Save HVDC overlay grid operation using redundant and cascaded system operation methods

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***Abstract*—HVDC overlay grids are considered by many parties in order to overcome new arising challenges regarding bulk power long distance power transmission. As an overlay grid the HVDC grid is likely to become the new power system backbone. Thus, it is mandatory to ensure redundant operation methods especially for disturbed situations. This concept paper provides an approach how to coordinate different operation methods considering availability requirements. Thereby operation planning as well as methods fast reacting after disturbances are taken into account. Fast reacting methods that come into action after a disturbance adapt converters' power reference in order to distribute unscheduled power flows between the AC and DC grid in such a way that at least equipment overloading is avoided. This can be realized in an actively coordinated or passively coordinated manner among converters. However, a pre-defined sequence or rules for activation is necessary to ensure that there is only one of the parallel running methods active at each time. This is what the paper is dealing with.**

***Index Terms*—HVDC grid, diverse redundancy, N-1 redundancy, network operation**

I. INTRODUCTION

The energy supply system undergoes a significant change during the last years: increasing amount of renewable energy in energy generation and a decreasing amount of conventional power plants. As most renewable energies can effectively be used only in a few areas it is necessary to have long transmission paths between renewable generation and fixed loads. For such kind of transmission tasks HVDC is often the preferred technology.

State of the art are point to point (P2P) HVDC transmission systems. However this implies a high risk in terms of redundancy. If the P2P interconnection trips there is no redundant power transmission path. Thus, in some areas the idea of a meshed HVDC system came up during the last years, e.g. for Asia and Europe [1], [2]. Beside technological challenges as fault handling equipment and appropriate converters in high voltage and power ratings it is completely open how to operate a meshed HVDC grid. Thus a number of approaches have been created representing methods that can be assumed to work fine in normal operation and if only one of these method is active at a time. So far there is no coordination concept combining different methods or coordinating different method is such a way to represent a backup for each other. This is a very important fact, as an HVDC overlay grid operated in parallel to the existing AC transmission grid will represent the new backbone of the whole power supply system and as such will be a highly critical infrastructure that must be equipped with redundant control methods working hand in hand.

This paper proposes a coordination concept, which is in line with actual developments at CENELEC [3] and Cigré B4.58. It combines control methods from different control instances and describes their interactions. In chapter II diverse redundancy is introduces as the control concept includes this new kind of redundancy that may replace N-1 redundancy when an HVDC overlay grid is created and represents a more economic criterion making use of new degrees of freedom that are introduces by HVDC converters.

Chapter III describes the general HVDC grid operation hierarchy concept proposed by CENELEC and describes different control methods from different control hierarchy levels. These are:

- scheduling of converter set points on a regular basis (III.A),
- converter set point adaptation to ensure diverse redundancy including local fault identification (III.B),
- converter set point adaptation if no local/concrete disturbance identification is possible (III.C),
- unscheduled central coordinated set point adaptation after a disturbance (III.D) and
- DC voltage control to ensure the energy balance within the HVDC grid.

Chapter V concludes the paper.

II. Diverse Redundancy

AC transmission systems are representing the backbone of the entire power grid. Thus N-1 security is required for this grid layer in order to ensure continuous operation without equipment limit violation or contingency if any equipment trips [4]. This approach could also be applied when an HVDC overlay grid is introduced, decoupled from the AC system by its converters. In this case N-1 security must be applied for both systems independently of each other. In Figure 1 a) system states related to N-1 security considerations are shown.

However, the introduction of an HVDC overlay grid offers new opportunities in the field of transmission redundancy. Converters coupling the AC and HVDC grid are highly dynamic and actively controllable. This characteristic enables to consider both parts of the system as a whole regarding redundancy. The AC grid can cover equipment trips within the DC grid and vice versa by triggering converters' power reference values adequately. This new kind of redundancy is introduced as *diverse redundancy* and considers a mutual support of both grids [5], [6]. This new approach reduces monetary and ecologically effort for further grid extension in order to provide sufficient redundancy for both grids respectively (Figure 1 b)).

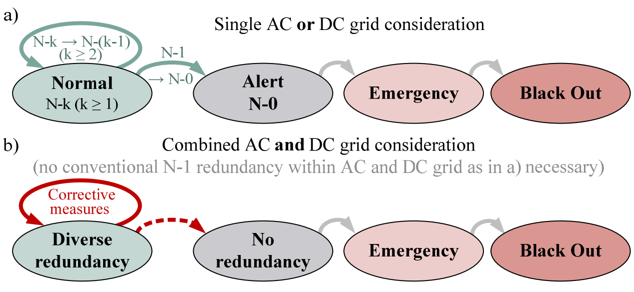

Figure 1. System's operating state changes - each arrow indicates a single equipment trip scenario. a) State of the art (N-1/N-k redundancy: green arrows), b) diverse redundancy (corrective measures: red arrows)

A fast adaptation of converter reference values after disturbance inception is necessary to provide diverse redundancy while the adaptation (measure) is highly dependent on the systems operating point before the disturbance and the disturbance itself. If the measures are well coordinated among the HVDC converters and both grid topologies are sufficient according to the systems overall loading it will be possible to continuously operate the overall grid system and restore a stable operating point within seconds. A concrete realization option for diverse redundancy is described in chapter III.B.

III. HVDC Grid Operation Hierarchy

For operation of an HVDC overlay grid several control layers will be necessary to deal with all arising challenges regarding the operation of the HVDC grid itself and regarding the interoperability of the AC transmission and HVDC overlay grid. CENELEC working group TC 8X/WG 06 deals with system aspects of HVDC grids and is still in progress [3]. First results show a general controller hierarchy according to Figure 2. Possible methods that can be categorized accordingly are described hereinafter while Coordinated System Control and AC/DC Grid Control layer are covered as these are the most important layers for controls related to interactions between the AC and HVDC grid.

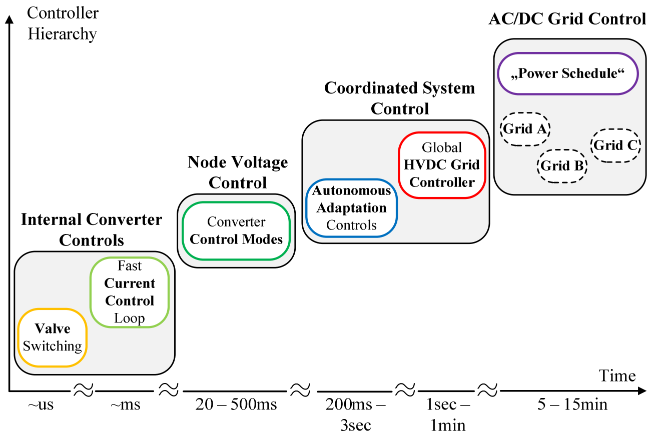

Figure 2. HVDC grid controller hierarchy [3]

A. *Scheduling – operation planning*

AC/DC Grid Control has the largest time horizon and is on the highest hierarchy level of HVDC grid control. It generates converter schedules on a regular basis ideally by coordinating their concrete use with the AC transmission system in order to receive an overall ideal operating point. This optimized operating point can be a result of different objective functions, which can be a classical overall loss minimization or a maximization of stability margins as well as a number of other targets.

Schedules not only include converter reference values (active and reactive power / DC and AC voltage), but also information on converters' control modes and control parameters. Additional information that will be provided with each schedule are addressed in subchapter III.B.

B. *Local converter set point adaptation based on centralized calculations – Diverse redundancy provision*

According to the classical N-1 criterion it is possible to calculate converter schedules in such a way that in case of any equipment trip both systems, AC and HVDC, are without contingencies. This implies that both systems are properly designed and having sufficient unused transmission capacity each. As described in chapter II this can be highly uneconomical and is avoidable using dynamic behavior and full controllability of HVDC converters.

Therefor it is one possible solution to determine replacement schedules (corrective optimal power flow – corrective OPF [7]) for each converter, each possible fault scenario and for each schedule period. This is exemplarily shown for one converter *x* and one schedule period in Figure 3. It is reasonable to calculate corrective OPFs in advance, e.g. during regular schedule calculation, and deliver them (together with the regular schedule) to converters. At converter level corrective OPFs are stored locally for each possible fault scenario and will be activated in case of local fault identification. In case of a fault scenario, corrective OPFs ensure a continued system operation without contingencies. [8]

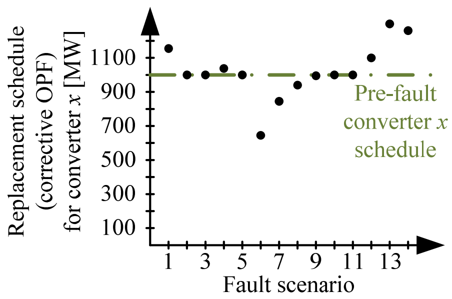

Figure 3.Schematic replacement schedules for converter x considering all possible fault scenarios exemplarily 1 to 14

As it is shown in [8] local identification of fault scenarios at converter stations is possible at least for converters that can avoid contingencies by its set point adaptation. The more distant a fault / disturbance to a converter location is, the less the converter's possible impact is. This is illustrated in Figure 4 using a tripped AC line as a fictive disturbance. Therefore it is not necessary to identify the fault at every converter but only at those that can give a useful contribution for contingency prevention.

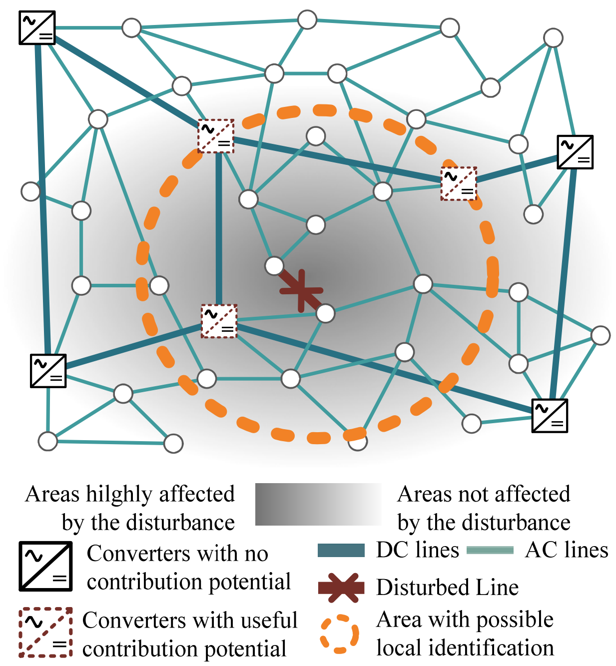

Figure 4. A disturbance within the AC grid (line trip) and its effect on the AC grid, the area where the fault can be identified locally and converters that can give a useful contribution after fault inception to avoid contingencies

A trip of an AC-line directly connected to the converter substation can be considered as a trivial detectable but unusual case, since the local identification of this trip scenario can be realized only by using the status information of the attached circuit breaker. Other AC line trips are identified locally using line current i_{ij} and voltage angle δ_u information while the latter is measured using phasor measurement units (PMUs). The measurement of steep ramps or steps of the voltage angle signal caused by transients is not standardized for PMUs yet, but can be considered as feasible according to [9] and [10].

Prior to possible fault identification, simulations define reference values indicating deviations between steady state values of i_{ij} and δ_u and its maximum/minimum within a 10 ms time window for each possible fault scenario Δi_{ij} and $\Delta\delta_u$. This requires less data handling effort than using continuous fault patterns (time series) as these reference values Δi_{ij} and $\Delta\delta_u$ for each fault scenario are send and stored at corresponding converters. During operation measurements within a 10 ms time window are compared to the predefined reference values (see Figure 5) for local fault identification.

There are some fault scenarios that cannot be distinguished from each other on a local basis. This mostly also implies that the corrective measure (converter set point adaptation) is the same for those fault scenarios. Thus, from a local point of view regarding corrective measures this is also defined as clear fault identification. If there is no clear fault identification possible, no operating changes will be activated.

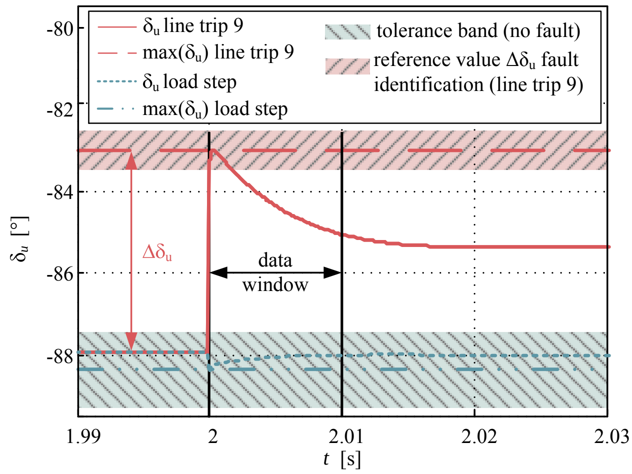

Figure 5. Identification principle for Δδu criterion concerning a line trip (simulation results) [8]

After clear local fault identification the dedicated precalculated converter reference active power is activated immediately. At the same time, the local DC voltage control is deactivated for this converter in order to prevent a significant active power deviation from the corrective schedule due to DC node voltage control. Converters within the same HVDC grid that have not locally identified the fault scenario will take care on the DC energy balance (DC node voltage control).

Replacement schedule for converters are coordinated a priori for each possible fault scenario and activated locally without another coordination instance. This control method can be categorized in Autonomous Adaptation Control as part of Coordinated System Control (see Figure 2).

C. Local converter set point adaptation – angle gradient method (AGM)

Probably some very unusual fault scenarios are not considered for a priori replacement schedule calculation (described in subchapter III.B) or a local identification is not successful for any reason. In such cases another control instance has to make sure that significantly changing AC power flows compared to the actual schedule are detected and converter reference values are adapted accordingly. This is essential in order not to overload any equipment in the grid but to share those additional power flows on certain power paths between the AC and the HVDC grid.

One possible solution to do so for HVDC overlay grids is described in [12]. This approach adapts HCDC converter power set points if any significant AC power flow changes take place. Therefore PMU / wide area monitoring system (WAMS) data are used in order to get an information on global power flow directions and amount given by voltage angle gradients Δδ between AC grid nodes. Angle gradient information as the control input for this method include an inherent coordination among the converters without an additional centralized coordination instance. As this control method is based on angle gradients between AC nodes it is called Angle Gradient Method (AGM).

This control method can also be categorized in the in Autonomous Adaptation Control as part of Coordinated System Control (see Figure 2).

D. SCADA update

As local fault identification for corrective OPF activation may be incomplete and, as the AGM, is less effective for contingency prevention, it is reasonable to include another centralized instance. This instance receives all information from local disturbance as well as WAMS information and is ideally the already existing supervisory control and data acquisition (SCADA). With those information it is possible to trigger corrective schedules from a central control instance.

This control method can be categorized to be a part of the Global HVDC Grid Controller as part of Coordinated System Control (see Figure 2).

E. DC voltage control

All control methods described in subchapters III.A-D define converters' active power reference values. However, the highest maxim in HVDC grid operation is the stability of the HVDC system itself. This is ensured by controlling the DC energy balance, which is comparable to AC systems. The indicator for an energy imbalance is the DC voltage.

There are small time constants in DC grids as DC voltage control is favored to be a local control at converter level, e.g. realized by $P_{\text{converter}}$-U_{DC}-Characteristics [11]. If the measured DC voltage deviates from its reference, the active power reference value (defined by the previous described instances in III.A-D) will be modified accordingly.

This control instance is the last one changing the converter power reference which is the input variable for the inner converter control loops as it is illustrated in Figure 2.

IV. COORDINATION OF METHODS

All methods described in chapter III represent parallel running control methods for future HVDC grid operation. Figure 6 illustrates its interaction and time ranges in which they act after a disturbance.

Using all those information a clear active power reference value must be created. On a regular basis converter schedules are provided based on a global coordination. As a lot of information can be input variable for this global coordination it may take a while to calculate. The schedule information is marked with a time stamp indicating that point in time when all necessary data for the central coordination and corrective OPF calculation have been collected.

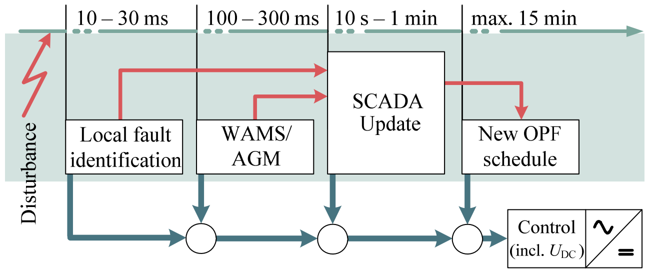

Figure 6. Operation instances for HVDC grids including time span for its action/effect after a disturbance

When a new schedule arrives at the converter its time stamp is compared to the time stamp when the last disturbance was identified locally (see Figure 7 b)). If this fault identification is younger than the schedule time stamp, not the new regular schedule is activated but the new corrective OPF schedule corresponding to the fault scenario identified before. I.e. the old corrective OPF schedule for the identified fault is replace by the new one corresponding to the new schedule period and the identified fault (see Figure 7 a)).

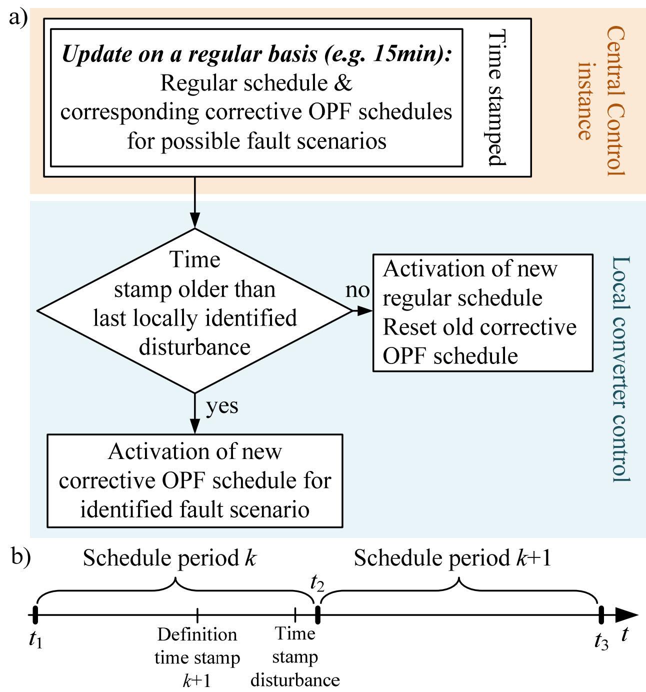

Figure 7. Schedule handling

If the disturbance identification is older that the schedule time stamp, it is assumed that the disturbance identification is already considered for schedule calculation. Thus, in this case the new regular schedule is activated and an old still active corrective schedule is reset (see Figure 7 a)).

The method used to provide diverse redundancy (subchapter III.B) is using the corrective OPF schedules provided with each regular schedule. Its activation is based on a local disturbance identification. In such a case the corrective OPF is activated immediately and replaces the regular schedule without any additional synchronization. The AGM (subchapter III.C) is also activated locally without any additional synchronization based on WAMS information. This can cause a conflict between both methods that must be avoided. If converter reference values are adapted in order to provide diverse redundancy this will probably also noticed by the AGM that will adapt converter references accordingly. This may happen in a contra productive manner probably endangering diverse redundancy.

Thus it is reasonable to block AGM after a local fault identification for some seconds but at least until power flows reached a steady state. Based on this steady state AGM is activated again and can react in case of additional disturbances.

V. CONCLUSION

Assuming that an HVDC overlay grid will become reality within the next decades, it will be the backbone of the future power system. Thus it is mandatory not only to create single HVDC operation methods but a whole set of operation methods including their interoperation and backup mechanisms. In order to ensure a safe interoperation coordination concepts between single methods are needed.

This concept paper proposes coordination between different operation methods that are related to different operation hierarchy levels. Therefore the following operation methods are described in chapter III:

- Scheduling of converters – operation planning
- Diverse redundancy – redundancy for the overall AC/DC grid by fast triggering of converters in case of disturbances
- Automatic participation of the HVDC grid in unscheduled AC power flow changes
- Irregular SCADA updates triggering converters after disturbances
- DC voltage control – DC energy balance

In chapter IV a coordination of those different operation methods is proposed in such a way that some methods provide a backup for others.

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