role in the DC system. The power-frequency control in the AC system is therefore very similar to the power-DC voltage control scheme. Several control schemes have been proposed in literature [16,20,15]. The consensus seems to lead to a droop controlled DC voltage [14,17,21], much like the primary control actions which are used in AC systems. This shift complicates the power control in the system, making it not possible to copy the AC control methodology. Contrary to the AC system, which exhibits a significant inertia from the kinetic energy in the rotating machines, the stored energy in the DC system is very limited, with only the charge in the DC capacitors and cables. This makes that the voltages in the DC system change much faster than in the AC case (frequency power imbalance). The response of the controllers should therefore be equally fast. The time constant for the primary control loop is in the order of a ten's of milliseconds and is thus dictated by the DC grid characteristics. For the secondary control this can be relaxed as the primary response already aims at stabilizing the system voltage. Consequentially, this control can be in the order of seconds or tens of seconds. Traditional tertiary controllers are off-line algorithms that react between 20 min and 1 h. Similarly as with the AC system, when a fault occurs (e.g. when a converter station is disconnected), the control of the DC voltage causes the different converter systems to adjust their power injections immediately, distributing the deficit according to the droop settings. As the voltage control at the DC side directly influences the power exchanges, there is a need to adjust the power injection set-points to meet the scheduled exchanges, especially if multiple zones or synchronous zones are connected to the DC grid. This requirement is very much in line with the secondary and tertiary control which is used in the AC system. The proposed control scheme introduces an upper level controller to the HVDC voltage control which can be compared to classical AC grid controls, consisting out of a primary, secondary and tertiary control [22]. This structure permits to create an easy interaction between power dispatch and the lower controllers using a methodology which is well accepted and known in the power sector.

A voltage controller is implemented in each VSC power converter and acts as a primary controller. Secondary control, or power control, is implemented to correct the exchanges so that the

[1] Note that fourth control action, time correction, is not discussed here.