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A Categorization of Converter Station Controllers Within Multi-terminal DC Transmission Systems

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***Abstract*—As more and more VSC-HVDC links are planned and commissioned, interconnection of neighboring links or connection to an existing link becomes a feasible step towards secure and reliable multi-terminal DC (MTDC) transmission systems. Multi-vendor MTDC (MV-MTDC) operation is anticipated as an impact of this gradual DC grids development. In order to achieve certain operation conditions, DC grid controller needs to send specific control settings to individual converter station controls. One of the challenges in MV-MTDC transmission systems occurs in coordination of converters since different types of controller might exist in the same system. It is therefore important to identify the parameters required by the converter station controllers to ensure a smooth coordination. In this paper, different converter station controllers available in the literatures are categorized. Challenges of converter station control coordination are also discussed.**

***Index Terms*—droop control, HVDC transmission, multi-terminal DC (MTDC), power system control, voltage-source converter (VSC)**

I. Introduction

As discussed in [1], voltage-sourced converter high voltage DC (VSC-HVDC) transmission systems give more economical benefit for connecting offshore wind farm to the main onshore grid as compared to high voltage AC (HVAC) links with break-even distance of 80 km. Hitherto, at least there are 7 HVDC links are under construction or in operation for collecting wind power from the North Sea region [2]. More VSC-HVDC links are expected in coming years as at least 9 new wind farms located beyond 80 km from shore were consented in 2014 [3].

Apart from connecting offshore wind farm to mainland, currently VSC-HVDC is also used for powering offshore oil/gas platforms from mainland, e.g. Troll A in Norway [4] or interconnecting two AC systems, e.g. Skagerrak 4 between Norway and Denmark [2]. Another two VSC-HVDC namely COBRAcable project, connecting Denmark and the Netherlands, and North Sea Network Link, between UK and Norway, are expected to be commissioned by 2019 and 2020.

As the number of point-to-point (PtP) HVDC links arise, DC interconnection composing multi-terminal HVDC (MTDC) transmission systems is expected in the near future. This DC interconnection can be formed as a radial network by interconnecting neighboring HVDC links or connecting a new converter into existing DC system [5], [6]. MTDC transmission systems provide significant improvement in flexibility, security of supply and utilization of transmission links [2], [5].

VSC-HVDC is the preferred technology for future DC grids [7]. Although there is a possibility to have a mixture of both technologies in the same DC grid as mentioned in [5], this paper only focus on VSC-based MTDC. Therefore, further in this paper MTDC is used to refer VSC-based MTDC.

It is anticipated that the DC grids will grow in organic way, started from a simple non-meshed multi-terminal into fully meshed configurations [5]. In line with this vision, COBRAcable project is also planned at later stage to be expanded into MTDC transmission sytems by connecting another onshore and/or offshore converters into the existing DC link [8]. The gradual development of DC grids creates an opportunity for different HVDC vendors to connect their converter(s) into the existing system at any stage creating multi-vendor MTDC (MV-MTDC) transmission systems.

Considering hierarchical control scheme as depicted in Figure 1 and explained in [9] and [5], DC grids control can be divided into two main levels, i.e. local converter station control (primary control) and common DC grid control (secondary control). The converter station control has a response time typically a few milliseconds while the secondary control has higher response time ranging from a few seconds until some minutes.

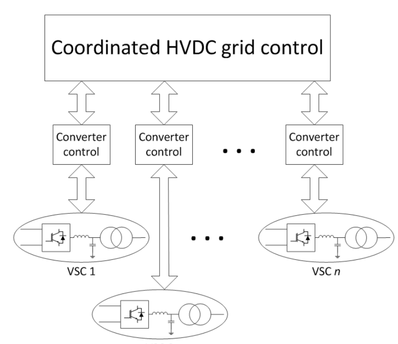

Figure 1. MTDC control level with n-number of VSCs.

The purpose of DC grid controller is to provide individual converter station controllers with their control characteristics and set points. In MV-MTDC transmission systems, challenge arises to keep the generality of DC grid controller as different converters might require different input signals to achieve certain task. In [10], uniform interface between DC grid control and converter station control was proposed in order to ensure a common communication pattern among them. This uniform interface adapts the data from DC grid controller to specific converter station controller type. However, a minimum data requirement to ensure uniform compliance was not yet defined [10].

As a first step to define this minimum control data set, classification of different converter station controller is needed. Recently, DC voltage droop control has gained attention as an alternative of constant DC voltage and power control. In [11], DC voltage droop control has been partly classified, i.e. power and current-based, basic and advanced droop control, while the droop control based on common measurement was not fully covered. Similar attempt was done in [12] to include how the droop control is implemented but the same limitation was present. In [13] and improved in [14], basic and advanced droop control were generalized as piece-wise function and the control implementation was proposed. Based on these papers and another literatures related to droop control, this paper aims to classify different types of DC voltage droop control so that required parameters to achieve certain droop characteristics can be identified and used for MV-MTDC.

II. Converter Station Control System

VSC-HVDC operation is based on fixed DC voltage and typically has a relatively large capacitor connected in parallel with the converter. DC voltage in an MTDC system is considered as an indicator of balanced operation of the system. Similar to frequency in the AC system, any mismatch in the power exchange can increase/decrease DC voltage.

However, DC voltage level is not common value in DC grids as frequency is in an AC system. Each converter terminal might have a different DC voltage level depending upon the power flow condition. Hence, the control of DC voltage needs to be carefully coordinated to fulfill a specific operation condition.

The DC voltage control can be classified into three modes: constant DC voltage, fixed flow and DC voltage droop. In constant voltage mode the converter controls the DC voltage to a specified reference point by balancing the power exchange with the AC networks. A converter station that operates in constant DC voltage control acts as a slack bus for the DC grids. On the other hand, when a converter is in fixed power or current flow mode, it maintains the power or current exchange with the AC network to follow a specific set point.

As an expansion of PtP system, the MTDC transmission systems will operate with one converter in constant DC voltage mode while the rest of the converters control the flow. This configuration is known as master-slave method where the DC voltage controlling station become a master and the flow controlling stations are the slaves. As more and more converters are connected to the MTDC transmission systems, the burden of the master station to balance the power is increased. In case of an outage of one or more converter station, the master station needs to keep the DC voltage by increasing/decreasing active power exchange with the AC networks connected to the master station which can cause high deviation of active power. The other problem occurs when the outage is at the master station. A handover of the DC voltage control task to the other station needs to be ensured in order to maintain the stability of the systems. Therefore, it is more desirable to operate the MTDC transmission system with several DC voltage controlling stations where the burden of power imbalance can be distributed among them. In these cases, a voltage droop in the DC voltage control loop is necessary to avoid conflicting between several DC voltage controllers. This situation is similar to power-frequency droop in the governor control of generators in the AC system that is used to avoid the potential conflict between these frequency controls.

Generally, these three DC voltage control modes can be expressed by their droop constant, i.e. voltage droop mode has negative constant (or positive, depends on the sign convention of the flow direction), constant DC voltage mode has zero droop constant and fixed flow has infinite droop constant [11], [15]. These three modes can be represented in current-voltage (I-U) plane as given in Figure 2.

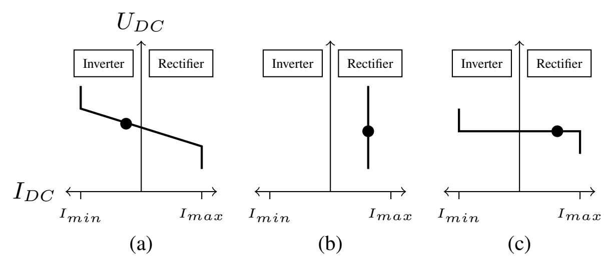

Figure 2. Different modes of DC voltage control: (a) DC voltage droop, (b) fixed flow control, (c) constant voltage control. Example operating point of the converter is represented as dot. Positive current as well as power is assumed to flow into AC networks and U_{DC} is the measured voltage at the DC terminal of converter.

Apart from these active power and DC voltage control, VSC-HVDC is also capable to control either reactive power exchange to the AC networks or AC voltage magnitude at the point of common coupling (PCC). The active and reactive power can be controlled independently by implementing the current vector control method as explained in [16]. Reference frame rotating synchronously with the AC grid is used and the AC voltage is aligned with the direct (d) axis of the reference frame. This means that the active power, P_{AC}, or DC voltage, U_{DC}, can be controlled by adjusting the d-axis current reference, i_d^*, that flows to the AC grid while the quadrature current, i_q^* can be used to control the reactive power, Q_{AC}, or AC voltage, U_{AC}. Both i_d^* and i_q^* are then linked with the inner current controllers to generate the voltage references (in dq-axis) for the lower level converter control.

In this paper, since both active power and DC voltage are relevant for DC grid control only these d-axis controller are considered. It is also assumed that the VSC-HVDC is connected to a relatively strong AC networks otherwise the converter station will be in islanded mode controlling the AC voltage magnitude and phasor.

III. DC Voltage Droop Control Types

Several DC droop control designs have been proposed in the literature. Although they have different characteristics and implementation methods, they can be classified based on criteria as follows:

A. DC voltage relation

In general, the DC voltage droop control can be formulated as a function of current (I-U relationship) or power (P-U relationship). Both methods are widely used. The current-based droop control benefits from its linear behavior, i.e. voltage deviation will result in an equivalent current deviation [11], [17]. On the other hand, power-based droop control is analogous to frequency control of synchronous generator in AC systems [12], [18], i.e. power deviation will result in changes of AC frequency in AC systems or similarly DC voltage in DC grids.

The general droop control formula is given as:

$$\chi = \chi^* - \frac{1}{k_{DC_\chi}}(U_{DC} - U_{DC}^*) \quad (1)$$

with χ as generalized flow variable that can either be power or current. Reference values are indicated by asterisk (*) sign. The DC voltage droop coefficient is denoted by k_{DC_χ}. In case of current-based droop control, (1) can be rewritten in term of DC current, I_{DC}, as:

$$I_{DC} = I_{DC}^* - \frac{1}{k_{DC_{I-U}}}(U_{DC} - U_{DC}^*) \quad (2)$$

while in case of power-based droop control, (1) become:

$$P_{DC} = P_{DC}^* - \frac{1}{k_{DC_{P-U}}}(U_{DC} - U_{DC}^*) \quad (3)$$

As mentioned in [12], it is common to assume a lossless system in the design of DC voltage droop control so that (3) can be rewritten as:

$$P_{AC} = P_{AC}^* - \frac{1}{k_{DC_{P-U}}}(U_{DC} - U_{DC}^*) \quad (4)$$

where P_{AC} is the measured active power at PCC terminal of the converter.

The behavior of both current-based and power-based droop controls are similar for the deviation near the reference point. However, as the DC voltage further deviates from the reference, the difference become larger.

Another type of power-based droop control is used in [19] where the power-balance equation across DC capacitor is used to form P-U^2 relationship. The droop control formula for P-U^2 based droop control is given as:

$$P_{AC} = P_{AC}^* - \frac{1}{k_{DC_{P-U^2}}}((U_{DC})^2 - (U_{DC}^*)^2) \quad (5)$$

B. Piecewise linear representation

Piecewise linear (PWL) function can be used to represent the droop control characteristics. Each piece represents a droop control mode that is defined by some margins/limits. As an example, the basic droop control characteristics depicted in Figure 2 has two control operation modes, i.e. normal operation mode, with a certain droop constant, when I_{DC} is within DC current limits (I_{max} and I_{min}) and constant current operation mode when I_{DC} hits one of these limits [11], [14].

In case of more advanced droop controls, as depicted in Figure 3, several modes can be defined depending upon the operating conditions of the converter [5], [13], [20]–[28]. Either DC voltage (Figure 3(a), (b) and (d)) or current (Figure 3(c)) or a combination of both can be used as the operation limits.

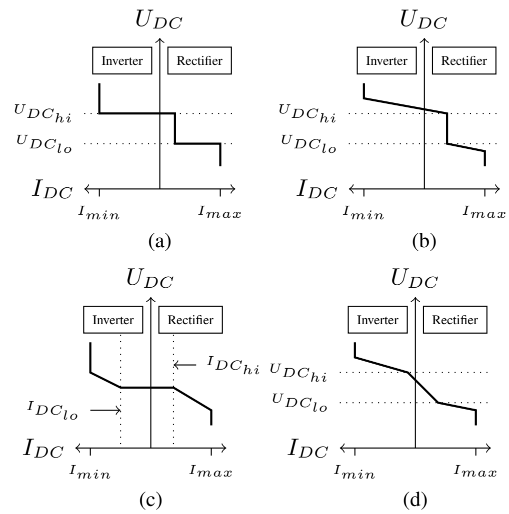

Figure 3. Advanced droop control examples: (a) voltage margin method, (b) constant current dead-band, (c) constant voltage dead-band, (d) undead-band.

As an example, Figure 3(a) is used in the voltage margin method (VMM) [5], [20]–[22]. In VMM method, during normal condition ($U_{DC_{lo}} < U_{DC} < U_{DC_{hi}}$) the converter with control characteristics depicted in Figure 3(a) will be in constant power or current mode. As soon as the DC voltage becomes higher than upper margin $U_{DC_{hi}}$ or below lower margin $U_{DC_{lo}}$, the converter will switch to a constant DC voltage controller or having zero droop constant.

The droop control characteristics depicted in Figure 3(b) and (c) are referred to dead-band droop control [22]–[24]. During the normal condition, the converter with the characteristics depicted in Figure 3(b) or (c) will be in either fixed power/current flow control or constant DC voltage control. Beyond the dead-band, the converter will switch to DC voltage droop control.

The undead-band droop control characteristics is depicted in Figure 3(d) [25] which reflects different priority is given to the converter to participate in balancing the active power depending on the level of DC voltage deviation.

C. Control implementation

The DC voltage droop control can be implemented in two ways:

1) direct link: In this structure the output of the DC voltage droop control is linked directly with the inner current controller [18], [22], [23], [29], [30]. An example of direct DC voltage droop control implementation is depicted in Figure 4. It should be noted that k_{DC_P} might include conversion factor from DC to AC value. The conversion factor can be avoided by dividing P_{AC} in (4) with AC terminal voltage [12].

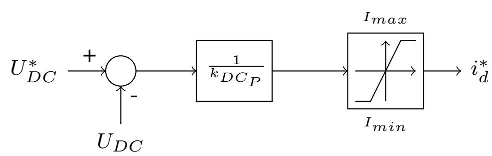

Figure 4. Direct implementation of DC voltage droop control.

2) indirect link: As an alternative, the droop control can be integrated with another d-axis outer controller loop, i.e. active power or DC voltage control. In this case, the droop control will give a deviation in the reference of the outer controller loop, e.g. depicted in Figure 5 where current-based droop is used to modify DC voltage reference in the DC voltage control loop. Another examples are given in [15], [31], [32]. In [14] and [13] advanced droop control were implemented using several control loops.

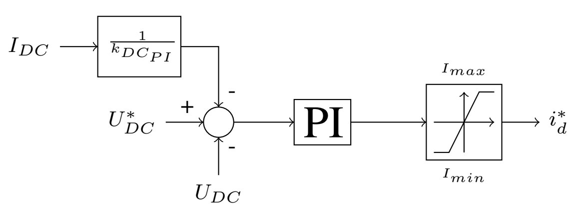

Figure 5. Indirect implementation of DC voltage droop as a contribution to a DC voltage controller loop [16], [33]–[36].

D. DC voltage measurement location

As mentioned earlier, DC voltage varies for different converter terminal locations within DC grids depending on the power flow. Following a disturbance it may happen that the converter closest to the disturbance point is more violated than the other converters which means this converter will contribute more to balance the power mismatch.

As an alternative of local measurement, common DC voltage measurement can be used to distribute the same DC voltage mismatch to different converters within the systems so that the contribution to power imbalance will depend only on the droop constant [37], [38]. This type of droop control is referred as pilot voltage droop control. The main drawback of pilot voltage droop control is its dependency on communication system. In [39], [40] methods to mitigate communication latencies and outage were proposed by combining local and common measurements to get more reliable control.

Pilot voltage droop control can be formulated in power-based form as:

$$P_{AC} = P_{AC}^* - \frac{1}{k_{DC_{pilot}}}(U_{DC_{pilot}} - U_{DC_{pilot}}^*) \qquad (6)$$

where $U_{DC_{pilot}}$ can be obtained as DC voltage measured at a specific point in the DC grids or as an average of several converter voltages.

IV. Challenges in Control Coordination

In order to ensure a dynamic stability of the MTDC system, DC grid controller needs to determine the dynamic characteristics for each converters by knowing the operation limits and restrictions of each converters within the system. These dynamic characteristics represent the operating point of each converters at a particular condition in I-U plane (or P-U respectively) [5].

Droop constant (regardless of the base) can be considered as the common parameter that is needed by every converter station controllers within the MTDC system to determine the operating mode of the converter. Moreover, in [9] islanded control mode can be expressed as power control mode (infinite droop constant), i.e. require a stiff DC system to accommodate the active power import or export.

In case that advanced droop control is adopted by DC grid controller, several voltage and power or current margins, along with different operating modes defined by these margins, given as different droop constants, will be sent down to individual converter station controllers. Challenge arises when not all the converters use the same control as defined by DC grid controller, i.e. some converters can only represent basic droop control (constant DC voltage, fixed power or current flow or DC voltage droop). In order to solve this, uniform interface can be used to convert the data given by DC grid controller to give a dynamic droop constant depending on the DC voltage deviation or power/current condition. However, further analysis on this method is still required.

Similar method might be applied for pilot voltage droop control, i.e. implementing such control in DC grid control and letting the uniform interface to adopt the data as needed. In principle every DC voltage droop control can be operated as pilot voltage droop control by exchanging the voltage measurement and reference with pilot values in the basic droop equation given in (2) and (4).

V. Conclusions

COBRAcable project will be expanded from a PtP link into MTDC transmission system at a later stage. The challenge arises in coordinating different converter station controls that come from different vendors. As a first step, in this paper different categories for classifying converter station controls used in MTDC transmission systems were defined. It was proposed that DC grid controller should be based on advanced droop and pilot voltage droop controls. It is then the responsibility of uniform interface to adapt the data from DC grid controller for a more basic converter station control.

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