21, rue d'Artois, F-75008 PARIS
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Impact of multi-terminal HVDC grids on AC system stability and operation

E. CIAPESSONI
D. CIRIO
A. GATTI
A. PITTO
RICERCA SUL SISTEMA ENERGETICO - RSE
Italy

A. M. DENIS
RTE - RÉSEAU DE TRANSPORT D'ÉLECTRICITÉ
France

L. HE
C.-C. LIU
UNIVERSITY COLLEGE OF DUBLIN
Ireland

C. MOREIRA
B. SILVA
INESC PORTO
Portugal

SUMMARY

During the last years, several plans for offshore grid development in Europe have been under discussion as a result of the need for the integration of large amounts of offshore wind power, providing additional transmission capacity and building adequate conditions for the single European electricity market. From the system operation viewpoint, technical constraints justify the need for adopting High Voltage Direct Current (HVDC) technology with Voltage Source Converters (VSC) for offshore grid development rather than conventional AC connections. Additionally, reliability and flexibility of operation is pushing for the development of the Multi-Terminal DC (MTDC) grid concept, by which a set of offshore wind farms is connected to a set of onshore AC nodes via a (possibly meshed) DC grid structure. This concept is in line with the envisioned plans for the development of the pan-European Transmission System.

A broad range of aspects related to MTDC grids planning, operation, and technology was dealt within the TWENTIES European research project (2009-2013). In particular, this paper presents some results regarding the impact of MTDC systems on the AC systems they are connected to: specific focus is devoted to provision of advanced ancillary services (primary frequency controls, Fault Ride Through capability to AC faults, reactive power support), to the possible contribution of the MTDC grid in enhancing the operational security of AC systems and in restarting them after partial or complete blackouts. To emphasize the advanced functionalities that can be provided for overall system operation, this MTDC grid is referred to in the paper as "DC Grid" (DCG). Simulation results illustrate the potential benefits for the AC systems deriving from the described advanced control functionalities of DCGs.

The work has been carried out within TWENTIES Working Package 5.

KEYWORDS

High Voltage Direct Current – Multi-terminal grid – Control – Stability – Protection – Ancillary Service

diego.cirio@rse-web.it

1 INTRODUCTION

Wind energy is already a mainstay of clean power generation in Europe, with over 100 GW of capacity installed so far, and another 120 GW anticipated by 2020 according to various analysts [1]. Much of this capacity is expected to be installed offshore, as it is a windier and steadier source compared to onshore wind energy. Hence, offshore wind has been envisaged as making a critical contribution to Europe's demand for electrical energy and to minimising the carbon emissions associated with meeting that demand.

It is well understood that installation, operation and maintenance of offshore facilities, whether associated with the generation, collection or transmission of the electrical energy, is extremely expensive; thus, the correct technologies must be deployed to provide the maximum cost-benefit. For quite long distances offshore, High-Voltage Direct Current (HVDC) transmission is preferred for economic and technical reasons; hence, this technology provides the platform that can be used to enable massive integration of offshore wind farms into AC onshore networks with minimum losses and increased flexibility over power control.

Although no Direct Current Grids (DCG) are operational yet, it has been speculated by many researchers that such grids will provide significant benefits beyond the only integration of multiple offshore wind farms dispersed over wide areas into AC onshore grid. In addition to optimisation of AC and DC transmission infrastructures, and potential improvement of reliability and security of supply, DCG are expected to provide additional functionalities and meet some requirements: wind power transfer function; smoothing of wind power fluctuations; interconnection function (i.e. use of the DCG to exchange power between AC zones); ancillary services (e.g. voltage support, frequency support to onshore AC grids).

Several aspects concerning DCGs planning, operation, and technology have been dealt within the TWENTIES European research project (2009-2013) [1]-[6]. In particular, this paper presents developments regarding the impact of DCGs on the AC systems they are connected to. The following sections respectively address the possibility of the DCGs to provide advanced ancillary services (section 2), to enhance the operational security of AC systems (section 3), and to restart them after partial or complete blackouts (section 4).

2 ANCILLARY SERVICES

A fully operational DCGs with offshore Wind Farms (WF) can be regarded as a large (virtual) power plant capable of providing ancillary services to the mainland AC grids. Therefore, it is expected that DCGs provide Fault Ride-Through (FRT) capability for faults occurring in the mainland AC grid. Moreover, large-scale integration of wind energy leads to a displacement of conventional generation units that negatively impacts frequency stability. Therefore, it is expected to involve offshore WFs in frequency regulation services carried out through DCGs. Proposals for control solutions addressing these two topics are discussed in the following.

2.1 FRT capability in DCGs

The DC voltage rise due to the onshore VSC power transfer reduction during AC grid fault is the major concern for the development of any control strategy. Some authors [7] develop control strategies assuming the use of communication links to perform power control at the WF level. Nevertheless, this solution may not comply with the restricted time-frame required to mitigate the DC voltage rise in case of a fault. Additionally, the specificity of DCGs increases the challenge for the implementation of communication networks for fast control actions. In general, a communication-based solution demands for some coordination regarding the decision making process for the definition and assignment of power in-feed reductions in the MTDC nodes required to control the DC voltage rise. In this specific case, communication delays or failures may cause unacceptable DC overvoltages, precluding the successful implementation of FRT capability. To overcome the bottlenecks of communication-based solutions, a new control philosophy to assure FRT compliance in DCGs has been developed within the project [5]: the implementation of a decentralized control structure fully based on local controllers to be housed at HVDC-VSC stations and at the offshore wind generators. The local control solutions aim to mitigate the DC voltage rise based on the fast control of wind turbine power output which is achieved through offshore grid voltage or frequency control strategies, as generally depicted in Figure 1.

The DC voltage rise can be used in order to control the magnitude of the AC output voltage of the offshore HVDC-VSC. Therefore it is suggested to include a local control at the HVDC-VSC station that proportionally decreases the AC voltage as a function of the DC voltage rise in the converter DC terminal:

$$V_{AC} = V_{AC_{ref}} - k_{DC/AC} \times \left(V_{DC_{ref}} - V_{DC}\right)$$

where V_{AC} is the offshore AC voltage magnitude, V_{ACref} is the AC voltage magnitude reference, $k_{DC/AC}$ is the droop gain that adapts the DC to the AC offshore voltage, V_{DCref} is the steady state DC voltage reference and finally V_{DC} is the actual DC voltage magnitude. With the use of this strategy, wind generators will be able to react to the offshore AC grid undervoltage and quickly reduce the injected active power. In this case, and in order to successfully implement the WT power regulation based on offshore AC grid voltage control, the WT generators must not inject reactive current when decreasing the offshore AC voltage as a function of the DC voltage rise.

The DC voltage rise can also be used in order to control the frequency of the offshore HVDC-VSC. In this case, it is suggested to include a local control at the offshore HVDC-VSC station that proportionally increases the AC grid frequency as a function of the DC voltage rise in the associated DC converter terminal:

$$f_{offshore} = f_{ref} + k_{DC/f} \times \left(V_{DC_{ref}} - V_{DC}\right)$$

where $f_{offshore}$ is the actual offshore frequency, f_{ref} is the reference value for offshore frequency, $k_{DC/f}$ is the droop gain that adapts DC voltage to offshore frequency variation. This control scheme is to be complemented at the wind generator level with a control loop that provides a fast generator power reduction as a function of the offshore AC grid frequency increase.

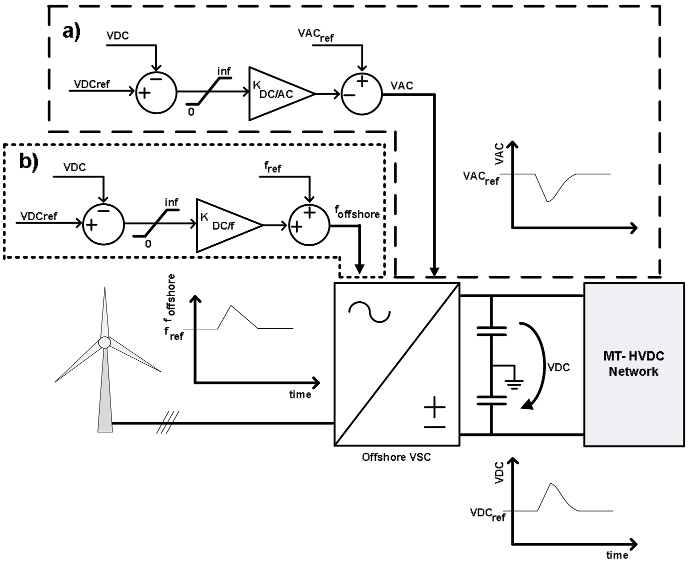

Figure 1. Control scheme for FRT provision: a) AC offshore grid voltage control, b) AC offshore grid frequency control

2.2 Frequency control services from DCGs

Some studies have investigated the possibility of endowing offshore WF connected to an AC grid with primary frequency control capability (PFCC), without neglecting inertial emulation, relying also on a solution based on a communication system. This paper presents also a communication-free solution based on local controllers to be installed at HVDC-VSC which will autonomously allow the provision of frequency control services. The proposed control strategies consist on the use of a cascading reproduction of AC grid frequency deviations into MTDC voltage variations. Subsequently, MTDC voltage variations are used by the offshore HVDC-VSC for controlling the offshore WF AC grid frequency. Thus, offshore WF AC grid frequency variations will be the driving signal for frequency regulation loops to be adopted at the wind generator level.

The general idea behind the development of the local control mechanics proposed in this work requires that frequency variations in the mainland AC grid are transposed to DC voltage deviations through the adoption of an AC frequency to DC voltage droop control. The onshore HVDSC-VSC converter station measures the terminal frequency and whenever it drops below a certain margin, the droop control relating onshore AC grid frequency and MTDC voltage enters in operation, according to the following equation:

$$V_{DC} = V_{DC}^{0} - k_{fv} \times f_{grid}$$

where V_{DC} is the reference value for the DC voltage at the onshore HVDC-VSC, V_{DC}^{0} is the pre-disturbance DC voltage, k_{fv} is the frequency/DC voltage droop and f_{grid} is the frequency of the onshore AC grid to which the converter is connected. At the offshore converter level, the WF AC grid frequency should be controlled based on the DC voltage variation. Therefore, the offshore HVDC-VSC control should include an additional control droop responsible for varying the offshore AC grid frequency proportionally to the DCGs voltage variation. In this case, conventional de-loading operating mechanisms for wind generators can be used to exploit frequency regulation services from offshore WF.

3 DC GRID OPERATION AND SECURITY OF THE AC SYSTEM

The future integration of DCGs into the AC systems calls for an updating of current security assessment analyses which should be extended to analyse the impact of contingencies, whether AC or DC, on the overall AC/DC system. Security assessment of the resulting AC/DC system will require detailed dynamic simulation of the overall system response to AC and DC contingencies. To this aim, accurate models of the protection and control systems of the DCG, suitable for stability evaluation, need to be integrated into conventional simulation tools. Specific aspects of the converter design must be taken into account, as converter configuration affects the AC response to DC faults. Similarly, dedicated controls such as the ones presented above, or other emergency control schemes may significantly impact stability, and need to be modelled for security assessment.

Completely new functions for security assessment and control of the joint AC/DC grid will be needed for operational planning and operations purposes. Moreover, the DCG can play an active role in enhancing security of operation of the AC system, as controllable power injections can take part in preventive control actions. Along these lines, some steps performed within TWENTIES consist in a tool for static security assessment of DCGs, which analyses the outage of DC components (DC cable or converter), and in a risk optimisation procedure for AC grids based on the DC injection redispatch.

3.1 Security assessment

"Static security assessment" is a fundamental assessment function not only for AC grids, but also for DCGs. In fact, only in radial DC links the power (and/or current) is controlled by the converters. With more complex grid topologies, the power flow may not be controlled, hence overloads may occur especially as a result of contingencies. Similarly, voltage may exceed the acceptable range e.g. in case converter control limits are reached. Static security assessment requires modelling the post-contingency steady state behaviour of the DCG. This includes modelling the steady state effect of the control paradigms that may be embedded in the DCG, e.g. both quasi-steady state controls such as P-V droop of converters, and more complex defence strategies needed to assure short-term stability. Within the developed DCG static security assessment function, a wind curtailment scheme is assumed to be operating in case of large unbalance between maximum power evacuation capacity of the DCG and wind power generation. Moreover, in case the DCG is split into islands as a consequence of the contingency, VSCs may shift the control mode in order to control voltage (constant V or V/P droop control). In fact, due to the envisaged small degree of meshing in DCGs, a contingency in the DCG may likely cause the separation of the DCG into islands.

The application of the tool on several DCG topologies (H-shape, three leg backbone or meshed topology, cf. [2]) highlights the most critical contingencies in terms of possible violations of security criteria in the post-contingency steady state. To this regard, the criteria to assess static security in DCGs are as follows:

- **N security criterion** (secure operation with no contingencies)
  - The current on all DC cables should not exceed 100% of the maximum current;
  - The voltage at all nodes of the DCG should not get out of a symmetrical band around its nominal value and with half-width equal to 3%;
- **N-1 security criterion** (secure operation after a single contingency)
  - The current on all DC cables should not exceed 110% of the maximum current
  - The voltage at all nodes of the DCG should not get out of a symmetrical band around its nominal value and with half-width equal to 6%

3.2 Participation to preventive controls to enhance AC system security

DCGs can be active players in enhancing security of operation of the AC system, as their power injections can be subject to preventive control actions aimed at improving AC system operational security.

The present subsection presents risk-based control strategies [8][9] to reduce the risk of high currents on AC corridors. The rationale of the proposed strategies is to minimize the overall high current risk over a certain time interval of analysis (relevant for the evaluation of contingency probability; e.g. 15 minutes), while minimizing the redispatching costs of conventional generation and power injections from the DCG. Generation redispatching is a typical preventive control action (others may be grid topological changes). On the other hand, power injections from the DCG can be controlled and possibly "shifted" from one converter to another, provided that operational limits are met.

The non-linearity of the high current risk indicators with respect to branch currents is solved by using a Successive Linear Programming (SLP) algorithm [10] which transforms the nonlinear optimization problem in a sequence of first-order approximations (i.e. linearisations) of the model. The independent variables of the problem are the injections at conventional generators and the power injections of HVDC terminals. Suitably small bounds are used for injection variations to assure a robust (though slow) convergence of the algorithm.

Two redispatching strategies are proposed as linear programming problems to be solved at each step of SLP:

- *weight-method linear programming* where the objective function is a linear combination of the operational risk and of the redispatching costs of conventional generation and DCG injections (OF = costs + $\mu \times$ risk). A penalty factor μ (called risk aversion cost) weights the importance of risk reduction in the OF. The rationale for this definition of the OF is to minimize the risk, while minimizing the power redispatch costs. “Shifting” power injections of the DCGs from one terminal to another may be less costly than redispatching generators.

- *constraint-method linear programming* where the risk is a constraint of the problem: the objective function consists only in the redispatching costs, and the operator has to set a suitable value of the residual (target) risk also on the basis of his experience.

Inequality constraints include the operational limits of generating units and the maximum currents on DC cables, while equality constraints include the invariance of conventional generation and the invariance of the overall active power injection for each DCG.

The strategies have been tested on several DCGs with different topologies (H shaped, three leg backbone) connected to the same AC system (the 39 bus New England tests system, see Figure 2). For both the DCG topologies, the contingencies under study affect bus 29 close to one of the DCG terminals.

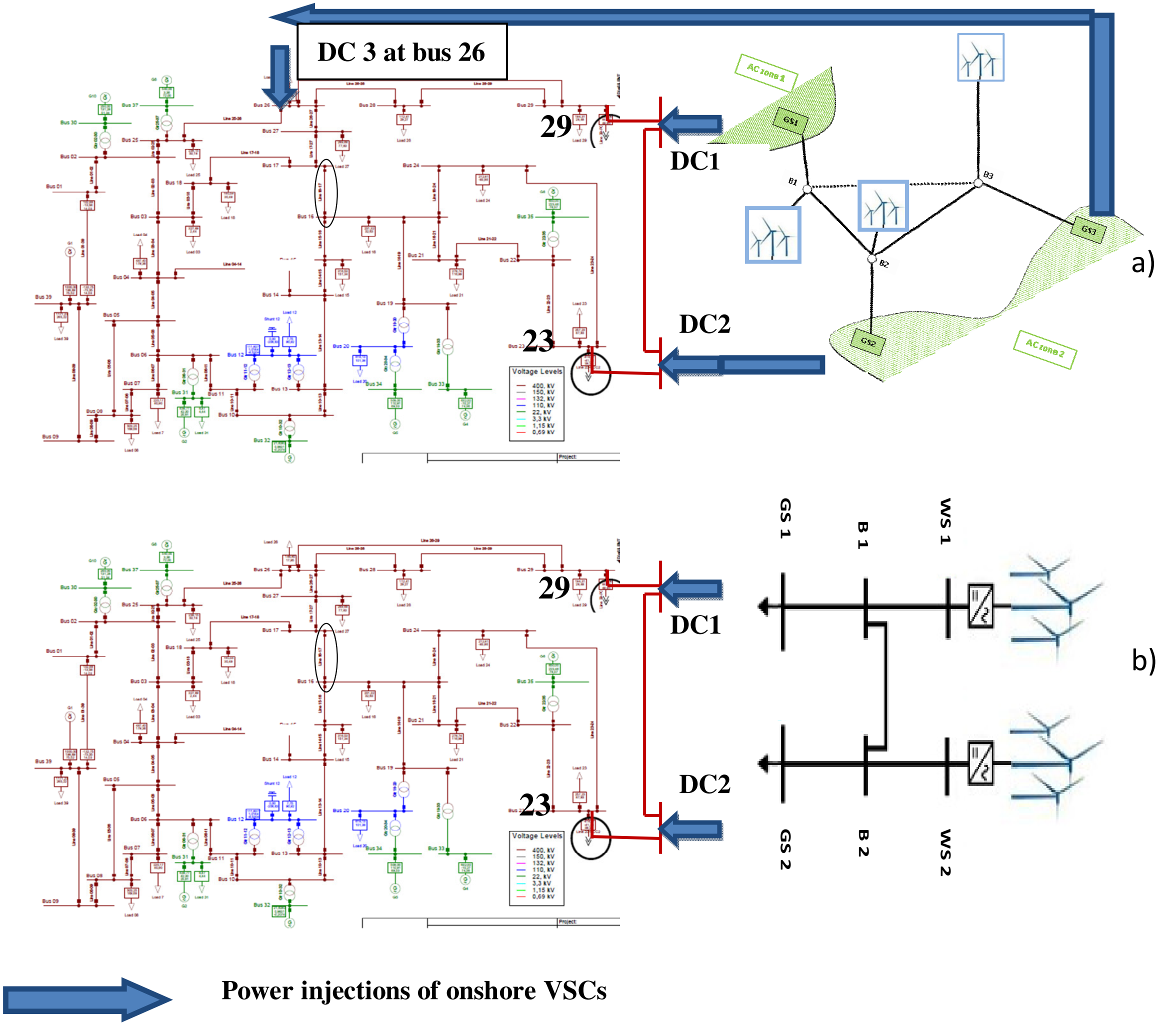

Figure 2 - AC/DC test systems. On the left, IEEE New England test system. On the right, (a) “backbone” 3-leg DCG; (b) “H” DCG [5]

The comparison between the H-shape topology and the three-leg topology case highlights the increase of flexibility that can be achieved by using a higher number of onshore terminals in DCGs. This implies assuring security on AC systems at lower redispacthing costs. In fact, given the specific contingency set under study and the location of the HVDC terminals (DC1 and DC2) of the H shaped grid, no benefit in terms of security improvement can be achieved by shifting the DCG injections (also for high aversion risk costs). Simulations also point out that operating DC cables close to their maximum currents can limit the support of DCG injections to the preventive control action.

Given the same three leg topology, simulations point out that the weight method approach (where the risk appears as a term of the objective function) provides a risk reduction which can be achieved by the constraint method (where the risk appears in an optimization constraint) at much higher costs. Given the same DCG topology (H-shape or three-leg) the comparison between the “deterministic” preventive control (based on DC OPF techniques, and on the strict fulfilment of N-1 security criterion) and the “weight method” risk based preventive control indicates that the risk based approach can help solve congestions on AC systems at lower costs wrt conventional deterministic controls: in particular they reduce operational risk of AC systems avoiding the fulfilment of strict security criteria (N-1 criterion) but limiting the branch overloads to acceptable levels which may be managed by operators’ actions over larger time intervals.

4 RESTORATION

The high level penetration of offshore wind power can dramatically increase loading of the transmission grid. The reduced system stability margin increases the vulnerability of a power system during severe contingencies. It may result in widespread power outages in integrated AC/DC systems following a major disturbance. System restoration after wide-area power outages can be difficult and time-consuming. Generally, the power plant selected as a black start unit is equipped with small diesel generators that provide its black start power support. For generators with steam turbines, the required black start power support can be up to 10% of the capacity of generators for boiler feed-water pumps, boiler forced-draft combustion air blowers, and fuel preparation. It is costly to provide such a large standby capacity at a power station, especially for the oversized diesel generators. With the innovation of wind technologies, the variable-speed wind turbine technology enables the regulation of power factor by absorbing or producing reactive power. Over the last decade, the DFIG has become the dominant technology in the global market for wind generators. Therefore, it is important to evaluate DFIGs as a potential black start unit to restore ac mainland grids through a HVDC connection.

Compared with the traditional restoration equipment, wind energy can be a valuable asset to significantly lower investment and maintenance cost. The DFIG inherent operation characteristics make it possible for wind farms to serve as a black start unit for ac system restoration through HVDC links **Errore. L'origine riferimento non è stata trovata.**. The simulation results show that flexible HVDC control can effectively alleviate transient and steady-state overvoltages due to energisation of unloaded lines and provide frequency control before the synchronization of generators. This will help to reduce the restoration time and smooth the restoration process.

5 CONCLUSIONS

The paper has presented some results of the activities performed within Work Package 5 of the EU FP7 co-founded Project TWENTIES, related to the assessment of the impact of multi-terminal HVDC networks, aimed to integrate large amounts of offshore wind power, on the AC bulk power system.

VSC control laws must assure flexible operation, which can be achieved by integrating different functions (wind power transfer, interconnection, and ancillary services). DCGs based on VSC technology can effectively provide ancillary services such as FRT capability, primary frequency reserve and other functions that can be achieved through proper control of the VSC and possibly of the wind generators, such as oscillation damping and inertia emulation. In particular, pros and cons of (both centralized and decentralized) solutions for FRT capability provision have been examined, in order to suppress dangerous overvoltages caused by sudden power unbalances on the DCGs. Moreover, a communication-free coordinated control has been proposed in order to make offshore wind farm generation sensible to frequency deviations on the mainland AC system. Simulations confirm the effectiveness of proposed controls.

As far as operational security assessment is concerned, the function for static security assessment developed within the project considers N-1 outages of main DC components (cables and VSCs), and applies conventional security criteria on the branch currents and voltages in the post-fault steady state.
Moreover, the power injections from the DCGs can be used to support preventive control strategies aimed to enhance the operational security of the AC system (e.g. by lowering the risk of overloading of AC corridors in case of AC contingencies). The proposed risk control strategies are aimed at allowing DCG injections participate in redispatching along with conventional generation, possibly reducing the overall costs associated to security.
Finally, it has been shown how offshore wind farms can be used as black start units to restore AC mainland systems through DCGs. DCG control can effectively alleviate transient and steady-state overvoltages due to energisation of unloaded lines and provide frequency control before the synchronization of generators.

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