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Decentralized model predictive control of voltage source converters for AC frequency containment

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ABSTRACT

This paper presents a novel control scheme for exchange of frequency support between asynchronous AC systems through a High Voltage Direct Current link or grid. The proposed controller bears the spirit of an emergency scheme. Using only locally available measurements, each converter can identify emergency situations that could potentially lead to unacceptable frequency values. Then appropriate control actions are taken to restrain the frequency decline and prevent it from reaching the thresholds of load shedding relays. Inspired of Model Predictive Control, the method uses simplified models of the AC and DC sides of the converter, and can incorporate various constraints. The effectiveness of the method is demonstrated on a test system consisting of two asynchronous AC areas interconnected through a five-terminal HVDC grid.

1. Introduction

High Voltage DC (HVDC) grids are contemplated as possible power system infrastructures to facilitate bulk power transfer over long distances and integration of distant renewable energy sources. To this purpose, apart from several point-to-point HVDC links already developed or planned, Multi-Terminal DC (MTDC) grid projects have been also proposed, such as the European Supergrid [1] and the North Sea Super Grid [2]. In order to improve the security of the resulting combined AC/DC grids, ancillary services will have to be provided by the HVDC grids to their adjacent AC systems, such as frequency and reactive power support [3].

HVDC grids act as "firewalls", thus the frequencies of two areas interconnected through an HVDC grid are independent and the power plants of one area do not respond to a frequency deviation in another. However, the decommissioning of conventional power plants in favor of converter-interfaced sources of energy, such as wind turbines and solar units, challenge the ability of the system to contain the frequency between acceptable limits following large disturbances [4]. To tackle this, HVDC grids should also accommodate frequency support services to the neighboring AC areas. This can be achieved by providing the Voltage Source Converters (VSC) with dedicated controllers, which can adjust the power transfer in response to frequency deviations and, subsequently, enable sharing of the primary reserves of the various connected AC sub-systems [3].

Frequency support through HVDC grids has been the subject of various publications and a review of the state of the art has been reported in [5]. In most of them, a supplementary droop control is added to the control structure of the VSC, enabling it to react to frequency deviations [6–9] by adjusting the power exchange with the AC system. The same concept was expanded in [10] for MTDC grids with Modular Multilevel Converters (MMC). A variant of the droop scheme was proposed in [2], where different values of droop are used depending on the severity of the disturbance. Other works have focused on improving the efficiency of the droop-based control. Ref. [11] demonstrated the strong interaction of the simple frequency droop control with its DC voltage droop counterpart and proposed a method to re-tune the frequency droop gain to achieve the desired participation to frequency support. This was also addressed in [12,13] with Receding Horizon Control taking into account DC voltage and power constraints.

A number of publications are devoted to control strategies enabling primary and inertia response by offshore wind farms connected to the main onshore grid through an HVDC grid [14–17]. In this application, the main idea is to enable the offshore converters to change the frequency (or the AC voltage magnitude) they impose on the offshore grid [18]. This in turn triggers the controllers of the offshore wind turbines,

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which modify their active power production to provide inertial or primary frequency support. An alternative method based on directly communicating the onshore frequency deviation to the offshore wind farm was proposed in [19].

A method for inertia emulation by VSCs has been proposed in [20]. However, it is mentioned that it can be used only for inertia emulation and not for sharing of primary reserves between two asynchronous AC areas.

In general, there are two options to consider for frequency support through HVDC grids: (i) a continuously active regulation, and (ii) activation only after large disturbances. In the first option, each VSC adjusts its power exchange with the AC grid in response to the frequency deviation resulting in a partial coupling between the balancing controls of the various AC systems, originally decoupled. Ref. [21] has also investigated the option of reaching a "frequency consensus" between the areas. In contrast, the second option considers frequency support by the VSCs as an emergency control scheme, inactive for small deviations around its nominal value [22]. Frequency support is usually activated when unusually large frequency deviations or Rates of Change of Frequency (ROCOF) are detected.

Despite the various implementation differences of the aforementioned methods for primary frequency support, the main idea remains the same: A frequency droop gain has to be selected relating the power of the VSC with the AC frequency deviation, sometimes complemented by an inertia emulation gain to provide some derivative response. This is the current practice in AC systems for primary frequency control by power plants, where the droop method has been the norm for several decades. However, although the droop control has proven indispensable for continuous regulation of frequency by the conventional units, the same does not necessarily hold true for the VSCs. In fact, simply specifying a frequency droop gain prevents the VSC from utilizing its maximum capacity in emergency cases, e.g. when an Under-Frequency Load Shedding (UFLS) threshold is approached. Therefore, there is a need for a more adaptive control scheme that will provide as much support as possible in stressed situations.

This paper explores a novel possibility for provision of frequency support by VSCs refraining from the requirement to select a frequency droop gain, and exploiting the almost instantaneous response of VSCs. The proposed method is activated as the last resort before the triggering of UFLS relays. It is inspired of Model Predictive Control (MPC), an optimization-based discrete-time control scheme, due to its ability to handle constraints, predict the system behavior and anticipate limit violations [23,24]. The paper focuses on MTDC grids, however, the proposed control can be also applied on point-to-point HVDC links with small adjustments.

The rest of the paper is organized as follows. First, Section 2 recalls some basics of VSC control. Section 3 details the proposed control. Simulation results are presented in Section 4. Finally, concluding remarks and future extensions are discussed in Section 5.

2. Overview of VSC control basics

This section briefly recalls some basics of VSC control with emphasis on the DC voltage droop technique.

Controlling the DC voltages is important for the secure operation of an HVDC grid. Power imbalances must be rapidly corrected, given the relatively small amount of energy stored in DC capacitors. Several methods have been proposed to this purpose, of which the DC voltage droop technique has received significant attention for MTDC grids, e.g. [25–28], and has been adopted in this work. This method, inspired of AC frequency control practice, allows multiple converters to share a power imbalance in the MTDC grid while ensuring redundancy against the outage of one of them. In a droop-controlled MTDC grid some of the VSCs obey a *P-V* characteristic defined by a power setpoint P^{set}, a voltage setpoint V^{set} and a droop K_V. In steady state the VSC power P is linked to the DC voltage V through:

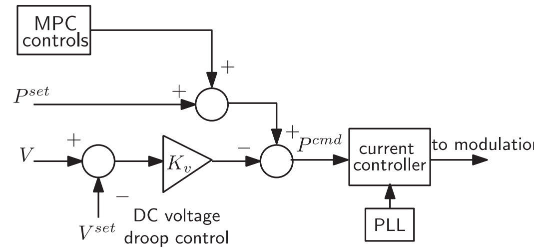

Fig. 1. Simplified diagram of the VSC control structure.

$$P = P^{set} - K_V (V - V^{set}) \tag{1}$$

where a positive power corresponds to flow from the AC grid towards the DC grid. Therefore, following a power deficit in the MTDC grid, the DC voltage will start decreasing and the VSC will increase the power it injects into the DC grid until the balance is restored.

A simplified diagram of the VSC control structure based on [25] is shown in Fig. 1, including the DC voltage droop control. The diagram focuses on the active power control loop, which provides the active power command P^{cmd} to the current controller of the VSC. A simple open loop without a PI controller is used for the DC voltage droop control, similar to the one in [25], but alternative control schemes are possible, as discussed in [27]. The current controller adjusts the internal AC voltage of the VSC in order to inject the required currents in the AC grid. A Phase Lock Loop (PLL) is usually used to synchronize the VSC to the AC grid, also providing a measurement of the local AC frequency. Generally, there is a clear decoupling between the various control levels shown in Fig. 1. The modulation level is the fastest with a response time of some μs. The response time of the current controllers and the PLL is usually in the range of some ms with the outer loops being 5–10 times slower.

Finally, the output of the "MPC controller" block is used to change the power setpoint of the VSC in response to large frequency deviations. Its operation is further described in Section 3.

3. Proposed control

3.1. Overall controller description

This work treats frequency support as an "emergency" control scheme, as also suggested in [12,22]. Therefore, for harmless frequency deviations the frequency support scheme remains inactive. This serves the purpose of preventing continuous interactions between the frequency controls of AC systems which were otherwise planned to operate asynchronously. On the other hand, in response to a large enough frequency deviation in an AC area, the VSCs connected to it correspondingly adjust the power transfer through the MTDC grid, benefiting from the primary reserves of the other AC areas.

As stated in the Introduction, this method does not require pre-defining a desired participation to frequency support. Instead, the main idea is to provide as much power as required to prevent the triggering of UFLS relays or at least reduce the amount of load shedding. Typically, these relays have multiple shedding steps with various frequency thresholds. For example, in [29] UFLS schemes with a maximum of ten shedding steps between 49 and 48 Hz are described. Therefore, prevention of UFLS can be translated as a constraint to keep frequency above the first frequency threshold of the relays. To achieve this, the power of each participating VSC has to be adapted when such a violation is predicted, by changing appropriately the VSC power setpoint P^{set} of its *P-V* characteristic (1).

Clearly, the added control should not jeopardize the operation of the MTDC grid as well the other AC areas. This imposes to obey constraints on the DC voltage, on the rate of change of powers, etc.

Finally, it is highly desirable to rely only on local measurements readily available to each VSC. By so doing, fast and reliable