A framework for dynamic security assessment of combined multi-terminal HVDC and AC grids

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***Abstract*—This paper discusses some challenges that dynamic security assessment and control will face due to the integration of multi-terminal high-voltage direct-current grids and the resulting interconnection of multiple asynchronous AC areas. A conceptual framework is outlined to address these challenges and ensure the security of the combined AC/DC system. The need for cooperation and exchange of information between the various transmission system operators is highlighted in order to take full advantage of the control flexibility of HVDC converters in post-contingency situations.**

***Index Terms*—Dynamic security assessment, mixed AC/DC networks, multi-terminal direct current grids, post-contingency corrective control**

I. Introduction

The progress in High Voltage DC (HVDC) technology and the possibility of extensions to Multi-Terminal Direct Current (MTDC) configurations opens new perspectives but raises new challenges in the operation of the resulting mixed AC/DC grids [1]. Most works have addressed the secure operation of such grids through Optimal Power Flows (OPF). For example, in [2] the classical Security-Constrained OPF (SCOPF) performed by the Transmission System Operator (TSO) of an AC grid, is extended to a combined AC/DC grid. The same spirit underlies the works in [3] and [4] presenting mixed AC/DC SCOPF formulations including preventive and corrective controls, while a hierarchical approach has been proposed in [5].

In the above works, SCOPF is intended to be performed in a centralized manner assuming that a single entity is responsible for ensuring the security of the whole system. This is the best option insofar as the MTDC grid is embedded in one AC system operated by one TSO. However, future MTDC grids are expected to interconnect multiple synchronous and asynchronous areas. Solving the combined SCOPF centrally will raise serious computational burden and model gathering issues. Therefore, alternatives should be investigated so that the computational burden is not increased prohibitively, the information exchange is minimal and the autonomy of each TSO is preserved.

To address those issues, a distributed OPF formulation was proposed in [6]. The area of responsibility of each TSO was extended to include the MTDC grid components directly connected to it. Iterations with information exchanges between TSOs are required to reach a common solution.

The most salient feature of Voltage Source Converters (VSCs) is their ability to quickly modify the power flows through the MTDC grid to which they are connected. They allow MTDC grids to contribute to security through corrective control applied after the occurrence of a disturbance.

Since an MTDC grid will require significant investments by the TSOs of the adjacent AC grids, those TSOs will expect to benefit from that infrastructure for security control. The MTDC grid will be operated as a "common asset" to which all adjacent TSOs have access to obtain support. As a counterpart, conflicts are expected to arise when multiple TSOs will be willing to act at the same time on the MTDC grid, or when the action of one TSO will come to the expense of insecure operation of another AC grid. To the authors' knowledge, those aspects have not been addressed in the literature.

This paper outlines a general framework to integrate MTDC grids into existing tools for Dynamic Security Assessment (DSA). Emphasis is put on using the MTDC grid for post-contingency corrective control and resolving the possibly resulting conflicts between the different TSOs connected to it. For instance, MTDC grids planned to be integrated in the European interconnection would be such cases. For simplicity, the focus is on an MTDC grid interconnecting asynchronous AC systems, each operated by a single TSO. It is common for a synchronous AC grid to be operated by several TSOs, acting in different areas, but the DSA of such AC multi-area systems has already been addressed in the literature (e.g. [7]) and is not considered here.

The paper is organized as follows. Section II outlines DSA in highly general terms. Section III discusses the challenges raised by the integration of MTDC grids. The general framework for DSA of combined AC/DC systems is outlined in Section IV. A method to check if such a system is correctively secure is described in Section V, while illustrative examples are given in Section VI. Section VII concludes the paper.

II. Checking whether an all-AC system is correctively secure

In this section, DSA is formalized in the context of all-AC grids. It will be extended to AC/DC configurations in later sections. It is assumed that each TSO has the task of assessing the security of its own grid, which entails simulating the system response to each contingency of a list of credible contingencies. In case the system response is not acceptable, preventive and/or corrective actions are identified. Since the focus is on corrective control, preventive actions are not considered here. Instead, the focus is on simply identifying whether there exists (at least) one acceptable post-contingency control to correct the system response. In fact, any post-contingency corrective action will be considered acceptable provided it does not entail shedding load (above a small pre-defined threshold).

This can be formalized as searching for a solution to the dynamic security constrained optimization problem:

$$\min_{\Delta \boldsymbol{u}} \|\Delta \boldsymbol{u}\|^2_{\boldsymbol{W}} + \left\|\Delta \boldsymbol{u}^{ls}\right\|^2_{\boldsymbol{W}_{ls}} \quad (1)$$

subject to: for all $t \in [0, T]$:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}\left(\boldsymbol{x}(t), \boldsymbol{y}(t), \Delta \boldsymbol{u}, \Delta \boldsymbol{u}^{ls}\right) \quad (2)$$

$$\boldsymbol{0} = \boldsymbol{g}\left(\boldsymbol{x}(t), \boldsymbol{y}(t), \Delta \boldsymbol{u}, \Delta \boldsymbol{u}^{ls}\right) \quad (3)$$

$$\boldsymbol{L}(t) \geq \boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{y}(t), \Delta \boldsymbol{u}, \Delta \boldsymbol{u}^{ls}) \quad (4)$$

$$\overline{\Delta \boldsymbol{u}}^{ls} \geq \Delta \boldsymbol{u}^{ls} \geq \underline{\Delta \boldsymbol{u}}^{ls} \quad (5)$$

$$\overline{\Delta \boldsymbol{u}} \geq \Delta \boldsymbol{u} \geq \underline{\Delta \boldsymbol{u}} \quad (6)$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the time-varying differential and algebraic system states, satisfying the initial conditions $\boldsymbol{x}(0) = \boldsymbol{x}_0$ and $\boldsymbol{y}(0) = \boldsymbol{y}_0$, respectively. $\Delta \boldsymbol{u}$ corresponds to the post-disturbance corrective actions. $\boldsymbol{W}$ is a diagonal positive-definite matrix that assigns a weight to each control action. The term $\Delta \boldsymbol{u}^{ls}$ corresponds to load shedding actions, with weighting factors specified in $\boldsymbol{W}_{ls}$.

The objective (1) is the minimization of the total control effort over a time interval T. Apart from setting the diagonal terms of $\boldsymbol{W}_{ls}$ much larger than those of $\boldsymbol{W}$, no specific weight tuning is assumed since the objective is not to find the "cheapest" solution but to identify if there is at least one acceptable. Nevertheless, different objective functions could be also envisaged. The equality constraints (2) and (3) take into account the dynamic response of the system to the initial contingency and to the corrective actions. Constraints (4) ensure that this system evolution satisfies specific limits, gathered in the time-varying vector $\boldsymbol{L}(t)$ and guaranteeing at least a stable transition towards the new operating point. Constraints (5) and (6) avoid unrealistic control adjustments, by specifying the upper and lower bounds $\overline{\Delta \boldsymbol{u}}^{ls}$, $\underline{\Delta \boldsymbol{u}}^{ls}$ and $\overline{\Delta \boldsymbol{u}}$, $\underline{\Delta \boldsymbol{u}}$.

If the solution of the above optimization problem is such that $||\Delta \boldsymbol{u}^{ls}||$ is negligible, the system is declared correctively secure for the contingency of concern.

III. Some issues of DSA in mixed AC/MTDC systems

Consider the generic system of Fig. 1 consisting of M asynchronous AC areas connected to an MTDC grid through N VSCs (or terminals). An area may be connected through more than one VSC, i.e. $N \geq M$.

Clearly, in order to encompass the MTDC grid, modifications of the traditional all-AC framework have to be made. Some of them are discussed next.

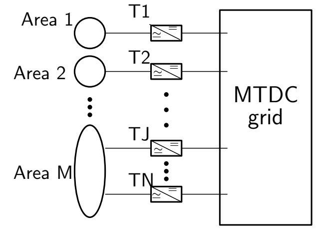

Fig. 1. Generic system of AC areas connected to an MTDC grid

A. Contingencies and remedial actions

As regards contingencies that take place inside an AC area, it makes sense to have them assessed by the TSO of concern. Related modeling issues are discussed in Section III-B.

The probability of two independent contingencies taking place at the same time in two different AC areas can be considered negligible. Hence, for post-contingency corrective control, it is reasonable to assume that, following an AC contingency, only one TSO would request corrective actions involving the MTDC grid.

On the other hand, the MTDC grid makes up an additional infrastructure exposed to disturbances. The latter include the outage of: (i) a VSC, (ii) a DC branch, or (iii) a part of the HVDC grid for a short period of time.

Since the MTDC grid is expected to carry large powers over long distances, a disturbance affecting one of its components can have significant impacts on the connected AC areas. Unlike AC contingencies, a DC contingency may lead to a situation where more than one TSO requests support from the MTDC grid. These actions may be conflicting, and a way to resolve (or avoid) those conflicts should be contemplated.

This emphasizes the need for a coordinating entity that can access the models and data of the AC areas in order to assess the impact of DC contingencies beyond the limits of the MTDC grid and take care of conflicts between TSOs.

B. Modeling requirements for AC contingency assessment

Let us come back to the assessment of AC contingencies.

For the security assessment of an all-AC system, the choice of an appropriate boundary in the network representation is important. The main idea is to keep enough detail so that the response of the system model is not significantly modified when replacing what is beyond the boundary by a much simpler model. In all-AC systems it is common to include a "buffer zone", i.e. include in the model branches, loads and generators of the external network which are significantly impacted by contingencies occurring inside the study system. Too small a buffer zone could lead to losing important information, whereas a widespread zone would increase the computational burden prohibitively.

Which buffer zone should be considered by a AC TSO connected to its neighbors through an MTDC grid only?

A unique feature of HVDC connections between asynchronous AC areas is that they can act as "firewalls" preventing the effects of a contingency in one AC area from being propagated in another AC area. This holds true as long as the MTDC grid

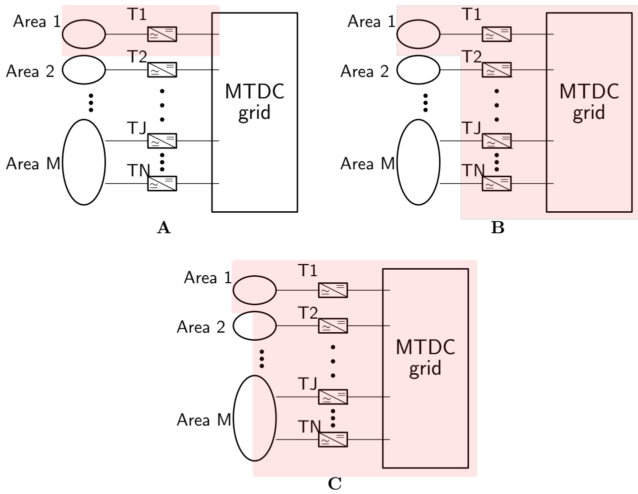

Fig. 2. Modeling options; shaded parts are preserved and included in the model used for DSA by Area 1

operates with constant power flows. In this case, for a given TSO, the model can include its own area and the VSCs directly connected to it, as sketched in Fig. 2.A for the TSO of Area 1.

However, the power flows in the MTDC grid vary owing to changes of VSC power set-points used as post-contingency corrective controls by the AC TSO. They can also change owing to the outage of a VSC, caused by an AC contingency. To deal with such cases, it becomes essential for each TSO to model the complete MTDC grid in addition to its own AC grid, as sketched in Fig. 2.B. In other words, the MTDC grid plays the role of a buffer zone retained in the model.

The size of the future MTDC grids is not expected to be large. Thus, the increase in computational burden of including a detailed model of the whole MTDC grid can be considered negligible. At the same time, this model extension will make it easier to account for local and/or centralized controls of the VSCs, such as those considered in [8].

In principle the buffer zone could be further extended to include parts of the AC grids of the other TSOs, as sketched in Fig. 2.C. Yet, there is not enough evidence of a real benefit associated to this model extension. The option of Fig. 2.B is thus considered in the rest of this paper.

C. Representation of external AC systems

Once the boundary has been selected, the simplified representation of the outside systems is important to account for their impact on the response of the study system, and ensure that the effects of a disturbance do not propagate into those external systems.

There is an abundant literature dealing with the identification of external equivalents in all-AC systems (e.g. [9], [10] and their references). In the case of asynchronous AC systems coupled through an MTDC grid, it seems sufficient to account for the MTDC grid controls that alter the power transfers between AC areas. Hence, in a first approximation, the dynamics of the external AC systems could be neglected and each VSC could be connected on its AC side to a Thévenin equivalent, as sketched in Fig. 3.

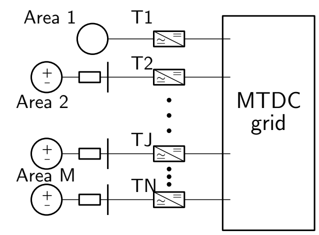

Fig. 3. Representation of external AC systems as Thévenin equivalents

IV. A GENERAL FRAMEWORK FOR DSA OF A MIXED AC/MTDC SYSTEM

Based on the above considerations, we outline a general framework for DSA of a mixed AC/DC system. As shown in Fig. 4, it involves the various AC TSOs as well as a coordinating entity, referred to as "DC TSO".

It is implicitly assumed that all TSOs are willing to cooperate, exchange information, and do their best efforts to ensure the security of the combined AC/DC system.

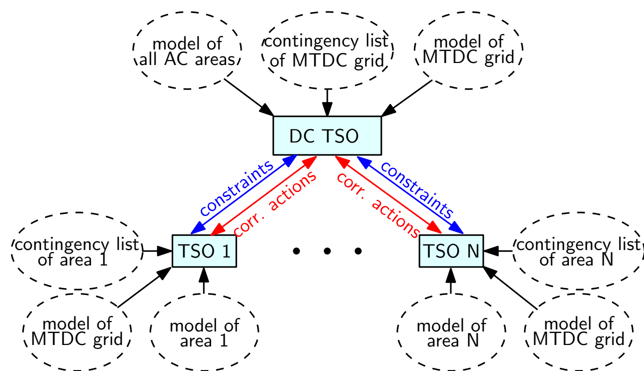

Fig. 4. Framework for security assessment of AC/DC system

The DC TSO exchanges information with all connected AC TSOs to coordinate them and resolve conflicts. Its role bears similarity with that of a regional security coordinator, such as CORESO [11], for instance. The concept of independent DC grid operator has been advocated also in [12].

The DC TSO has a model of the whole AC/DC system, and it performs DSA of the complete system, but with respect to contingencies in the MTDC grid only. Although the model used would be large, the number of DC contingencies to be investigated would be small. This allows to perform DSA with a full view of the system without prohibitive increase in computational burden. If the system is insecure with respect to a DC contingency, it is checked if it is correctively secure by acting on the whole system (in particular the MTDC grid).

Each AC TSO uses a model of its AC system together with the MTDC grid to perform DSA with respect to contingencies in its own system. If the latter is insecure with respect to an AC contingency, the TSO checks whether it is correctively secure by acting on its system as well as the MTDC grid.

Resorting to corrective control in one AC area may cause trouble to the other AC areas. To anticipate and hopefully avoid such situations, it is proposed to incorporate in the corrective control determination upper and lower limits on the deviation of the various VSC powers with respect to their pre-contingency values. It is assumed that violating such a VSC limit would result in unacceptable behavior in the AC area to which the VSC is connected.

Each TSO should receive those limits on all VSCs, and determine the corrective actions while obeying those limits. Grid codes could oblige the AC TSOs to provide and update the values of these limits frequently.

While the determination of such limits is rather straightforward when an AC area is connected to the MTDC grid through a single VSC, it is less obvious when more VSCs are involved (e.g. Area M in Fig. 3).

V. Checking whether a mixed AC/MTDC system is correctively secure

The formulation of Section II is now revisited to account for the various areas and TSOs.

A. AC contingencies

For the i-th TSO ($i = 1, \ldots, M$), an optimization problem similar to that of Eqs. (1)-(6) is considered, with the addition of MTDC grid controls:

$$\min_{\Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}_i, \Delta \boldsymbol{u}_i^{ls}} ||\Delta \boldsymbol{u}_i||^2_{\boldsymbol{W}_u} + ||\Delta \boldsymbol{v}_i||^2_{\boldsymbol{W}_v} + ||\Delta \boldsymbol{u}_i^{ls}||^2_{\boldsymbol{W}_{ls}} \quad (7)$$

subject to: for all $t \in [0, T]$:

$$\dot{\boldsymbol{x}}_i(t) = \boldsymbol{f}_i\left(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}_i, \Delta \boldsymbol{u}_i^{ls}\right) \quad (8)$$

$$\boldsymbol{0} = \boldsymbol{g}_i(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}_i, \Delta \boldsymbol{u}_i^{ls}) \quad (9)$$

$$\boldsymbol{L}_i(t) \geq \boldsymbol{h}_i(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}_i, \Delta \boldsymbol{u}_i^{ls}) \quad (10)$$

$$\overline{\Delta \boldsymbol{u}_i}^{ls} \geq \Delta \boldsymbol{u}_i^{ls} \geq \underline{\Delta \boldsymbol{u}_i}^{ls} \quad (11)$$

$$\overline{\Delta \boldsymbol{u}_i} \geq \Delta \boldsymbol{u}_i \geq \underline{\Delta \boldsymbol{u}_i} \quad (12)$$

$$\overline{\Delta \boldsymbol{v}_i} \geq \Delta \boldsymbol{v}_i \geq \underline{\Delta \boldsymbol{v}_i} \quad (13)$$

$$\boldsymbol{L}_i^v \geq \boldsymbol{h}_i^{th}(\Delta \boldsymbol{v}_i) \quad (14)$$

where $\Delta \boldsymbol{v}_i$ is a vector of VSC power set-point changes, also involved in the functions $\boldsymbol{f}_i$, $\boldsymbol{g}_i$ and $\boldsymbol{h}_i$. The diagonal entries of $\boldsymbol{W}_v$ are the corresponding weighting factors. The time-varying vector $\boldsymbol{L}_i$ includes also the physical and operational bounds of the MTDC grid. All other symbols and initial conditions have been defined in Section II.

The MTDC grid is included in the model and $\Delta \boldsymbol{v}_i$ leads to modifying the MTDC grid power flows. If the other AC areas are simply replaced by Thévenin equivalents as in Fig. 3, the resulting MTDC grid power flows are only limited by the MTDC grid constraints and the VSC ratings, taken into account in the upper and lower bounds $\overline{\Delta \boldsymbol{v}_i}$ and $\underline{\Delta \boldsymbol{v}_i}$ in (13).

The constraints (14) correspond to the limits on VSC powers introduced in Section IV and aimed at preventing the corrective actions taken in the i-th AC area to have detrimental impacts in the other AC areas. Namely, $\boldsymbol{L}_i^v$ is a vector of (lower and upper) limits on the actions available to the i-th TSO, as determined by the other AC TSOs.

B. DC contingencies

The assessment of MTDC grid contingencies is performed by the DC TSO, using a model of the whole AC/DC system. Corrective actions can be identified by solving the following optimization problem, which minimizes the total control effort over all AC areas and the MTDC grid:

$$\min_{\Delta \boldsymbol{u}, \Delta \boldsymbol{v}, \Delta \boldsymbol{u}^{ls}} ||\Delta \boldsymbol{u}||^2_{\boldsymbol{W}_u} + ||\Delta \boldsymbol{v}||^2_{\boldsymbol{W}_v} + ||\Delta \boldsymbol{u}^{ls}||^2_{\boldsymbol{W}_{ls}} \quad (15)$$

subject to: for all $t \in [0, T]$ and for $i = 1, \ldots, M$:

$$\dot{\boldsymbol{x}}_i(t) = \boldsymbol{f}_i\left(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}, \Delta \boldsymbol{u}_i^{ls}\right) \quad (16)$$

$$\boldsymbol{0} = \boldsymbol{g}_i(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}, \Delta \boldsymbol{u}_i^{ls}) \quad (17)$$

$$\boldsymbol{L}_i(t) \geq \boldsymbol{h}_i(\boldsymbol{x}_i(t), \boldsymbol{y}_i(t), \Delta \boldsymbol{u}_i, \Delta \boldsymbol{v}, \Delta \boldsymbol{u}_i^{ls}) \quad (18)$$

$$\overline{\Delta \boldsymbol{u}_i}^{ls} \geq \Delta \boldsymbol{u}_i^{ls} \geq \underline{\Delta \boldsymbol{u}_i}^{ls} \quad (19)$$

$$\overline{\Delta \boldsymbol{u}_i} \geq \Delta \boldsymbol{u}_i \geq \underline{\Delta \boldsymbol{u}_i} \quad (20)$$

$$\overline{\Delta \boldsymbol{v}} \geq \Delta \boldsymbol{v} \geq \underline{\Delta \boldsymbol{v}} \quad (21)$$

where $\Delta \boldsymbol{u} = [\Delta \boldsymbol{u}_1 \ldots \Delta \boldsymbol{u}_M]$ and $\Delta \boldsymbol{u}^{ls} = \left[\Delta \boldsymbol{u}_1^{ls} \ldots \Delta \boldsymbol{u}_M^{ls}\right]$. All other symbols and the initial conditions have been defined in Section II. The above procedure results in a single set of MTDC actions $\Delta \boldsymbol{v}$ as well as suggested AC actions $\Delta \boldsymbol{u}_i$ for each AC area.

In case an AC TSO does not agree with the proposed control change in its area, it should provide properly updated constraints back to the DC TSO. The latter should perform a new DSA taking into account the updated constraints.

VI. Illustrative examples

The following simulation results illustrate a few aspects presented in the previous sections. Time-domain simulations typical of DSA have been used to assess the dynamic response to contingencies and corrective actions.

A. Test system

A simplified diagram of the test system is shown in Fig. 5. It consists of two asynchronous AC areas and one offshore wind farm, connected through a five-terminal MTDC grid. Each AC area is based on the Nordic test system, set up by an IEEE Task Force and documented in [13]. The two areas are referred to as "East" and "West", respectively. Each of them has two points of connection to the MTDC grid. They are shown in Fig. 6 for the East area.

Each VSC is modeled with 28 differential-algebraic equations involving the phase reactor, the phase locked loop, inner and outer control loops, etc.

T3 and T4 control the power balance in the MTDC grid based on the DC voltage droop control [14]. The rest of the VSCs inject constant power into the MTDC grid. The initial power in each VSC is shown in Fig. 5.

If the MTDC grid is not used for corrective control, both East and West systems operate at an insecure point (operating point A in [13]) with several contingencies leading to long-term voltage instability. Namely, these involve the outage of a transmission line in the North-Central corridor, the outage of a generator or a load increase in the Central region (see

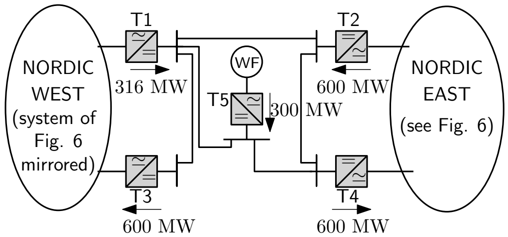

Fig. 5. Simplified diagram of combined AC/DC system

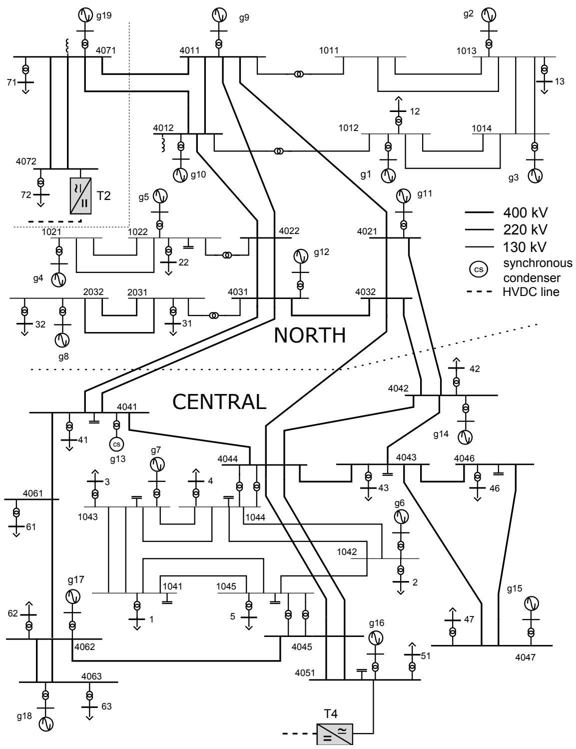

Fig. 6. East test system with connections to MTDC grid

Fig. 6). The load increase could stem from a change of the power of T3 in the West or T4 in the East system.

B. Example of AC contingency

1) Full system response without corrective actions: The first scenario involves the outage of line 4021-4042 in the East system. Long-term voltage instability results. Voltages in the East system drop progressively under the effect of load tap changers and over-excitation limiters, ending up in system collapse. Figure 7 shows the evolution of the voltage at representative buses in the Central regions of East and West systems, respectively. It is evident, that while the East system is experiencing voltage instability, the impact on the West system is negligible.

2) Using an equivalent of West system: DSA with respect to this contingency falls under the responsibility of the East TSO. The latter should use a model of its own system, together with the MTDC grid and an equivalent representation of the West system. While the previous simulation (yielding the curve shown with solid red line in Fig. 7) was performed without any simplification, the simulation is repeated with the West system replaced by two Thévenin equivalents, in accordance with Fig. 3. Those equivalents are attached on the AC sides of T1 and T3, respectively.

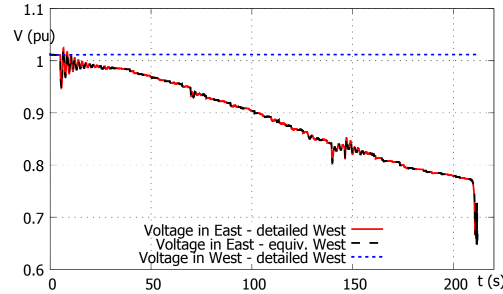

Fig. 7. AC contingency: voltages in the Central regions of both systems

Figure 7 shows (with dashed black curve) the evolution of the same East bus voltage. No difference is observed compared to the case with detailed representation of the West area, confirming that such a simplified presentation is acceptable for security assessment.

3) Constraints of West system: The constraints (14) relative to the West system should be determined and communicated in advance by its TSO. An example of determination of such limits is provided in Fig. 8. It shows that drawing more than 100 MW from T3 leads to unacceptable, or even unstable voltage response of the West system. As a result, the West TSO will announce that no more than 100 MW can be obtained from T3 for corrective control purposes.

4) Determination of corrective control actions: Next, the East TSO checks the existence of corrective actions able to stabilize its system, while respecting the constraints set by the West TSO. In fact, in this case, it is possible to redirect some power from T2 to T4, i.e. without asking the support of the West system. By redirecting 300 MW, stability can be restored, as shown in Fig. 9. The gradual ramping of powers of T2 and T4 is shown in Fig. 10. The constraint of T3 is respected, since the impact on the powers of T1 and T3 is negligible. Hence, the East system is correctively secure with respect to that contingency.

C. Example of DC contingency

The second case involves the tripping of VSC T2, which initially injects 600 MW into the MTDC grid (see Fig. 5). The contingency is applied at $t = 5$ s. As shown in Fig. 11, the DC voltage droop controllers of T3 and T4 quickly respond to that outage by adjusting their powers, thereby restoring the MTDC power balance.

As a result, additional power is drawn from T3 and T4. This power has to flow through the North-Central AC corridors of the East and West systems, respectively. This leads to long-term voltage instability in both systems, as shown in Fig. 12.

The corrective actions in this case are calculated by the DC TSO. The East system needs support from West, while the power drawn from the Central region of the latter (through T3) should not be increased. Thus, the corrective action consists

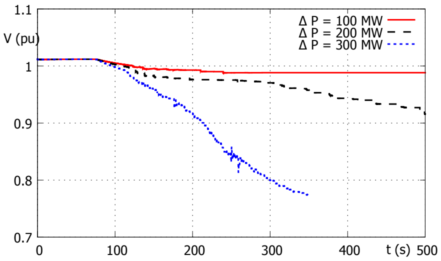

Fig. 8. AC contingency: voltage at a representative bus of the West system

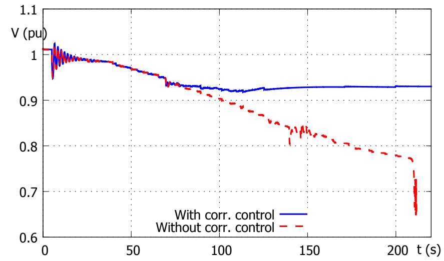

Fig. 9. AC contingency: voltage at a representative bus of East system with corrective action

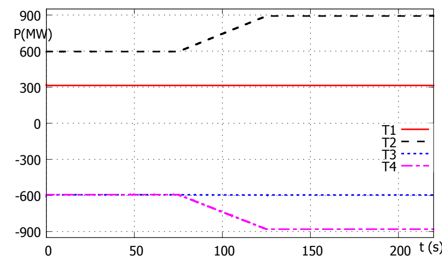

Fig. 10. AC contingency: VSC powers with corrective action

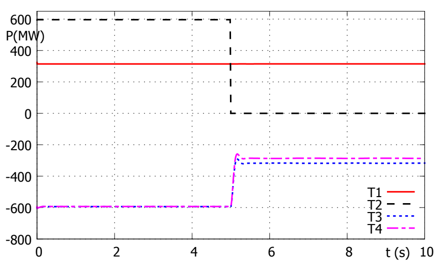

Fig. 11. DC contingency: VSC powers

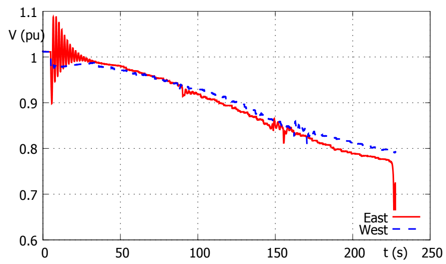

Fig. 12. DC contingency: voltages in Central regions of both AC systems

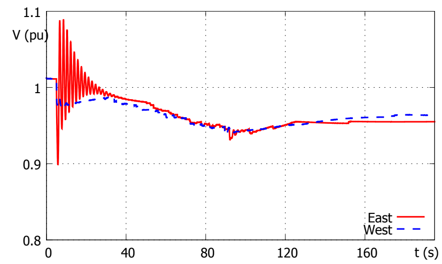

Fig. 13. DC contingency: voltages in Central regions of both AC systems with corrective control

of increasing the power injected by both T3 and T4, while drawing that power from T1. Specifically, the power setpoint of T1 is increased from 316 to 816 MW (similar to T2 in Fig. 10), and this power change is equally shared between T3 and T4. This is sufficient to restore stable operation in both systems, as observed by the voltage evolutions in Fig. 13. Hence, the whole system is correctively secure with respect to that contingency.

VII. Conclusion

This paper has proposed a conceptual framework for DSA of a mixed system including asynchronous AC areas connected through an MTDC grid. Advantage must be taken of the control flexibility of VSCs in post-disturbance situations.

However, conflicts between AC TSOs are possible. To address them, the proposed framework resorts to a coordinating entity, referred to as DC TSO, that has full view of the system and exchanges information with the AC TSOs.

A contingency in an AC grid is assessed by the TSO of concern, including the MTDC grid in its system model. The MTDC grid is used for corrective actions, while obeying limits on VSC power changes announced by the other AC TSOs.

A contingency in the MTDC grid is assessed by the DC TSO which suggests corrective actions throughout the whole system. Further iterations may be required in case they are not accepted by the AC TSOs.

Acknowledgment

The authors gratefully acknowledge the support of the R&D Dept. of RTE, the French Transmission System Operator.

References

[1] D. Van Hertem and M. Ghandhari, "Multi-terminal VSC HVDC for the European supergrid: Obstacles," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 3156–3163, dec 2010.

[2] R. Wiget, *Combined AC and Multi-Terminal HVDC grids – Optimal power flow formulations and dynamic control*. PhD thesis, ETH Zurich, 2015.

[3] J. Cao, W. Du, and H. F. Wang, "An improved corrective security constrained OPF for meshed AC/DC grids with multi-terminal VSC-HVDC," *IEEE Trans. on Power Systems*, vol. 31, pp. 485–495, jan 2016.

[4] R. Teixeira Pinto, M. Aragues-Penalba, O. Gomis-Bellmunt, and A. Sumper, "Optimal operation of DC networks to support power system outage management," *IEEE Trans. on Smart Grid*, vol. 7, no. 6, pp. 2953–2961, 2016.

[5] K. Meng, W. Zhang, Y. Li, Z. Y. Dong, Z. Xu, K. P. Wong, and Y. Zheng, "Hierarchical SCOPF considering wind energy integration through multiterminal VSC-HVDC grids," *IEEE Trans. on Power Systems*, vol. 32, no. 6, pp. 4211–4221, 2017.

[6] E. Iggland, R. Wiget, S. Chatzivasileiadis, and G. Anderson, "Multi-Area DC-OPF for HVAC and HVDC grids," *IEEE Trans. on Power Systems*, vol. 30, no. 5, pp. 2450–2459, 2015.

[7] L. Wehenkel, M. Glavic, and D. Ernst, "A collaborative framework for multi-area dynamic security assessment of large scale systems," in *Proc. of IEEE Lausanne PowerTech*, 2007.

[8] L. Papangelis, M.-S. Debry, P. Panciatici, and T. Van Cutsem, "Coordinated supervisory control of multi-terminal HVDC grids: a model predictive control approach," *IEEE Trans. on Power Systems*, vol. 32, no. 6, pp. 4673–4683, 2017.

[9] X. Feng, Z. Lubosny, and J. W. Bialek, "Identification based dynamic equivalencing," *Proc. of IEEE Lausanne PowerTech*, 2007.

[10] D. Fabozzi, M. Glavic, L. Wehenkel, and T. Van Cutsem, "Security assessment by multiple transmission system operators exchanging sensitivity and tie-line power flow information," in *Proc. of IEEE Bucharest PowerTech*, 2009.

[11] ENTSO-E, "Regional security coordinators." https://docstore.entsoe.eu/major-projects/RSC/Pages/default.aspx.

[12] F. Gonzalez-Longatt, "Optimal power flow in MTDC systems based on a DC-independent system operator objective," in *Proc. of IEEE Eindhoven PowerTech*, 2015.

[13] IEEE PES Task Force, "Test Systems for Voltage Stability Analysis and Security Assessment," 2015. Technical Report PES-TR19, Available online on IEEE PES Resource Center. http://resourcecenter.ieee-pes.org/pes/product/technical-publications/PESTR19.

[14] C. Dierckxsens, K. Srivastava, M. Reza, S. Cole, J. Beerten, and R. Belmans, "A distributed DC voltage control method for VSC MTDC systems," *Electric Power Systems Research*, vol. 82, no. 1, pp. 54–58, 2012.