Ancillary services and operation of multi-terminal HVdc systems

Yannick Phulpin and Damien Ernst

Abstract—This paper addresses the problem of ancillary services in ac systems interconnected by a multi-terminal HVdc system. It presents opportunities for new control schemes and discusses operation strategies for three types of HVdc grid operators, namely a coordination center, an independent operator, and the transmission system operator in charge of one of the areas interconnected by the multi-terminal HVdc grid. In these contexts, the paper envisions the challenges of using the HVdc infrastructure to provide frequency, voltage, and rotor angle stability-related ancillary services. It also analyzes the technical and economic impacts of the operation strategies on the ac areas' dynamics.

I. INTRODUCTION

MULTI-TERMINAL HVdc (MT-HVdc) systems have received much attention recently. They represent actually an alternative pathway to connect non-synchronous power systems and integrate offshore renewable energy sources [1]. While decisive technology-related issues are still to be addressed [2], [3], many questions already arise on the operation of such systems and their interactions with onshore and offshore ac grids. In particular, as manufacturers of converter stations tend to develop devices whose real and reactive power injections can be independently controlled, specific operation schemes could be designed to provide ancillary services to the ac areas.

At the master control level, the reactive power injection of an HVdc conversion station equipped with voltage-source converters (VSC) can be controlled with no significant impact on the other converters. On the contrary, the real power injections into the ac areas are related, as they depend on the power flows through the HVdc grid, which can be controlled by means of settings for dc voltages, dc currents, and/or voltage/current droops at the converter stations [4]. In operation, the instantaneous value of those control variables, which will be referred to from now on as "control setting," must be consistent with both the technical abilities of the converters, including the internal control dynamics, and the transmission capacity of the MT-HVdc system. In the long term, its average value over a period of typically 15 minutes should be equal to a "set point" that corresponds to electricity market outcomes in the ac areas interconnected by the MT-HVdc infrastructure [5] and could be modified to coordinate the balancing markets of the areas [6]. In this paper, we will consider a given set point and discuss how the control settings can be modulated in the shorter term to handle imbalances in the ac areas and smooth transitions from one set point to another.

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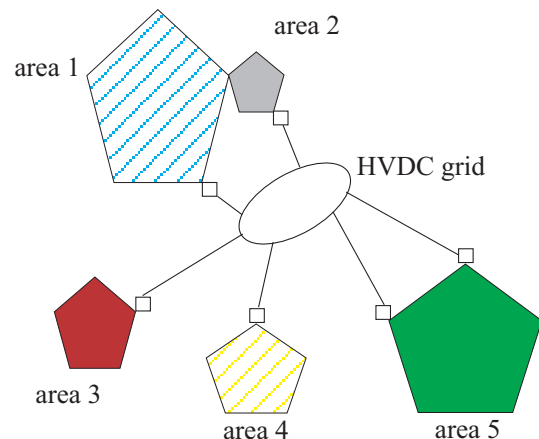
Fig. 1. Example of a system with ac areas interconnected by an HVdc grid. The colored pentagons represent the ac areas, the squares the ac/dc converters, and the dark lines the dc transmission lines.

In practice, such control of a MT-HVdc grid requires specific control schemes for voltage and currents throughout the dc grid, which impact the interconnected areas. To assess the dynamics of a system where a MT-HVdc grid provides ancillary services, we consider in this paper a power system with N areas operated by independent transmission system operators (TSOs). The areas are interconnected by ac tie-lines and/or by the MT-HVdc infrastructure through conversion stations. An example of such a system is depicted in Fig. 1, where no area is synchronous with another one, except area 1 and area 2.

In this context, we discuss different operation strategies to valorize the ancillary services that could be provided by the MT-HVdc grid. The discussion will account for the type of entity that operates the MT-HVdc system, namely an independent operator, an inter-TSO coordination center, or one of the interconnected TSOs. The paper also presents a qualitative study of the operation strategy's impact on the dynamics of the interconnected regions. More specifically, it discusses the technical and economic outcomes of different policies in terms of frequency deviations, reserve requirements, rotor angle stability, and need for reactive power support.

The paper is organized as follows. First, we present the potential use of MT-HVdc systems in terms of frequency, voltage, and rotor angle stability-related ancillary services and discuss the related dynamics. Second, we elaborate on different policies for the operation of a MT-HVdc infrastructure and discuss their influence on the power system dynamics.
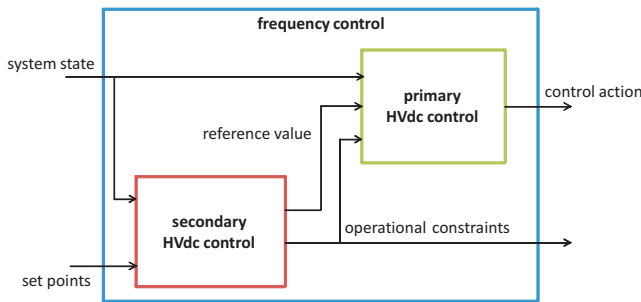
Fig. 2.   Frequency control scheme for a multi-terminal HVdc system.

II. Frequency Control

If sufficient operational margins are available for the HVdc system, the control setting can be modulated in the short-term to modify power flows in the interconnected power system. The HVdc systems could then address issues related with sudden imbalances in the ac areas, which induce frequency deviations, by modifying the power injections depending on the values of the frequencies in the ac areas.

A. Implementation

As frequency control is usually hierarchical in ac systems [7], the same delineation is most likely to be used for HVdc control. This would lead to a two level scheme as represented in Fig. 2. More specifically, the following functionalities are envisioned.

- *Primary HVdc control* acting in a few seconds to share primary reserves (i.e. the additional amount of power that each area can inject within a few seconds [8]) between the ac areas. In this perspective, there are two alternatives:
a) Sharing reserves at all time (i.e. make frequency deviations stay close to each other as in [9], [10] for example).
b) Sharing reserves only during emergency situations (e.g. when the frequency of at least one area is out of the range of normal operation conditions), as for load shedding for example.
Both alternatives require strong agreements between TSOs that use different definitions of the reserves, at least in terms of time of deployment and duration [11].
To avoid any delay and reliability issues related with communication, the practical implementation of primary HVdc control relies on local control based on local measurements of the system state and taking into account the reference value of the control variable and the associated operational constraints.
- *Secondary HVdc control* when the HVdc grid is subjected to the dynamics of the ac areas. This is the case if the HVdc grid connects an area with intermittent generation only, or if primary HVdc voltage control is activated. Secondary HVdc control may also aim to smooth variations from a (long-term) set point to another. In these contexts, secondary HVdc control adapts the reference value and the operational constraints of primary HVdc control within a few tens of seconds.

B. Effects

Implementing short-term control of the MT-HVdc infrastructure to provide frequency control-related ancillary services has practical consequences in terms of frequency deviations and reserve requirements.

1) Impact on frequency deviations : As secondary HVdc control is to smooth variations of the power injections into the ac areas, it should not involve significant frequency deviations. On the contrary, short term variations of the HVdc setting are likely to affect the frequencies of the ac areas. We discuss therefore the two schemes for HVdc primary frequency control that are introduced in Section II-A.

a) In the case of a power flow modulation directly related with the frequency deviations of the areas, as primary frequency control effort is shared among several areas, any imbalance can impact all the areas regardless of its location. Hence, HVdc primary frequency control induces a smoothing effect between the imbalances of the areas, which consequently undergo frequency deviations with a much lower amplitude [12].

b) If the power flow is modulated in emergency situations only, the ac areas will face the same probability of occurrence for small frequency deviations as with no specific short-term HVdc control. However, by virtue of the smoothing effect, individual areas will face more frequently deviations of a medium amplitude corresponding to significant disturbances.

Note that using HVdc connection to share primary frequency reserves does not increase the risk of generalized blackout if the associated control is disabled when the reserves of balanced areas are depleted.

2) Impact on reserves: The benefit of sharing primary reserves among the ac areas is mainly economic, as TSOs would need to contract less reserves from local generators to face the same contingencies. However, the possibility to lose hundreds of MW, and the associated reserves, at a converter station could have an impact on the amount of reserves that is necessary for each area. To this extent, the number of HVdc connections and the architecture of the HVdc grid are decisive.

III. Rotor Angle Stability-Related Control

The independent control of real power injections into the ac areas and the very short time response of up-to-date HVdc converters could be leveraged to address problems related to both small oscillations and large-scale disturbances (i.e. loss of synchronism) [13]. It may even become a necessity, since rotor angle stability problems are expected to worsen with the parallel operation of ac systems with HVdc grids [14].

A. Implementation

Specific control schemes have been proposed to improve rotor angle stability in systems including two-terminal HVdc-links. They consist typically in power injection modulation during a few tens of milliseconds. To the knowledge of the authors, only a few applications of the master control level (e.g. [15]) have been investigated in the context of MT-HVdc systems. Nevertheless, most control schemes for two-terminal HVdc-links could be also applied to multi-terminal systems
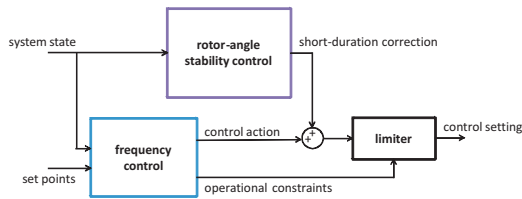
Fig. 3. Rotor angle stability-related control scheme for a multi-terminal HVdc system.

as represented in Fig. 3 with two main objectives, namely avoiding loss of synchronism and damping electro-mechanical oscillations.

1) Avoiding loss of synchronism: Usually, loss of synchronism results from a lack of synchronizing torque, which makes a group a generators swing coherently with the other generators of the system. As power electronics can manage fast changes of power injections, MT-HVdc infrastructures could provide in certain circumstances significant synchronizing torque to avoid loss of synchronism.

For example, let us consider the power system represented in Fig. 1. Suppose that synchronism in area 3 is about to be lost after generators located close to the converter station have stored too much kinetic energy during a disturbance. One way to avoid instability would be to transfer part of this extra energy through the HVdc grid from area 3 to the other areas.

Several research papers have already proposed to use HVdc-links to improve transient stability in power systems (see e.g. [16], [17], [18]). Their implementation is difficult yet, as those control schemes do not account for the communication and application delays, which are considerable as actions need to be taken within a few tens of milliseconds. However, as power electronics can manage fast changes of significant power injections, MT-HVdc represents a promising alternative to improve transient stability in power systems.

2) Damping electro-mechanical oscillations: The lack of damping torque between different areas of a system may also result in electro-mechanical oscillations between machines from ac-interconnected areas. As it is the case for transient stability, these could be damped by appropriately modifying the active power injected into the MT-HVdc grid [15].

For example, with respect to the power system plotted in Fig. 1, a weak ac interconnection between area 1 and area 2 may result in electro-mechanical oscillations between these two areas. By operating the HVdc grid so as to reduce the electrical distance between these two areas, the oscillations could in principle be mitigated.

B. Effects

Providing rotor angle stability-related services involves fast changes of the power injections from the MT-HVdc grid into the ac areas. Hence, it could induce transient dynamics in the ac areas that might affect ac voltage magnitudes and angles, especially at buses close to the converter stations. To avoid any contingency in the ac areas, the range of rotor angle stability-related control should thus account for the available margins of both the MT-HVdc grid and the ac areas.

Under these conditions, the MT-HVdc infrastructure can help increasing the reliability of the system. The technical outcomes of implementing the above mentioned control schemes are increased transient stability margins, which allows more time for protection schemes, and improved small-signal stability, which reduces the need for power system stabilizers on generators.

IV. Voltage control

In normal conditions, VSC-based converters can offer reactive power reserves to the ac areas, depending on their respective real power injections [19]. Furthermore, the reactive power injection at a conversion station depends only on local settings for the converters and does not impact the other converters.

A. Implementation

The implementation of voltage control for VSC-based converters is expected to be similar as for the generators located in the same area. Hence, the reactive power injections should be controlled depending on the voltages in the ac areas according to the hierarchical control scheme used by the local TSO.

More practically, the reactive power reserves offered by the HVdc converters can be called by the local TSO with respect to the dynamics of its areas. By modifying the reactive power setting of the converters, the TSOs can dispatch those reactive power reserves very rapidly. As for FACTS and synchronous generators in general, this fast deployment capability is also valuable for short-term voltage control [20].

HVdc converters are also suitable for other types of voltage support. In particular, emergency control actions as proposed in [21] could be implemented to avoid instability phenomena in abnormal conditions. In this perspective, converter stations should remain in operation through balanced and unbalanced faults.

B. Effects

The application of voltage control at the HVdc converter stations is to increase the reactive power reserves of the ac areas. Hence, if the voltage control strategies account for the internal dynamics and limitations of the areas, HVdc converters shall improve the capability of the ac areas to face transient phenomena that could threaten voltage stability.

However, in the case of significant power injections, the redirection of power flows through ac grids might induce new needs for voltage support in terms of quantity and location. In particular, the envisioned flexibility in real power injections at the converter stations requires significant reactive power reserves.

V. Operation strategies

We investigate in this paper several operation strategies for the MT-HVdc system that correspond to different ways to assess the control variables for the HVdc converters. The analysis focuses on three types of operators for the MT-HVdc grid, namely a coordination entity, an independent operator,
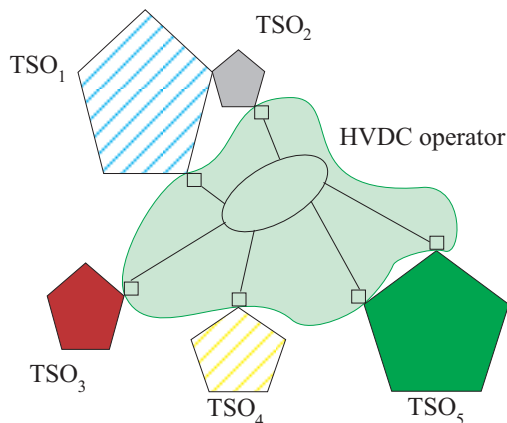
Fig. 4. Control areas in the context of an inter-TSO coordination center.

and the transmission system operator in charge of one of the areas interconnected by the multi-terminal HVdc.

We will assume hereafter that the type of HVdc system operator does not influence the assessment of long-term set points with respect to the market outcomes. In this context, we discuss how each type of operator is likely to deal with ancillary services in the short-term.

A. Coordinated operation

Let us consider in the first place that the MT-HVdc infrastructure is operated by an entity, whose practices are decided together by all interconnected TSOs. From now on, we will refer to such an entity as "inter-TSO coordination center." Such coordinated operation is advocated for security assessment in large-scale multi-TSO power systems [22], for example. In this context, the inter-TSO coordination center is in charge of the area represented in Fig.4, including the converter stations and the dc transmission lines.

The main driver for the operation practices of an inter-TSO coordination center is that its control actions must benefit to all TSOs, as any of them would oppose a decision-making process that conflicts with its objectives. This principle makes it unlikely that TSOs share primary frequency control reserves, if they have not previously agreed on a common definition of the reserves in terms of time of deployment and duration. Indeed, exchanging primary reserves between two TSOs with different reserve durations could only satisfy the one with the shortest duration.

With no primary HVdc control, the motivations of the secondary HVdc control is limited to handling unscheduled changes of the power flows through the MT-HVdc system and smoothing the evolution from a set point to another. This may involve issues related to potential short-term imbalances in areas with very limited reserves, such as offshore wind farms for example, for which the TSOs should agree at least on appropriate incentives and/or penalties.

To improve small-signal and transient stability in the ac areas, the inter-TSO coordination center must handle fast changes of the control settings during a short period of time (typically a few seconds). For areas connected by at least two

converters, such changes can be managed without a significant impact on the other areas. In this case, rotor angle stability-related HVdc control could be easily implemented. As to areas connected by a single converter, the implementation of specific control schemes shall depend on a preliminary agreement on transient power exchanges with other areas.

As to voltage control-related ancillary services, the coordination center is expected to provide reserves to the TSOs depending on the rated power of the converters. Hence, the coordinated HVdc operator controls the real power injections at the converter stations under the constraint of being able to inject the respective reactive power reserves. The reactive power control at each converter would then remain a prerogative of the local TSO.

B. Independent operation

Let us consider now that the MT-HVdc system is operated by an independent entity that aims at maximizing its operational benefits subject to the connection rules and economic policies of each interconnected TSO. In this context, the independent dc grid operator is in charge of the area represented in Fig.4, including the converter stations and the dc transmission lines.

The potential value of primary HVdc control is strongly dependent on the policy in terms power injections during disturbances. If HVdc converters are subject to the same rules as generators, the independent HVdc operator would be rewarded to provide reserves to an imbalanced area and should refund part of this value to the TSOs that generate the corresponding reserves. Nevertheless, the primary frequency control reserves provided by the independent HVdc operator to the TSOs should fit with local attributes (time of deployment and duration), which usually differ from one area to another. Consequently, it is likely that the independent HVdc operator could provide reserves only to the TSOs with the least restrictive definition of the reserves.

Although the secondary HVdc control will face more deviations with respect to the reference values of the control settings, its implementation will be similar as for a coordinated operation. In particular, the independent HVdc operator is likely to charge TSOs with very limited reserves that induce needs for secondary HVdc control. A specific regulation might then be difficult to design, as the independent HVdc operator can be in situation of a monopoly over trans-national regions.

As rotor angle stability-related services are usually not priced, an independent HVdc operator is unlikely to provide them unless the service is mandatory.

On the contrary, as voltage support is usually priced [23], the independent HVdc operator is expected to supply reactive power reserves at its converters. Nevertheless, the offered quantity may depend on a trade-off between the incomes related to reactive power reserves and real power injections, as for conventional generators for example [24]. Unlike with coordinated operation, the quantity of reactive power reserves is considered as a variable here, which might involve more risks of contingencies and requires ad-hoc policies to address critical situations.
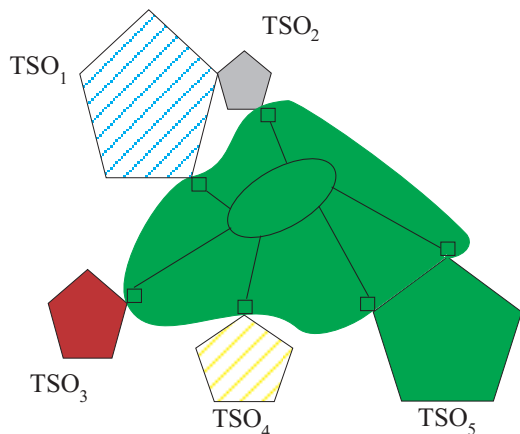
Fig. 5. Control areas in the context of integrated operation by TSO 5.

C. Integrated operation

As for a new ac transmission infrastructure close to an interconnection, a TSO operating one of the interconnected areas could extend its control area to the HVdc conversion stations and power lines/cables. In that context, the "extended TSO" would have to manage an area including the conversion stations as represented in Fig. 5.

The extended TSO should then operate the dc grid as an extension of its own network, supporting the operation costs and taking advantage of the infrastructure to support its own operation practices. It could more easily set up bilateral agreements to purchase system services in terms of primary frequency control from the TSOs whose reserve definitions correspond to a longer duration and a shorter time of deployment. It could then sell those reserves to the TSOs that have reserves with a shorter duration and a longer time of deployment.

As to secondary HVdc control, the extended TSO could manage the imbalances related with primary control and ac areas with intermittent generation only. This would however require the definition of adequate tariffs for sudden changes of the power injections into the HVdc grid. In this particular case, the regulation entity of the extended TSO might be relevant to design the tariff.

Providing rotor angle stability-related services could be easier with an integrated operation through bilateral agreements between the extended TSO and the other ones on transient modulation of the power exchanges.

Reactive power reserves associated to the converters connecting the ac area operated by the extended TSO shall be easily integrated. Those located at the other converters shall depend on pricing policies and operational trade-offs, as for an independent HVdc operator.

VI. Conclusions

This paper discusses ancillary services that can be offered by MT-HVdc grids in terms of voltage control, frequency control, and rotor angle stability. It presents three operation strategies that could be used to operate HVdc systems.

The paper emphasizes that the potential use of the MT-HVdc system to share primary reserves relies on adequate technical and economic policies about which the TSOs might fail to agree, leading to no action in the case of coordinated operation. On the contrary, an independent HVdc system operator, by maximizing the income it can make with the infrastructure, could propose reserves if economic incentives are sufficient. As emphasized in [25], the consequent redistribution of the primary frequency control reserve costs is to benefit the TSOs, which should in turn reward the independent HVdc operator for transmitting reserves. An extended TSO could even rely on bilateral agreements with the neighboring TSOs, which should ease the integration of reserve transmission costs.

Providing rotor angle stability-related ancillary services with a MT-HVdc grids may induce benefits mostly in terms of reducing needs for local investments to maintain the reliability of the systems. If grid codes do not make those services mandatory, an independent HVdc operator is unlikely to implement specific control schemes. On the contrary, an inter-TSO coordination center or an extended TSO is more likely to apply emergency control improving rotor angle stability. This would involve little operational costs, while the technical and economic benefits would mainly concern TSOs with multiple connections to the MT-HVdc systems.

As to voltage-related ancillary services, the quantity of reserves may depend on a trade-off between incentives for reactive power support and benefits in terms of real power transfers, in particular for an independent HVdc operator and an extended TSO. As an inter-TSO coordination center might not be directly dependent on economic incomes, its supply might be more regular.

In any case, the operation of an MT-HVdc grid relies on both the technical flexibility of the infrastructure and the policies of the TSOs in terms of interdependent dynamics between the ac and dc grids and pricing for ancillary/system services. Although such policies are decisive, their implementation in the context of multi-national MT-HVdc systems remain hypothetical. Further works should thus focus on the design of grid codes and tariffs for MT-HVdc grids, which might be particularly challenging to define for offshore ac areas that do not depend of an existing regulated transmission entity, such as an offshore wind farm for example.

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