HVDC links between North Africa and Europe: Impacts and benefits on the dynamic performance of the European system

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ABSTRACT

In the last decade, there have been several initiatives for the deployment of cross-Mediterranean HVDC (High Voltage Direct Current) links to enable the transmission of electrical power from renewable energy sources between North Africa and Europe. These initiatives were mainly driven by the potential economic, environmental and technical benefits of these HVDC interconnections. In previous studies on these projects, some technical aspects of critical importance have not been addressed or studied in sufficient detail. One of these key aspects relates to the impact and possible benefit of these HVDC links on the dynamic performance of the European system which is the major focus of this paper. Several issues relating to the dynamic performance of the system are addressed here. Based on the experience gained from existing AC/DC projects around the world, this paper shows that the HVDC links between North Africa and Europe can greatly improve the dynamic performance of the European system especially in the southern regions. In addition, some challenges on the operation and control of these HVDC links are highlighted and solutions to overcome these challenges are proposed. This review paper, therefore, serves as a preliminary study for further detailed investigation of specific impacts or benefits of these interconnections on the overall performance of the European system.

Keywords: Renewable energy, HVDC, HVDC modulation, power system stability, power system security, Transmission planning.

1. Introduction

With the growing demand for energy worldwide and global concerns on environmental impact and energy security, green and renewable energy resources have received increasing attention these recent years.

Energy policies in Europe have been continuously promoting the adoption of renewable energy sources and supporting the investment of renewable energy technologies while maintaining acceptable system security standards. The European Union (EU) has set itself an ambitious target of achieving a 20% share of its overall energy consumption from renewables by 2020. Projects such as the Mediterranean Solar Plan (MSP), DESERTEC, and MEDGRID have been launched, in order to interconnect MENA (Middle East and North Africa) countries with Europe and transfer renewable energy from the South to the North of the Mediterranean via HVDC (High Voltage Direct Current) links [1-3]. The MSP [3], sponsored by the Union for the Mediterranean, envisions 20 GW of renewable generation capacity in the Mediterranean region by 2020 in order to supply Europe with green electricity mainly generated from CSP (Concentrating Solar Power). The DESERTEC project describes an enhanced concept [2], in which the electric power generated from CSP plants in the MENA countries is transferred to Europe through HVDC lines. The DESERTEC concept anticipates that 17% of electricity consumption in Europe is to be provided by the MENA region in 2050. The MEDGRID is a large industrial consortium, created at the end of 2010 in Paris [1], which was aimed to promote the development of a Mediterranean interconnection system through the provision of a reference grid development plan to meet future European energy policy targets.

Due to several advantages, the initiatives of clean energy export projects, like DESERTEC or MSP, have given CSP plants a paramount role in North Africa. CSP uses concentrated solar irradiation in order to heat a heat transfer fluid which then drives a power generation process using a conventional steam turbine connected to an electrical power generator. When combined with thermal storage facilities, CSP plants can continue to produce electricity even in periods without solar activity (cloudy days or after sunsets). CSP plants can also be equipped with backup power from combustible fuels. Due to these characteristics, CSP is suitable for large-scale renewable energy projects [4,5]. In Europe, The concept of large-scale transmission of electrical power from renewable sources over long distances is generally called Supergrid (see, Fig. 1) [6,7]. This project has recently received significant attention not only from the electricity sector, but also from the media and research communities.

Fig. 1. Supergrid in Europe: The Desertec concept [2].

Technical and economic advantages such as sharing generation reserves and using more economic energy resources to enhance the reliability of the system are the main drivers for the interconnection of adjoining large-scale networks. However, heavily coupled networks might also be at risk of uncontrollable cascading effects since disturbances that may at first seem of minor importance can cascade over large areas [8]. This problem has drawn special attention after the series of large-scale blackouts which affected some parts of the world [9,10]. Furthermore, through this development of power systems, different forms of system instability have emerged. For example, voltage stability and inter-area oscillations have become greater concerns than in the past [11]. The stability of electromechanical oscillations between interconnected synchronous generators (inter-area modes) is necessary for secure system operation [12]. Research on ways to ensure a reliable and efficient operation of a large-scale interconnected system is becoming an even more pressing issue worldwide.

In recent years, several feasibility studies have been conducted on HVDC interconnections between North Africa and Europe and their role to support electricity export from renewable energy resources [1,4,5, 13-16]. However, most of the currently available literature deals mainly with the political and economic issues, with little attention given to the technical aspects. In this paper, a very important technical aspect addressing the benefits and possible effects of the HVDC links on the dynamic performance of the European interconnected system is discussed. The aim of this research review paper is to present a state-of-

the-art on the assessment and analysis of existing HVDC facilities deployed around the world from the technical and economic perspectives and to investigate the potential advantages of interconnecting North Africa and Europe via HVDC links. This study provides a rigorous and comprehensive evaluation of the merits of such an ambitious project and also highlights the major key challenges for which the authors have identified a range of potential solutions. This paper is intended to provide an initial basis for further work in this area of research.

The rest of the paper is organized as follows. The HVDC transmission technology is briefly reviewed in Section 2. The possible impacts and benefits of the HVDC links are discussed in Sections 3 and 4, respectively. A comprehensive discussion is presented in Section 5. The conclusions of this research study are summarized in Section 6.

2. HVDC Transmission Technology

Fig. 2 shows a simple representation of an HVDC system, describing the basic principle of bidirectional electric power transfer between two AC systems (or nodes).
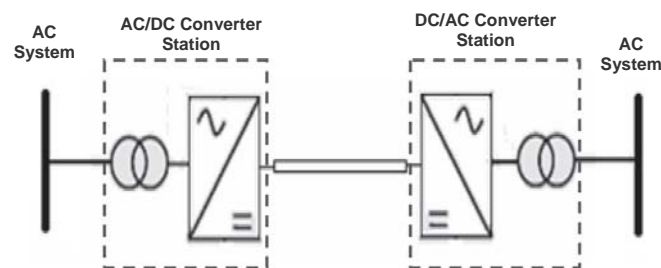

Fig. 2. Simplified diagram of HVDC system.

The AC power is converted into DC at a converter station (rectifier), and then transmitted to the receiving point through an underground cable or an overhead line. At the receiving end converter station (inverter), the power is converted back to AC and then injected into the receiving AC network. In the back-to-back schemes, the two converters are placed at the same location and coupled only by short busbars. The transmitted power is independent of the AC supply frequency and phase. The choice of HVDC systems over conventional HVAC (High Voltage Alternating Current) systems is justified by the substantial technical, economic and environmental advantages HVDC technology has over a comparable HVAC system [17]. Usually, HVDC is the technology of choice when the distance between sending- and receiving-ends is too long for stable and/or economic AC transmission. In particular situations, DC transmission may be the only feasible method of power transmission, such as interconnection of asynchronous systems, and long submarine cable crossings.

An HVDC system requires a power electronics converter for converting electrical energy from AC to DC or vice versa. Two basic converter technologies are used in modern HVDC transmission systems (Fig. 3) [18].
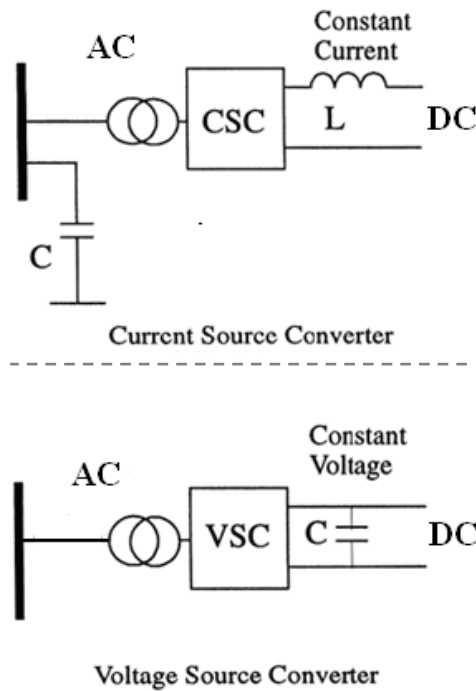

Fig. 3. Converters of the CSC and VSC types.

The most common and oldest technology is based on thyristor valves. It is referred to as line-commutated converter (LCC), or current source converter (CSC). In 1997, voltage source converter (VSC) based HVDC technology was introduced to the DC transmission market. VSC utilizes power electronic valves with both turn-on and turn-off capability, usually based on IGBTs (Insulated Gate Bipolar Transistors).

LCC technology is the most cost-effective solution for large-power and long-distance power transmission, and it has now reached a very high degree of maturity in terms of performance and reliability. Considering the large submarine distances to be covered and the high amount of power to be transported, LCC is the technology is necessary for trans-Mediterranean submarine interconnections [10].

Although LCC plays an important role in long distance bulk power transmission around the world, there are still some problems associated with this technology. One well-known problem is that LCC always consumes reactive power, either in rectifier mode or in inverter modes of operation. The reactive power consumption of an LCC-HVDC converter station is approximately 50-60% of the transmitted power [19]. Shunt capacitor banks are usually connected at the converter stations to compensate for such deficit in

reactive power. Another problem of the LCC-HVDC system is the occurrence of commutation failures at the inverter side caused by disturbances in the AC system [20]. A commutation failure can cause a temporary interruption of power transfer, injection of second harmonic and overheating of the valves. Several repeated commutation failures may force the HVDC link to trip. A major drawback of the LCC-HVDC is that the thyristor valve cannot work properly if the connected AC system is weak (its impedance relative to the DC power is high, or its inertia is low). A common measure of the adequacy of this is the short-circuit ratio (SCR) [21].

Although the recent VSC-HVDC technology overcomes most of the weaknesses of the LCC-HVDC technology, the LCC-HVDC still out-performs the VSC in long distance bulk power transmission due to its higher efficiencies. The VSC-HVDC technology has a relatively low power rating and is still quite new; it is particularly suitable for small-scale power transmission applications such as interconnection of small isolated remote loads, and transmission of power from offshore wind farms.

It is worth noting that an improved topology of the LCC-HVDC using series capacitors in the HVDC converter (see, Fig. 4) has been utilized to overcome some of the problems mentioned above [17]. This converter is referred to as capacitor-commutated converter (CCC). It has been found that CCC has superior performance when it comes to voltage and power stability, especially when it is connected to a weak AC system [18].
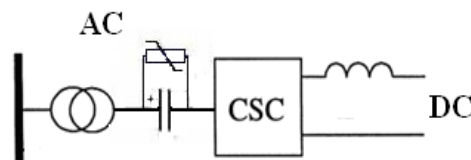

Fig. 4. CCC configuration.

3. Impact of integration of HVDC links into the European interconnected grid

There are two important dynamic phenomena which should be considered whenever an electric power system is expanded:

1. The risk of cascading outages and large blackouts.

2. The inter-area electromechanical oscillations.

The two phenomena are addressed next:

3.1 Cascading failures and blackouts

Detailed analysis of large blackouts has shown that they originate from cascading events in which a triggering failure (e.g., line fault or loss of a power plant) produces a sequence of secondary failures that lead to the blackout of a large area of the grid [8]. Therefore, the interconnections between North Africa and Europe may provide doorways for the propagation of disturbances as already experienced in several large blackouts in different parts of the world. For example, the Northeastern America blackout of August 2003 has spread to a sizable region in USA and Canada by a cascading phenomenon [8]. Another example is the European blackout of November 2006 in which failures propagated from Germany to Southern Europe [8]. These real-life examples demonstrate how a small initial disturbance can, through cascading, lead to a large blackout.

One of the most important features of HVDC systems is that the DC link can dynamically insulate part of the grid from the rest of the system. This, indeed, serves as an automatic firewall against cascading disturbances and prevents large blackouts [24,25]. A good example is the 2003 blackout in the USA and Canada, where the Quebec grid was not affected by the outage due to its DC interconnection to USA, whereas the province of Ontario which had no DC interconnection at its border with the USA was fully affected by the large disturbance [26]. For this reason, an interesting concept is proposed and verified in [27, 28] to reduce the risk of cascading disturbances that cause widespread blackouts. The basic idea of this technique is to segment large AC grids into smaller sub-grids by means of DC links.
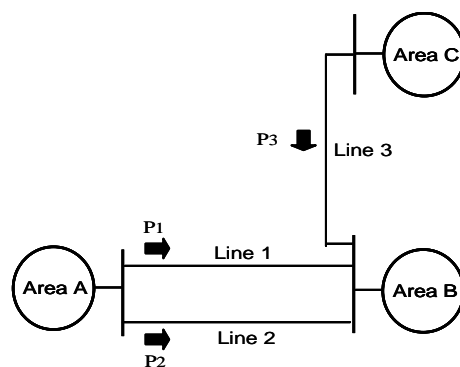
Fig. 5. Power system example.

There are many different mechanisms involved in the dynamics of the cascading phenomenon in electric power systems by which one failure can propagate and cause other failures. However, one common feature of blackouts is the successive outage of transmission lines [29]. The power system shown in Fig. 5 is used to illustrate this. It is

assumed that a large power is generated in area A and the load center is connected to area B, i.e., there is a significant power flow from area A to area B. Suppose that a fault occurs, and line 1 is disconnected from the system. The power flow will be instantly redistributed across line 2 resulting in overloading of line 2 which will subsequently be tripped through the action of its protection system. The fault will then propagate causing new failures, such as tripping of line 3 or loss of generation in Area B. Italy's 2003 blackout scenario is a good example of this cascading failure mechanism where a cascading outage of the tie-lines serving the country led to the separation of the Italian grid from the ENTSO-E (European Network of Transmission System Operators for Electricity) system [32-33]. The 2006 blackout is the most significant disturbance on the ENTSO-E system due to the large number of countries affected. This incident is also associated to cascading overload phenomena leading to the segmentation of the ENTSO-E system into three islands with significant power imbalances in each island [33]. The risk of uncontrollable cascading effects is higher if the power system were to be operated at very high loading conditions, because every component is constrained to operate closer to its loading limit and consequently the cascading outage size is more likely to increase than in the case of low loading condition [8]. The final reports from the 2003 and 2006 blackouts [30,33] state that the two incidents were due to the high cross-border exchanges of power following the opening of the electricity market. With the liberalization of electric utilities in Europe, the capacities of cross-border tie-lines of the electricity transmission systems are gaining significance [34]. Several border sections are identified as critical bottlenecks, particularly the Italian border (where the Italian blackout of September 2003 started) due to the permanent heavy power import from the North as shown in Fig. 6. In general, there are large power transfers in the North-South direction which results in several critical bottlenecks in cross-border networks. Moreover, the fast development of renewable energies of variable nature (such as wind and photovoltaics) at different corners of the region and far from the load centers creates new challenges for the European power grid. The transmission grids will be operated closer to their limits in the future, and consequently the vulnerability of cross-border flows in the North-to-South direction will tend to increase. To ensure security of supply and to improve system stability it is essential to increase transmission capacities between European countries and within market zones, especially in the Eastern and South central region. However, this solution is now no longer sufficient due to the low public acceptance of new overhead power lines (due to their adverse environmental impacts),

which forces TSOs (Transmission System Operator) to maximize the use of the existing corridors [35]. This can lead to the non fulfillment of the N-1 criterion, as already reported in various studies [30-33].
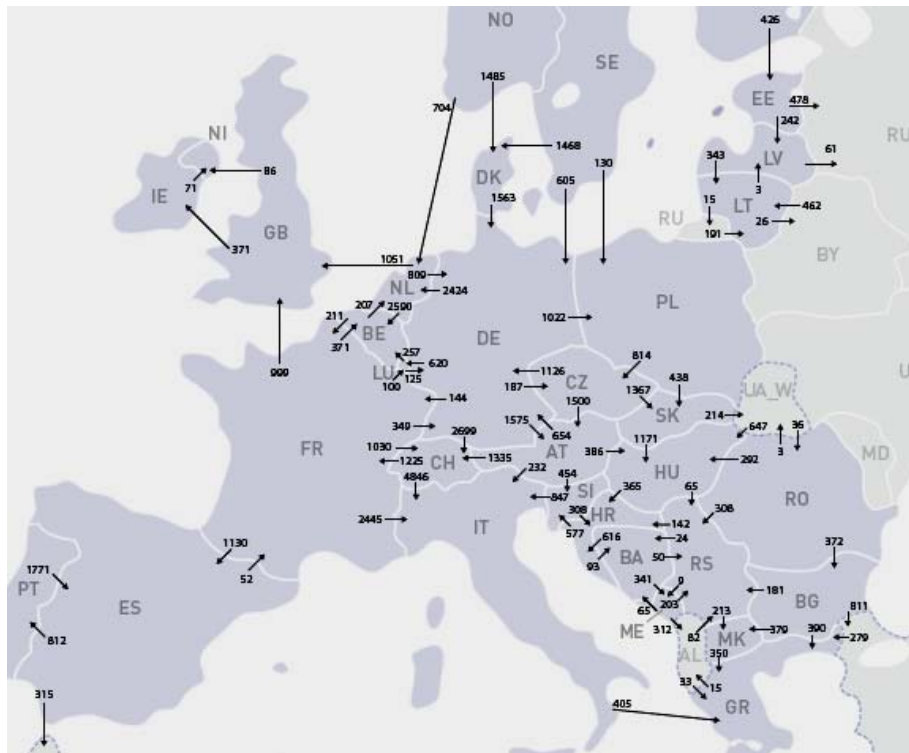

Fig. 6. Cross-border power flows in ENTSO-E system recorded on 21/01/2015 (Source: ENTSO-E).

HVDC links between Europe and North Africa will not only act as a buffer between the two systems against instability problems and voltage collapse, but are also likely to be the key for improving both security and efficiency of the European interconnected system, especially at the Italian border by reducing the massive power imports from the Northern countries. Power flows through the HVDC links are directly controlled by their interconnector operators, so being essentially independent of the phase angle difference of the voltages at the two ends of the link. Therefore, HVDC links will never be subject to unforeseen increases of power flow due to the outage of system components. They will continue to deliver power and provide valuable generating support to the Southern areas.

The reduction of power transfers in the Italian Northern border offers a valuable solution to the problem of parallel flows that take place in different parts of the ENTSO-E system. Parallel (or loop) flows is a major problem in a highly meshed power system, which can be described as follows: while two neighboring system buy and sell contracted power through the tie-lines between them, a portion of transacted power may loop around through other systems in the interconnected power system [36]. This

problem has recently become more stringent because of the difficulty in constructing new transmission lines [37]. Unscheduled parallel flows often force the TSOs to operate their systems below the security levels [38]. Power Transfer Distribution Factors (PTDF) are the most commonly used indices to assess the problems of loop flows when considering large exporters or importers of energy in a meshed network. PTDFs show what percentage of a transfer would appear on each interface if a given power is sent from a specified source to sink [39]. As an example, Fig. 7 shows PTDFs in base case conditions during a transaction between France and Italy with the numbers indicating a percentage flow through a given border. Only 39% of the contracted power crosses the French–Italian border while consistent parallel flows involve Belgium, Germany, Austria, Slovenia, and especially Switzerland. The Swiss network is also highly affected by power exports from Germany to Italy as can be seen in Fig. 8. The power imports from Africa to Italy will contribute significantly to the reduction or even elimination of loop flows in several systems. Consequently, this will alleviate the grid charges to be paid to the TSOs of countries that are not directly involved in the transaction as a result of hosting cross-border flows of electricity on their network [40].

The HVDC links between North Africa and Spain can have a positive impact on the cross-border lines between Spain and France which is considered as a critical zone [34].
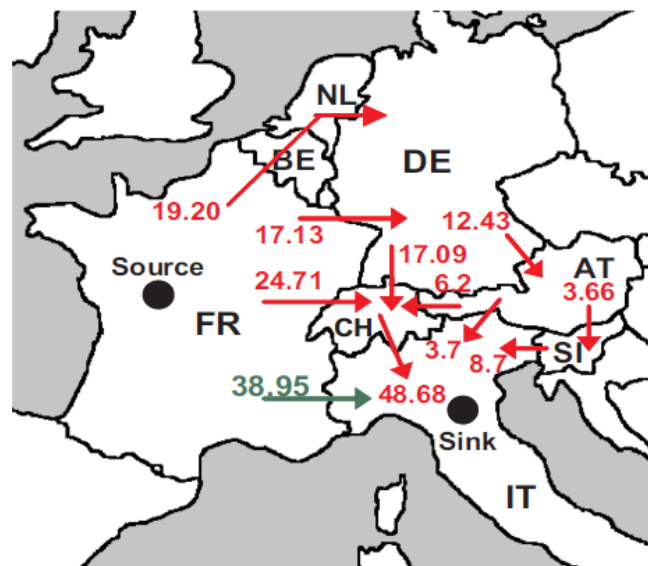

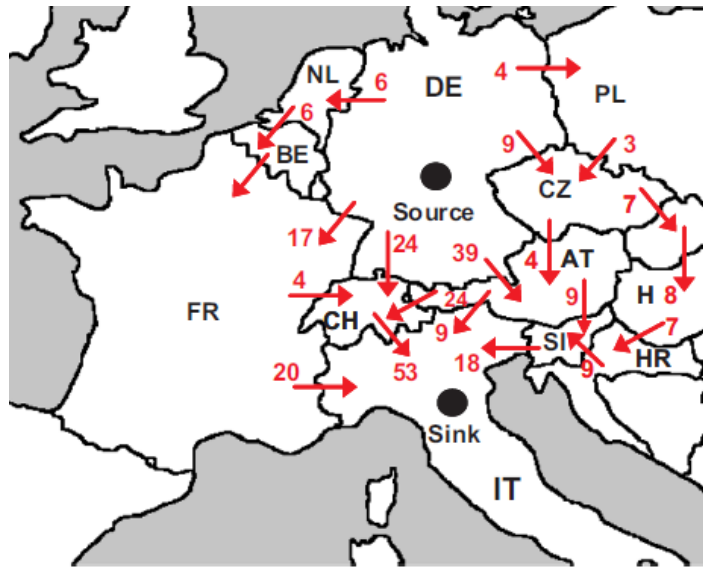**Fig. 7.** PTDF values for a France–Italy transaction [37].

Fig. 8. PTDF values for a Germany–Italy transaction [39].

3.2 Inter-area oscillations

With the expanding interconnections and increasing power interchanges in electrical grids, low-frequency (0.1-1 Hz) oscillations called inter-area oscillations have been observed in power systems for many years [41]. With the expansion of modern interconnected power system such as the ENTSO-E network in Europe, inter-area low-frequency oscillations are becoming a phenomenon of concern in power system operations. In many cases, unacceptable inter-area oscillations have become the limiting factor for the transfer capabilities. In addition, these oscillations may pose a serious threat to power system security if they are not controlled properly as in the case of the Western American blackout of August 1996 when the 0.25 Hz western inter-area mode became unstable, leading to system separation with heavy loss of loads. The negative damping of the 0.25 Hz inter-area mode occurred due to loss of two transmission lines [12].

Several studies have been carried out in the past using modal analysis and time-domain simulations to assess the nature of oscillation patterns in the ENTSO-E system [42-48]. With the help of the evolving technology of wide-area measurement system (WAMS) which has been installed in different countries, it has become possible to record information about the profiles of the inter-area oscillations of interest [49,50]. Many inter-area oscillation studies have been carried out in the past and it was revealed that the ENTSO-E system comprises only three global inter-area modes which affect the whole system, whereas most modes present regional inter-area modes. The three global modes are of particular importance due to their considerable effect on the whole system stability under insufficient damping conditions. The observed

inter-area oscillations (global modes) are shown in Fig. 9. The main mode of interest is the North-South mode with a frequency around 0.23-0.27 Hz and which causes generators in Southern Italy to oscillate against those in Northern Germany and Denmark. The other two modes are swings in the East-West direction. The well-known East-West mode (0.17-0.23 Hz) causes the generator groups in Spain and Portugal to oscillate against the Eastern part. The connection of Turkey to the ENTSO-E system, at the end 2010, resulted in a new East-West mode (0.13-0.15 Hz) in which generators in Portugal and Spain oscillate against those in Turkey. Besides these three global modes, several regional modes are identified, especially in the Italian system due to its longitudinal structure. It is well known that damping of inter-area modes is influenced by the global load flow in the system. Also, the expansion of the interconnected system causes the inter-area modes to become lightly damped or even unstable. The large-scale integration of renewable energy sources within Europe is expected to result in higher cross-border as well as internal power transfers. Therefore, the reinforcement of the existing power systems will be essential to avoid stability problems. When considering further possible extensions of the ENTSO-E system towards the countries of North Africa via HVDC links, the system stability will become more and more important. For example, when the Turkish power grid was connected to the ENTSO-E system in 2010, a new East-West inter-area mode with insufficient damping was detected at 0.15 Hz and the former East-West mode of 0.2 Hz was deteriorated [45,51]. Therefore, a prerequisite for these interconnections with North Africa is to investigate the impact of the planned HVDC links on the stability of the overall system and assess their impact on TSO planning and operations because the HVDC links have controllable characteristics which could potentially affect system stability, especially the Spanish and Italian systems which are actively involved in the three global modes.

Based on the study presented in [52], the addition of a DC link with remote generation to an interconnected AC system has a small impact on the existing inter-area modes and does not introduce an inter-area mode owing to its asynchronous nature. In other words, there will be no inter-area modes between Europe and North Africa. Furthermore, based on this study [52], the generating units in North Africa will not participate in any inter-area mode in the ENTSO-E system, and this would be beneficial for monitoring and controlling inter-area oscillations in the ENTSO-E system.

Fig. 9. Dominant inter-area modes in the ENTSO-E system.

Since the damping of the global modes depends essentially on the loading of the tie-lines between different areas (i.e. countries), the electricity imports from North Africa will have a significant impact on the damping of these modes. For instance, in Italy, the electricity imports from North Africa can reduce the power imports from the Northern border (France and Switzerland) [14,15], and this will improve the damping of the North-South mode and some regional modes in the Italian system. On the other hand, in Spain, the electricity imports from North Africa will increase the power exports to the centre of the system (i.e. from Spain to France). This export will lead to a deterioration in the damping of the East-West mode (former mode) as already pointed out in several studies [42,46].

4. Benefits of HVDC links for system enhancement

As mentioned above, there are already some plans to build a "Supergrid" for connecting all Europe, North Africa, and even parts of the Middle East. HVDC technology has been proposed for power transmission due to its technical, economic and environmental advantages. In fact, it is the only feasible method of power transmission in the Mediterranean Sea. The HVDC system offers a number of benefits for the system interconnection due to its ability to control the power flow and its flexibility to adapt to different AC system characteristics at both sides of the interconnection. These benefits are discussed below:

4.1 Power flow control

Unlike in HVAC interconnections, the power flow through HVDC links can be controlled rapidly and accurately. Both the power level and direction of power flow can be controlled simultaneously. The DC power flow control has an impact on the global grid power flows, which can be used to improve the performance of the interconnected system in terms of reliability and blackout prevention. As discussed above, one common cause of blackouts is the cascading failure of transmission lines. The active power through the HVDC link is determined by the control system and is not dictated by the phase angle difference of the voltages at the two ends of the link. This means that if an AC line tripping occurs, power flow will change in the other AC lines, however, there will not be any change of power at the HVDC link. Therefore, the HVDC links do not become overloaded and will continue delivering power even under varying AC voltage, frequency and phase angle conditions [53]. For example, during the large 2006 blackout in Europe, the operation of the HVDC links between Scandinavia and Europe was not affected by the frequency deviation on the ENTSO-E side and the available capacity of all these links was almost fully used [33].

As discussed previously, the HVDC links in Québec acted as an effective "firewall" against stability problems and voltage collapse during the 2003 North American blackout. Furthermore, the HVDC links of Québec continued to supply power to Western New York and New England and supported the US network during the system restoration after the blackout [26]. The blackout in Western North America on the 22nd of December 1982, is another example which demonstrates the potential advantages of HVDC links. The Pacific HVDC Intertie was the only transmission to the Southern California Island that remained in service after the outage. The HVDC system limited the extent of system outages and provided valuable generating support to the Southern California and Southern Nevada areas [24,54]. Based on these experiences, it is expected that HVDC links between Europe and North Africa will play an important role in supporting the Southern European network and minimizing customer outages after the separation from the rest of the ENTSO-E system contrary to what happened in Italy during the September 28, 2003 blackout.

Due to its inherent control capability, HVDC transmission can be used to improve the security of the AC interconnection following contingencies such as loss of generation or tripping of nearby AC line. A rapid balancing of the DC power (either in a manual or automated way) will reduce stress on the AC system and

thereby prevent large cascading outages or even blackouts in the grid. An ideal application of this type of control is in situations where the HVDC is connected in parallel with AC lines [55]. With such a control, the DC power can be automatically adapted to protect the parallel AC lines from being overloaded, especially when an AC line is out of service. However, even though the HVDC link is not operating in parallel with the AC lines, there is still a possibility of controlling and limiting the AC system load [56].

Traditionally, cascading line outages could be prevented only if some deterministic security rules are applied. The well-known rule is the N-1 criterion which can be defined as follows: the system should always be operated with a sufficient security margin in such a way that it is able to withstand any single component failure, e.g. outage of a line or generator, without resulting in unacceptable consequences. However, due to the liberalization of electricity markets and the increasing penetration of intermittent renewable generation, this preventive method may be insufficient in modern power systems as indicated by several recent large blackouts in different parts of the world. Thus additional post-disturbance controls might be necessary in such circumstances. Due to its fast controllability, the HVDC link can be used as an emergency measure to ensure a secure operation of heavily loaded power systems with small stability margins. To illustrate this, the simple system proposed in Section 2 is shown in Fig. 10 with an HVDC line operating in parallel with line 3. The HVDC line can be used to reduce the loading of the AC lines during emergency situations [57]. As can be seen in Fig. 11, the HVDC system helps keep the loading of line 1 at its margin point PM1 (this transfer value is called transmission transfer capability margin [58]) by increasing its DC power to an appropriate level. PC1 and PDCMAX are the transfer limits of line 1 and HVDC line respectively [57]. Thus, DC links can be used to improve the security of supply for Southern European countries, particularly for Italy, where energy can be imported from North Africa and avoid the heavy congestion across the Trans-Alpine electricity corridors (often limited by severe congestion). When an AC line is out of service, due to a fault or a planned outage, the DC links will increase their active power to relieve the remaining interconnection lines from overloading and reduce the risk of cascading outages and blackouts (Italy's 2003 blackout scenario is a good example). Should the AC system experience a large load/generation unbalance (e.g. major loss of generation at the receiving-end) then fast ramping of the DC power can be used to compensate any loss of power, hence reducing the risk of load shedding or even the occurrence of blackouts due to possible congestion in the AC interconnection lines. It should be noted that

the DC link can increase its active power as long as it does not exceed its maximum active power limit. However, some transient overload capability is available (typically 10–20%) when the DC link is already operating near its maximum tolerance. HVDC systems can transmit more than their rated power for short periods, and sometimes even longer, depending on the reliability of the equipment used. As examples, the SwePol HVDC (Sweden-Poland) link can be overloaded up to 20% [56], the CU HVDC link (USA) has a continuous overload capability between 10% and 20% depending on the ambient temperature [59], and the Tian-Guang HVDC link in China can be overloaded for more than seven hours [60].

Fig. 10. Power system with DC transmission.

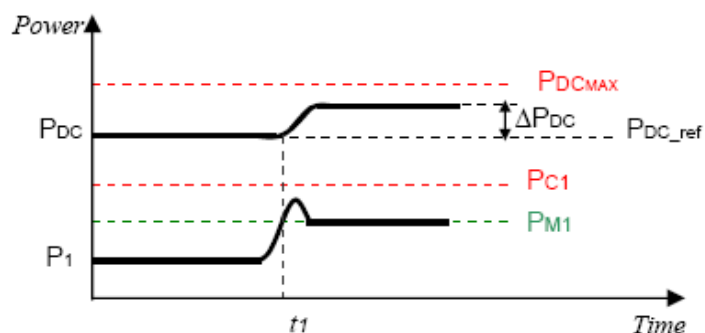**Fig. 11.** Power profiles.

4.2 Damping of power Oscillations and improving transient stability

The controllability of HVDC link can be used to enhance the stability of its associated AC system. This feature can be achieved by modulating the DC power. Thus, there is a need for supplementary HVDC controls to improve system dynamic performance. This modulation control signal is triggered in response to

variations in some AC system quantities such as frequency, power or phase angle. The DC power can be controlled to improve transient stability (sometimes referred to as "first swing stability") and to damp power oscillations (dynamic stability). Transient stability improvement and damping of power oscillations by active power modulation has been the subject of extensive research and there is a considerable literature covering these topics [61-65]. Discontinuous control signal can be used to improve transient stability during system disturbances, and continuous control signal (i.e. active at all times) is used to increase damping. With the recent rapid development in wide-area phasor monitoring, discontinuous control signal can be used to suppress inter-area oscillations during emergency conditions or major disturbances when the system may become small signal unstable. Small-signal instability often appears as poorly damped, sustained, or even growing oscillations due to insufficient damping under unforeseen highly stressed operating conditions.

In the past, several supplementary signals for DC power modulation have been designed and successfully applied to aid AC system performance and examples of these, in various regions around the world, are discussed in [55,59,66]. According to these experiences, HVDC links between Europe and North Africa can effectively support the AC system stability and damp inter-area oscillations in the southern European system. Since the dominant inter-area modes in the ENTSO-E system (global modes) are strongly observable in the Italian and Spanish networks and since the generators in the two countries participate heavily in these modes [45,46], the prospective HVDC links can effectively contribute to improve the damping of the global modes which will have a positive impact on the stability of the entire European grid. The events of the 19th and 24th February 2011 [67] have clearly shown that the North-South mode is strongly observable in the Southern Italy and the Italian system is currently more sensitive to this mode. For this reason, special attention was paid to oscillation monitoring and analysis in the Italian WAMS application and Terna (the main transmission system operator in Italy) has reinforced the power system stabilizers (PSS) in the country [67]. Since stability is of major concern for the ENTSO-E system, additional damping devices must be installed in the border areas especially in Southern Italy which is characterized by a weak level of interconnection. Based on the observability of the three global modes [42–46], the HVDC links in Southern Italy can contribute to improving the damping of the North-South mode and some other regional modes, meanwhile, the HVDC links in Spain can contribute to improving the

damping of the two East-West modes. To achieve this objective, the interaction problem must be considered when designing damping controllers. For example, if a DC modulation signal is used to damp a specific inter-area mode, this may destabilize other modes. Also, a lack of coordination between the HVDC links may weaken the effect of damping modulations and lead to undesirable interactions. This problem has previously been addressed by several authors and some techniques have been proposed to minimize the interactions between HVDC damping control loops and other oscillation modes [68–71].

Although power modulation control of HVDC links can effectively improve the dynamic response of the European system, it must be emphasized that the DC modulation applied on one side may adversely affect the other side (i.e. North African countries) [21,66], especially during large disturbances where a large modulation signal is required for the system to return to normal operating conditions. It is vital to use the DC power modulation judiciously in amounts that do not compromise the stability of the AC system at the other side. This problem will be discussed further in Section 5.

4.3. Reactive power control and voltage support

Several major blackouts experienced in different countries around the world were related to voltage stability phenomena [9]. For this reason, voltage stability enhancement has become a challenging issue in planning and security assessment of power systems. Voltage stability is very dependent on the demand for reactive power, and thus it is essential to balance reactive power supply and demand to maintain the scheduled voltage levels. As explained above, the LCC consumes reactive power, which needs to be supplied through shunt capacitor banks. Some, or all, of the shunt capacitors are normally configured as large AC capacitive filters at the converter stations. However, additional compensation in the form of shunt capacitor banks or other reactive support devices (e.g. synchronous compensators) is usually used for the AC loads. Since the reactive power requirement varies with the active power transfer, the converter filters and VAR compensation systems need to be adjusted as DC power varies. The shunt capacitors are normally subdivided and switched in steps by circuit breakers depending on the transmitted power and the needs of the AC network. With an appropriate control scheme, the HVDC can contribute to the stabilization of the AC voltage during steady-state and transient conditions by switching shunt capacitors and filters banks and/or by modulating the station's reactive power consumption through the firing angle of the converters. Various continuous and discrete control strategies have been successfully used for reactive power and

voltage control [59,66]. A supplementary control for reactive power modulation can also be used to improve the damping of certain oscillation modes, such as the one used in the inverter of the Itaipu HVDC link in Brazil [21,66]. AC voltage control can represent a major challenge to the DC control if the connected AC system is weak, especially at the inverter side. With a relatively weak AC system, various potential problems may arise such as voltage/power instability, temporary over-voltages (TOV), low order resonances and long fault recovery times [23]. Therefore, particular attention must be paid during the design stage to ensure successful operation of those power systems exhibiting such problems. Over the past decades, substantial research efforts have been devoted to exploring these problems and to find viable countermeasures [21,23]. For the HVDC links between North Africa and Southern Europe, the problem of weak AC system can be faced in the Italian power system, especially in the central and Southern regions. Due to the possible weak connection points of the planned HVDC links in Southern Italy and Sardinia, it is advisable to carry out comprehensive studies to investigate the above problems and identify the most appropriate mitigating measures because voltage instability is a phenomenon that spreads rapidly across the shared AC systems. In the case of a very weak AC system, a static VAR compensator (SVC) or other fast VAR compensation equipment is needed to provide effective reactive power and voltage control. A low-order harmonic filter may also be required. However, these additional devices can greatly increase the investment and maintenance costs of an HVDC project. It should be noted that the use of CCCs has effectively increased the limits for stable operation of HVDC links in weak AC systems as compared with the limits for LCCs [23].

4.4. Frequency Control

Major system upsets generally result in large excursions of frequency and other system variables. An increase in the frequency often associated with a surplus of generation (e.g. load rejection event), whereas a lack of generation (e.g. loss of generation event) will result in a frequency drop. The ability of a power system to maintain steady frequency following a severe system upset resulting in a significant unbalance between generation and load is of crucial importance from the perspective of system security. The magnitude of the frequency deviation does not only depends on the amount of imbalance, but also on the inertia of the power system. In general, small power systems are usually exposed to higher frequency

deviations than larger power systems. The ENTSO-E is a large system, however, the frequency excursion problem is most commonly associated with conditions following the separation of the system into islands. Stability in this case is a question of whether or not each island will reach a state of operating equilibrium with minimal unintentional loss of load [11]. In 2003, the Italian system collapsed two minutes and thirty seconds after the separation of the country from the European network, when the frequency reached the threshold of 47.5 Hz due to tripping of some generating units [30].

Frequency support can be provided by regulating the active power output of the generating units in response to a frequency deviation from its nominal value. Generally, some reserve capacity (spinning reserve) is available for this purpose. The power lost due to an outage may be compensated by activating the spinning reserve of the remaining generators as a first step, or by shedding the system load as a second step.

DC transmission can be used to assist the existing power generation station in controlling the frequency of one of the AC networks connected to the HVDC link by adjusting the transmitted power in proportion to the frequency deviation. By including a frequency control in the DC/AC terminals, it is possible to maintain a stable frequency in the Southern European system following the occurrence of faults associated with large imbalances between demand and generation (as in the case of the Italian blackout of 1994 [72]). This reduces the risk of load shedding and can even prevent the occurrence of blackouts. It has been shown in [73] that when an HVDC link is equipped with a frequency controller, it is possible to substitute spinning reserves in the thermal units. Furthermore, it has been shown that the economic benefits from substituting thermal primary control reserves with HVDC capacity are significant because the costs related to primary control (i.e. spinning reserve) in thermal units are considerable [73]. Since the energy production in the most Southern European countries (i.e. Italy, Spain and Portugal) is dominated by thermal plants [74], this strong economic benefit of the HVDC link is obvious.

In the past, HVDC links have been successfully used to directly control the frequency of the AC network, such as the Nelson River HVDC link in Manitoba, Canada and the Itaipu HVDC link in Brazil. There are many examples where the HVDC links have helped to limit the consequences of severe system upsets. In 1979, the ELSAM Network in Western Denmark was islanded together with parts of the German network. The load on the island was 5000 MW and power generation reached 3850 MW [24]. The

frequency dropped rapidly which initiated load shedding. The Skagerrak and Konti-Skan HVDC links from Norway and Sweden (see Fig. 12), which remained in service, automatically increased their power transfers which permitted a recovery of the frequency after it had fallen to 48.1 Hz and hence a blackout was prevented [24]. When an HVDC link is used to supply an islanded system with low inertia, the link plays an important role to control the island frequency. Numerous examples of such applications exist, for instance, the island of Gotland in Sweden and the island of Corsica in France [21].
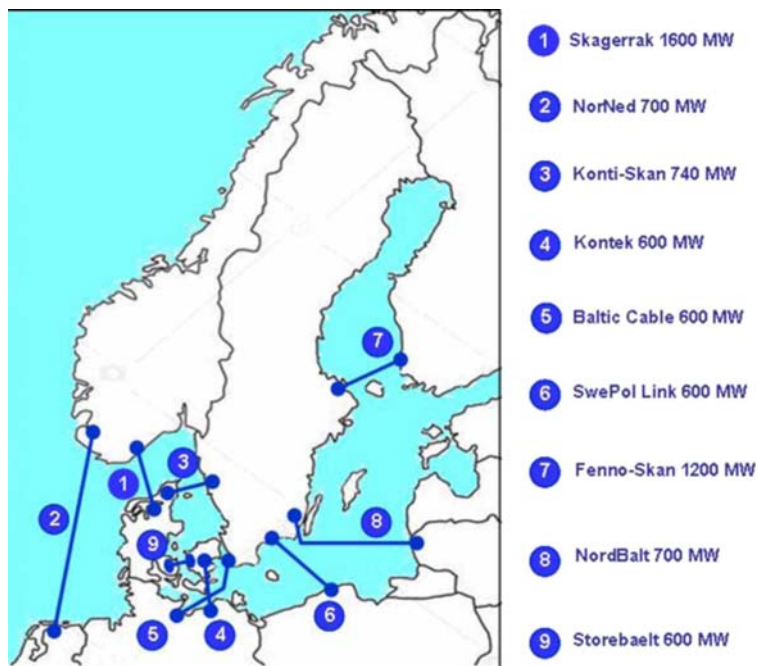

Fig. 12. Existing HVDC links in Scandinavia and between Scandinavia and Continental Europe.

5. Discussion

In Europe, a number of factors have contributed to an increasing consideration of HVDC solutions. As AC/DC systems become further integrated, it is likely that future development will require several HVDC converters on a common AC bus, or on AC buses in close proximity to each other. Such system configurations are commonly referred to as multi-infeed HVDC systems [75]. These configurations already exist for instance in Scandinavia and between Scandinavia and Continental Europe (Fig. 12). Other schemes with such configurations are being planned such as those in Southern Europe. The existing and planned HVDC links in Southern Europe are shown in Fig. 13. The multi-infeed HVDC configuration has been developed inside some regional grids, such as the Italian power system. While some of HVDC systems offer better controllability and improved grid dynamic operation, it is anticipated, on the other

hand, that these system configurations, could give rise to new undesired phenomena associated with the interactions among the AC and DC systems components, during both transient and steady-state operations. These include small-signal instability, voltage instability and collapse, and simultaneous commutation failures. The interaction problem is especially important when one or more of the AC/DC interconnections are relatively weak. Multi-infeed HVDC configurations have been analyzed in several research studies [75-78]. The findings from these researches give a general insight into various potential problems arising from multi-infeed HVDC systems with a particular attention to the HVDC inverter multi-infeed schemes, since such a configuration will be the most commonly used in future applications and usually results in the most severe AC/DC interactions [77]. As an example, a commutation failure in HVDC1 will distort the waveform of the voltage so badly that will also cause HVDC2 to develop a commutation failure, and so on. Thus, all inverters will suffer from a commutation failure and the DC power transmission will be interrupted. The sustained interruption of the DC power will cause large power imbalance and power flow transfer inside the AC system, which may lead to a possible blackout [79]. Therefore, a careful evaluation and analysis of these interactions between converters is necessary to identify the operating conditions that could potentially lead to those problems and propose appropriate counter measures if necessary. Traditionally, coordination among the constituent HVDC links was identified as potential counter measure [78].

An interesting technique is presented in [79] to improve the performance of multi-infeed HVDC systems using a grid dynamic segmentation technique based on fault current limiters. The experience gained from the existing multi-infeed HVDC schemes in Northern Europe would be very beneficial for the construction of Trans-Mediterranean submarine electricity highways. It is worth noting that with several HVDC links in the system, the degree of system controllability is improved, and therefore, not only problems can be expected from multi-infeed HVDC schemes, but also the system's performance is enhanced with the existence of multiple controlled power electronic devices in the same area [77]. However, to take full advantage of their controllability, coordinated control between the HVDC links is also required. For example, a lack of coordination between multiple HVDC links may weaken the effect of damping modulations and lead to undesirable interactions. As mentioned above, several approaches have been proposed in the literature to design coordinated control strategies for multiple HVDC links and interesting

results have been achieved. Although the policy of providing controls which enable the HVDC links to improve the dynamic response of the European system should be encouraged, it must be considered that any action taken by an HVDC link to control the power at one end (Europe) tends to produce some disturbance at the other end (North Africa). It is not acceptable to prevent instability in one system if this leads to instability in the other system. For example, the continuous control of AC voltage on either side of the McNeill HVDC link (Canada), by means of converter control, was precluded because corrections on one side would detrimentally affect the voltage on the other side [21]. Due to this problem, the direct export scenario could be the best option for importing renewable energy from North Africa (Fig. 14). In this case, power would flow directly towards the export destination (i.e. without a need to integrate the renewable generation units into the Maghreb grid). This means that the renewable generation plants would be exclusively set up for electricity exports to Europe [80]. The direct export scenario is also considered as the preferred option for the European stakeholders of renewable electricity imports from North Africa [80]. In 1997, an AC submarine cable of 27 km was put into operation to interconnect the grids of Spain and Morocco across the Straits of Gibraltar. The thermal limit of this interconnection is 730 MW. As there are other AC interconnections between Morocco, Algeria and Tunisia, this part of North Africa is now synchronously connected to the ENTSOE system [81]. Therefore, some of the described benefits may be impacted, especially those benefits related to the asynchronous nature of the DC link. However, there are some solutions that can be used to effectively exploit and maximize all the benefits of the HVDC technology. For example, by converting the existing AC lines between Spain and Morocco into HVDC links which can probably double or triple the power capacity with corresponding economic benefits. This technique is discussed in more detail in [82].

6. Conclusion

The HVDC links between North Africa and Europe will undoubtedly play an increasing role in the quest for a low-carbon energy system in Europe. However, the large-scale integration of renewable energy sources within Europe is expected to pose technical problems leading to stability challenges and bottlenecks at different locations in the ENTSO-E system. Large blackouts in Europe in the last two decades confirmed clearly that many transmission systems are already operated close to their limits. Therefore, it is vital to

develop innovative solutions to improve stability and prevent congestion. From the above discussions it is clear that the HVDC links themselves may prove to be the most cost-effective solution as they minimize or even eliminate the need for additional transmission. However, the wide range of benefits provided by HVDC links requires additional attention for their integration into the European system. The paper discussed some major technical problems that need to be addressed to ensure enhanced grid performance, reliability and successful expansion projects. The interactions between HVDC converters which are close one to another that might arise in perturbed conditions. This is a potential area that needs to be thoroughly investigated. The interactions between various supplementary controls must be considered.

The above benefits could be sharply limited unless the adverse interactions are suitably investigated and appropriate coordination measures are taken.

Although this review paper has focused on the HVDC links between North Africa and Europe, the proposed solutions and discussions would generically apply to similar HVDC projects elsewhere.

References

[1] Monforte LI, Celozzi M, Bardach A, Kowal J, Adam P. Co-development of the Mediterranean transmission grids. CIGRE Tech Report 2012. [Report no: C1-207].

[2] DESERTEC. The desertec concept for energy, water and climate security. Whitebook 4th ed. DESERTEC Foundation; 2009.

[3] RAL. Identification Mission for the Mediterranean Solar Plan. Resources and Logistics (RAL), Final Report; 2010.

[4] DLR. Trans-Mediterranean Interconnection for Concentrating Solar Power. German Aerospace Center (DLR); 2006.

[5] DLR. Characterisation of Solar Electricity Import Corridors from MENA to Europe. German Aerospace Center (DLR); 2009.

[6] Battaglini A, Lilliestam AJ, Haas A, Patt A. Development of SuperSmart Grids for amore efficient utilisation of electricity from renewable sources. J Clean Prod 2009;17:911–8.

[7] Elliott D. Emergence of European supergrids–essay on strategy issues. Energy Strategy Rev 2013;1:171–3.

[8] Dobson I, Carreras BA, Lynch VE, Newman DE. Complex systems analysis of series of blackouts: cascading failure, critical points, and self-organization. Chaos 2007;17:1–13.

[9] Andersson G, Donalek P, Farmer R, Hatziargyriou N, Kamwa I, Kundur P, et al. Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance. IEEE Trans Power Syst 2005;20:1922–8.

[10] Makarov YV, Reshetov VI, Stroev VA, Voropai NI. Blackout prevention in the United States, Europe, and Russia. Proc IEEE 2005;93:1942–55.

[11] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions. Definition and classification of power system stability. IEEE Trans Power Syst 2004;19:1387–401.

[12] Rogers G. Power system oscillations. Norwell, MA: Kluwer; 2000.

[13] Cova B, Abougarad F, Allagui S, Colla L, Rebolini M, Touileb R, et al. Linking Europe to Africa through long distance HVDC submarine interconnectors: methodology applied to the feasibility study and technical challenges to be overcome. CIGRE Technical Report, Report no: B4-116; 2008.

[14] Martinez-Anido CB, L'Abbate A, Migliavacca G, Calisti R, Soranno M, Fulli G, et al. Effects of North-African electricity import on the European and the Italian power systems: a techno-economic analysis. Electr Power Syst Res 2013;96:119–32.

[15] Pfluger B, Sensfuss F, Wietschel M. Agent-based simulation of the effect of an import of electricity from renewable sources in Northern Africa into the Italian power market. In: Proceedings of the 2009 International Energy Business Conference (IEWT); Vienna; 2009.

[16] Purvins A, Wilkening H, Fulli G, Tzimas E, Celli G, Mocci S, et al. A European supergrid for renewable energy: local impacts and far-reaching challenges. J Clean Prod 2011;19:1909–16.

[17] Sood VK. HVDC transmission. In: Rashid MH, editor. Power electronics handbook. San Diego: San Diego: Academic Press; 2001. p. 575−97.

[18] V.K. Sood. HVDC and FACTS controllers - applications of static converters in power systems. Boston: Kluwer; 2004.

[19] Arrillaga J, Liu YH, Watson NR. Flexible power transmission: the HVDC options. Chichester: Wiley; 2007.

[20] Thio CV, Davies JB, Kent KL. Commutation failures in HVDC transmission systems. IEEE Trans Power Del 2011;25:946−57.

[21] IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities. IEEE Standard 1204-1997; 1997.

[22] Menzies DF, Graham J, Ribeiro FU. "Garabi" the Argentina − Brazil 1000 MW Interconnection Commissioning and Early Operating Experience. Presented at ERLAC Conference, Brazil; 2001.

[23] CIGRE Working Group 14.05. On voltage and power stability in AC/DC systems. Technical Brochure 222, CIGRE; 2003.

[24] Carlsson L. HVDC A "firewall" against disturbances in high-voltage Grids. ABB Review; 2005. p. 42−6.

[25] Povh D, Retzmann D, Teltsch E, Kerin U, Mihalic R. Advantages of Large AC/DC System Interconnections. CIGRE Technical Report, Report no: B4-304; 2006.

[26] U.S.-Canada Power System Outage Task Force. Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations; 2004.

[27] Clark H, Edris AA, El-Gasseir M, Epp K, Isaacs A, Woodford D. Softening the blow of disturbances. IEEE Power Energy Mag 2008;6:30−41.

[28] Mousavi OA, Bizumic L, Cherkaoui R. Assessment of HVDC grid segmentation for reducing the risk of cascading outages and blackouts. In: Proceedings of Symposium Bulk Power System Dynamics and Control (IREP); 2013; pp. 1−10.

[29] Dobson I, Kim J, Wierzbicki1 KR. Testing branching process estimators of cascading failure with data from a simulation of transmission line outages. Risk Anal 2010;30:650−62.

[30] Union for the Coordination of Transmission of Electricity. Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy. UCTE Report; 2004.

[31] Berizzi A. The Italian 2003 blackout. in: Proceedings of the IEEE power engineering society general meeting; 2004; pp. 1−7.

[32] Corsi S, Sabelli C. General blackout in Italy Sunday September 28th, 2003, h 03:28:00. in: Proceedings of the IEEE Power Engineering Society General Meeting; 2004.

[33] Union for the Coordination of Transmission of Electricity (UCTE). Final report on system disturbance on 4 November 2006. Tech Rep; 2007.

[34] IAEW/ CONSENTEC. Analysis of Electricity Network Capacities and Identification of Congestion. Final Report; 2001.

[35] Henry S, Panciatici P, Parisot A. Going green: transmission grids as enablers of the transition to a low-carbon European economy. IEEE Power Energy Mag 2014;12:26−35.

[36] Huang GM, Zhang H. Coordinating simultaneous energy transaction as an extended OPF function. in: Proceedings of the IEEE Power Engineering Society General Meeting; 2000.

[37] Granelli G, Montagna M, Zanellini F, Bresesti P, Vailati R. A genetic algorithmbased procedure to optimize system topology against parallel flows. IEEE Trans Power Syst 2006;21:333−40.

[38] Bresesti P, Sforna M, Allegranza V, Canever D, Vailati R. Application of Phase Shifting Transformers for a secure and efficient operation of the interconnection corridors. In: Proceedings of the IEEE Power Engineering Society, General Meeting; 2005.

[39] Hutcheon N, Bialek JW. Updated and validated power flow model of the main continental European transmission network. In: Proceedings of the 2013 IEEE Grenoble Conference; 2013; pp. 1−5.

[40] Daxhelet O, Smeer Y. Inter-TSO Compensation Mechanism, 〈https://sites.hks.harvard.edu/hepg/Papers/Daxlet_Smeers_11.07.05.pdf〉; 2005 [accessed 20 July 2017].

[41] Kundur P. Investigation of low-frequency inter-area oscillations problems in large interconnected power systems. Can Elect Assoc 1993. Rep. 294T622.

[42] Elices A, Rouco L, Bourlès H, Margotin T. Design of robust controllers for damping interarea oscillations: application to the European power system. IEEE Trans Power Syst 2004;19:1058−67.

[43] Lehner J, Kaufhold M, Treuer M, Weissbach T. Monitoring of Inter-Area Oscillations within the European Interconnected Network based on a Wide Area Measuring System. In: Proceedings of the 2010 IEEE/PES Transmission and Distribution Conference and Exposition; 2010; pp. 1−8.

[44] Küßner K, Kasztel Z, Erlich I, Wilfert HH, Schegner P. Damping control of inter-area oscillations in the European power system using aggregated models. Electr Eng 2001;83:275−85.

[45] Larsson M, Korba P, Sattinger W, Owen P. Monitoring and Control of Power System Oscillations using FACTS/HVDC and Wide-area Phasor Measurements. CIGRE Technical Report, Report no: B5-119; 2012.

[46] Breulmann H, Grebe E, Lösing M, Winter W, Witzmann R, Dupuis P, et al. Analysis and damping of inter-area oscillations in the UCTE/CENTREL power system [Report no: 38-113]. CIGRE Tech Report2000. [Report no: 38-113].

[47] Al-Ali S, Nassar I, Weber H. Interconnection of the European ENTSO-E-CE system with the Turkish system: investigation of the expected inter-area-oscillations behaviour. In: Proceedings of the 17th Power Systems Computation Conference; 2011.

[48] Al-Ali S, Haase T, Nassar I, Weber H. Impact of Increasing Wind Power Generation on the North-South Inter-Area Oscillation Mode in the European ENTSO-E System. In: Proceedings of the 19th World Congress the International Federation of Automatic Control; 2014.

[49] CIGRE Working Group C4.601. Wide Area Monitoring and Control for Transmission Capability Enhancement. Technical Brochure 330, CIGRE; 2007.

[50] Zhang X, Lu C, Liu S, Wang X. A review on wide-area damping control to restrain inter-area low frequency oscillation for large-scale power systems with increasing renewable generation. Renew Sustain Energy Rev 2016;57:45−58.

[51] Euro-Mediterranean Energy Market Integration Project (MED-EMIP). Analysis and proposals of solutions for the closure of the ring and North-South electrical corridors. MEDRING update Volume 2; 2010.

[52] Klein M, Rogers GJ, Kundur P. A fundamental study of inter-area oscillations in power Systems. IEEE Trans Power Syst 1991;06:914−21.

[53] Wheeler JD, Andersen BR, Sadullah S, Gulati R. Building India's grid: an examination of the infrastructure benefits of HVDC transmission [Report no: 14-114]. CIGRE Tech Report2002. [Report no: 14-114].

[54] Lee RL. DC System Support to Southern California during Pacific AC Intertie Failures of December 22, 1982. in: Proceedings of the Symposium on Urban Applications of HVDC Power Transmission; 1983; pp. 24−26.

[55] CIGRE Joint Working Group C4/B4/C1.604. Influence of Embedded HVDC Transmission on System Security and AC Network Performance. Technical Brochure 536; 2013.

[56] Eriksson R, Knazkins V. On the coordinated control of multiple HVDC links. In: Proceedings of the 2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America, 2008; pp. 1−7.

[57] Benasla M, Allaoui T, Brahami M, Boudali A. Benefits of HVDC for reducing the risk of cascading outages and large blackouts in AC/DC hybrid grid. In: Proceedings of the3rd International Conference on Control, Engineering & Information Technology (CEIT), 2015; pp. 1−6.

[58] NERC. Available transfer capability definitions and determination. North Am Electr Reliab Counc (NERC) 1996.

[59] IEEE Committee Report. Dynamic performance characteristics of North American HVDC systems for transient and dynamic stability evaluations. IEEE Trans Power Appar Syst 1981:3356−64. [PAS-100].

[60] Aidong X, Xiaochen W, Chao H, Xiaoming J, Peng L. Study on Overload Capability and Its Application of HVDC Transmission System in China Southern Power Grid. In: Proceedings of the 2007 IEEE Power Engineering Society Conference and Exposition in Africa; 2007; pp. 1−4.

[61] Vural AM. Contribution of high voltage direct current transmission systems to interarea oscillation damping: a review. Renew Sustain Energy Rev 2016;57:892−915.

[62] Cresap RL, Mittelstadt WA. Small-signal modulation of the pacific HVDC intertie.IEEE Trans Power Appar Syst 1976:536−41. [PAS-95].

[63] Smed T, Andersson G. Utilising HVDC to damp power oscillations. IEEE Trans Power Deliv 1993;08:620−7.

[64] Kamwa I, Grondin R, Asber D, Gingras JP, Trudel G. Large-scale active-load modulation for angle stability improvement. IEEE Trans Power Syst 1999;14:582−90.

[65] Juanjuan W, Chuang F, Yao Z. Design of WAMS-based multiple HVDC damping control system. IEEE Trans Smart Grid 2011;02:363−74.

[66] IEEE Committee Report. HVDC controls for system dynamic performance. IEEE Trans Power Syst 1991;6:743−52.

[67] ENTSO-E. Analysis of CE inter-area oscillations of 19 and 24 February 2011, ENTSO-E SG SPD Report; 2011.

[68] Heniche A, Kamwa I. Control loops selection to damp inter-area oscillations of electrical networks. IEEE Trans Power Syst 2002;17:378−84.

[69] Mao X, Zhang Y, Guan L, Wu X. Researches on coordinated control strategy for inter-area oscillations in AC/DC hybrid grid with multi-infeed HVDC. In: Proceedings of the 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific, 2005; pp. 1−6.

[70] Eriksson R. Coordinated control of HVDC links in transmission systems [Doctoral thesis]. Sweden: Royal Institute of Technology; 2011.

[71] Azad SP, Taylor JA, Iravani R. Decentralized supplementary control of multiple LCC-HVDC links. IEEE Trans Power Syst 2016;31:572−80.

[72] CIGRE Task Force 38-02-14. Large Frequency Disturbances: Analysis and Modeling Needs. In: Proceedings of the IEEE Power Engineering Society, Winter Meeting; 1999.

[73] Bakken BH, Faanes HH. Technical and economic aspects of using a long submarine HVDC connection for frequency control. IEEE Trans Power Syst 1997;12:1252−8.

[74] ENTSO-E. Synthetic overview of electric system consumption, generation and exchanges in the ENTSO-E Area, ENTSO-E Electricity in Europe; 2015.

[75] Bui LX, Sood VK, Laurin S. Dynamic interactions between HVDC systems connected to AC buses in close proximity Source. IEEE Trans Power Deliv 1991;6:223−30.

[76] Reeve J, Lane-Smith SP. Multi-infeed HVDC transient response and recovery strategies. IEEE Trans Power Deliv 1993;8:1995−2001.

[77] Pilotto LAS, Szechtman M, Wey A, Long WF, Nilsson SL. Synchronizing and damping torque modulation controllers for multi-infeed HVDC Systems. IEEE Trans Power Deliv 1995;10:1505−13.

[78] CIGRE Working Group B4.41. Systems with multiple DC infeed. Technical Brochure 364, CIGRE; 2008.

[79] Huang H, Xu Z, Lin X. Improving performance of multi-infeed HVDC systems using grid dynamic segmentation technique based on fault current limiters. IEEE Trans Power Syst 2012;27:1664−72.

[80] Wuppertal Institute/CREAD. Algeria − A Future Supplier of Electricity from Renewable Energies for Europe? Wuppertal Institute/CREAD; 2010.

[81] Union of the Electricity Industry (EURELECTRIC). European, CIS and Mediterranean Interconnection: State of Play 2004. 2nd SYSTINT Report; 2005.

[82] EPRI. AC-to-DC power transmission line conversion. California: Electric Power Research Institute (EPRI); 2010.

[83] Meola A. Key issues for effective development of interconnections. The 11th WEC Central & Eastern Europe Energy Forum; 2012.