Supergrid or Local Network Reinforcements, and the Value of Controllability — An Analytical Approach

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***Abstract*—In this paper, an analytical approach is developed to address network planning questions for meshed AC networks. First, relationships are derived to compare the effectiveness of expansion measures, such as the building of long lines in the form of overlay grids, or local reinforcements along the transmission path in the existing grid. Results show that overlay networks are preferable, transferring more power for the same line-kilometers and line capacity. Second, upper bounds for the maximum utilization of long AC lines over a meshed network are extracted. The derived bounds prove to be significantly limiting in a highly meshed network. This stresses the need for controllable power flows. The obtained relationships are confirmed on the two-area RTS-96 system and through simulations on a single-node per country European network, based on real network data. Controllable flows, through the installation of HVDC lines, can save up to 8 billion Euros/year in comparison with the non-controllable AC technologies.**

***Index Terms*—HVDC, local network reinforcements, Overlay Grid, Supergrid, UHVAC**

I. INTRODUCTION

A fundamental change in terms of operation and planning of the European interconnected power system took place over the last one or two decades. The transmission grid no longer serves only as a tool for mutual assistance in case of emergencies but has become a complex "platform" for shifting growing power volumes all across the continent [1]. Market developments result in higher cross-border and long-distance energy exchanges. Other cross-continental power flows result from the fast and successful development of intermittent energy generation with limited predictability, e.g., wind power. With the increasing penetration of renewable sources, installed in bulk quantities, as, for example, in the North Sea, network investments on the transmission level seem not only necessary, but inevitable.

Different options for network upgrade exist. One possibility is to strengthen the network with local reinforcements. As the additional necessary transmission capacity for accommodating large power transfers is significant, such reinforcements are expected to take place at several points along the determined transmission path. A different possibility is to install direct transmission lines near major generation and demand centers, in the form of an overlay grid, usually referred to as "Supergrid". Such lines can either be based on the High Voltage Direct Current (HVDC) or the High Voltage Alternating Current (HVAC) technology. For HVDC, it is expected that lines forming an overlay network should be based on the Voltage-Source Converter technology. For the HVAC option, voltages of 400 kV or higher are expected for the long transmission lines. Lines at the level of 750 kV, as have already been installed in India, is a quite probable candidate in the case of an AC overlay network.

In Section II of this paper, we develop an analytical method in order to compare the option of local network reinforcements along the determined transmission path with the installation of direct transmission lines. In Section III, the method is extended in order to extract upper bounds on the maximum line utilization that can be achieved in the case of an AC overlay network. We confirm the relationships we derived with case studies on the two-area RTS-96 network and a single-node per country European network, presented in Section IV. Section V concludes the paper.

II. OVERLAY GRIDS VS. LOCAL REINFORCEMENTS

In this section we develop an analytical approach in order to address the question of what is more preferable as a transmission expansion measure: building long lines in the form of overlay grids or carrying out local reinforcements in the existing grid along the transmission path. Before we detail our approach, we further define the objectives and the assumptions of this work.

A. Objective of the comparison

The underlying assumption for the comparison is that we want to connect point A in country A to point B in country B, as shown in Fig. 1. Such a potential network expansion poses the question, which option allows for a higher power flow: a long direct line connecting points A and B, or line segments inside the country which will reinforce the internal network, and then transmit the power to point B.

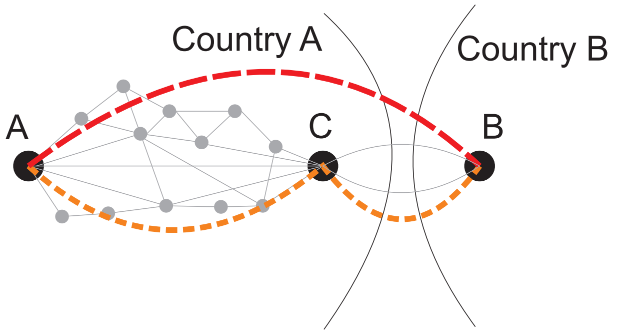

Fig. 1: Illustrative example of a direct overlay AC line (in red) or local reinforcements (in orange). The existing network is represented in grey color.

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In other words, the objective is to identify which expansion measure leads to better network utilization. It has been shown that an increase of the effective transmission capacity is usually associated with the increase of the overall social welfare (e.g., [2]). As a result, an expansion measure that increases network utilization is also beneficial from a societal point of view.

B. General Assumptions

We focus our study on the interconnections between regions or countries as we are following a European perspective on network expansion. We assume that the power grid inside each country is more meshed than the grid connecting each country to its neighbors[1]. In this Section, we limit our study only on AC lines, as the HVDC technology is usually used either for long distance transmission or for submarine cables.

C. Overlay Grid

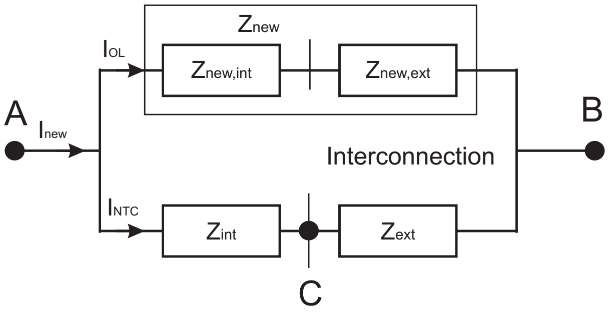

Fig. 2: Representation of the existing grid and the new overlay line between points A and B.

Figure 2 relies on equivalent impedances to represent the existing grid and the overlay line as shown in Fig. 1. Z_{int} is the aggregated impedance of all existing transmission paths between points A and C, while Z_{ext} is the aggregated impedance of all existing interconnecting lines between points C and B. The new direct overlay line is connected between points A and B and has an impedance of Z_{new}. We divide this impedance in two parts as follows: $Z_{new,int}$ corresponds to the length of the line inside country A, i.e., the distance from A to C, while $Z_{new,ext}$ corresponds to the length of the line between points C and B. Thus, it is equivalent to an interconnection.

We assume that we want to transmit a certain amount of power from point A to B. Of specific interest is the resulting power flow on the two parallel paths, knowing that the transmissible power in the existing path (i.e., Z_{int} and Z_{ext}) is limited by the Net Transfer Capacity (NTC) between the countries. Instead of power, we selected to work with currents, since the ends of both paths are connected to the same points, and, therefore, have the same voltages. With I_{NTC} we denote the current which corresponds to the NTC power for the existing path. According to the current divider rule, the current which will flow on the overlay line is defined as:

$$I_{OL} = \frac{Z_{int} + Z_{ext}}{Z_{new,int} + Z_{new,ext}} \cdot I_{NTC}. \tag{1}$$

Without loss of generality, we assume that the overlay line has enough capacity to carry the current I_{OL}.

D. Local Reinforcements

Figure 3 represents the effect of local network reinforcements with equivalent impedances.

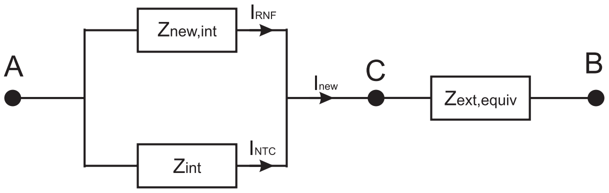

Fig. 3: Representation of the existing grid and the internal reinforcements between points A and C.

Z_{int} is, as in the case of the overlay grid, the aggregated impedance of all existing transmission paths between points A and C. $Z_{new,int}$ is the additional line we add between points A and C within the same country. It represents the local reinforcement that is necessary in order to remove the bottleneck. $Z_{ext,equiv}$ corresponds to the interconnecting lines between points C and B. The value of $Z_{ext,equiv}$ is equal to Z_{ext} in parallel with $Z_{new,ext}$. We assume that the main bottlenecks are inside country A, while the interconnecting path has enough transmission capacity to transfer the additional flows. Therefore, the limiting factor for the cross-border power flow is the segment A-C. This assumption appears realistic in a European context, as the NTC values are often determined by bottlenecks inside the countries. Working again with the current divider rule, and assuming that through the existing path flows current equal to I_{NTC}, the current which will flow over the additional line is given by:

$$I_{RNF} = \frac{Z_{int}}{Z_{new,int}} \cdot I_{NTC}. \tag{2}$$

E. Analytical Approach

We make the following assumptions with respect to the line impedances:

- $Z'_{ext} \leq Z'_{new,ext}$, where Z'_{ext} and $Z'_{new,ext}$ stand for impedances per unit length. Most countries are already interconnected by more than one parallel line. As a result, assuming that Z_{ext} and $Z_{new,ext}$ have the same length l_{ext}, the impedance of a new line should be greater[2].
- $Z'_{int} \leq Z'_{ext}$ (per unit length). Normally the network within a country is significantly more meshed than at the border. From a point A within the country, the current can follow several paths to "reach" an interconnection substation. As a result, the per unit length impedance Z'_{int} should be smaller than the impedance Z'_{ext}. The relationship between Z_{int} and Z_{ext} in absolute values depends on the length of the interconnections and the distance of point A from the borders (point C in Fig. 1).

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[1] We will usually refer to the network inside a country as "internal network", while the lines that connect each country to its neighbors will be usually referred to as "interconnections".

[2] In order to be able to compare the two options, we use the same voltage level for both local reinforcements and long AC lines. In a European context, local AC reinforcements are probably going to be carried out in the 400 kV level. As most European countries are interconnected by at least one 400 kV line, the assumption $Z'_{ext} \leq Z'_{new,ext}$ should hold. At the end of this section we comment on higher voltage levels for overlay grids.

- For overlay lines we assume the relationship: $Z'_{new,int} = Z'_{new,ext}$ per unit length, as it is the same line. However, for absolute values $Z_{new,int} \geq Z_{new,ext}$. For example, assume that we have a 400 km line of which only 80 km represent the interconnection. If we assume that, except for the interconnection, most of the line is within country A, this corresponds to about 320 km. As the line segment within the country is much longer, the respective impedance should be greater.

From the above assumptions follows (with l_{int} and l_{ext} denoting the line lengths):

$$\frac{Z'_{int}}{Z'_{new,int}} \leq \frac{Z'_{ext}}{Z'_{new,ext}} \Rightarrow \tag{3}$$

$$\frac{Z'_{int} \cdot l_{int}}{Z'_{new,int} \cdot l_{int}} \leq \frac{Z'_{ext} \cdot l_{ext}}{Z'_{new,ext} \cdot l_{ext}} \Rightarrow \tag{4}$$

$$\frac{Z_{int}}{Z_{new,int}} \leq \frac{Z_{ext}}{Z_{new,ext}}. \tag{5}$$

If Eq. 5 holds and all values are positive, then:

$$\frac{Z_{int}}{Z_{new,int}} \leq \frac{Z_{int} + Z_{ext}}{Z_{new,int} + Z_{new,ext}} \leq \frac{Z_{ext}}{Z_{new,ext}}. \tag{6}$$

We assume that the current I_{NTC} and the impedance $Z_{new,int}$ in both the overlay line and the local reinforcements have the same value. From Eq. 1, 2, and 6, we can derive that:

$$I_{RNF} \leq I_{OL}. \tag{7}$$

As, a result the total current (or power) that can be transmitted with the addition of an overlay line is higher than if similar line kilometers were installed, but in the form of local reinforcements along the transmission path:

$$I_{new,RNF} \leq I_{new,OL}, \tag{8}$$

where:

$$I_{new,OL} = I_{NTC} + I_{OL}, \tag{9}$$

$$I_{new,RNF} = I_{NTC} + I_{RNF}. \tag{10}$$

Eq. 8 will be true, as long as the condition in Eq. 3 is fulfilled. This, in turn, is fulfilled if it holds $Z'_{int} \leq Z'_{ext}$ and $Z'_{new,int} \geq Z'_{new,ext}$. In other words, even if we assume that the interconnecting network is as meshed as the internal one ($Z'_{int} = Z'_{ext}$), the equivalent impedance (per unit length) of the internal reinforcements $Z'_{new,int}$ must be less than the impedance of the external segment of the parallel line (per unit length), for local reinforcements to achieve a higher network utilization than for a long direct transmission line. For $Z'_{new,int}$ to be smaller than $Z'_{new,ext}$, we need to install more than one line in parallel in the internal network. The more meshed the internal network is with respect to external (i.e., $Z'_{int} \leq Z'_{ext}$), the more parallel lines will be necessary to be installed. This means that if we decide for the option of local network reinforcements in weakly interconnected meshed networks, we will probably build more kilometers of lines in parallel compared with a single long transmission line, in order to achieve a similar network utilization.

Translating these conclusions to numbers, we assume that we want to reinforce the interconnection Germany-Switzerland with a 400 kV/3000 MVA transmission line. The length of the interconnection is 20 km. We also assume that the non-congested substation (point A) has a distance of 150 km from the interconnection point C, which results in a total distance of 170 km for a direct line (point A to B). We also assume that the internal network in Germany, being more meshed than the cross-border lines, has an equivalent impedance per km $Z'_{int} = 0.5Z'_{ext}$. This means that for each interconnecting line, at least two paths of similar voltage level that connect points A and C should exist (these paths do not necessarily need to be direct lines). According to the considerations above, in the case of internal reinforcements, we should install at least 2 parallel 400 kV lines to the substation at the German border, i.e., 300 km of lines, so that $Z'_{new,int} = 0.5Z'_{new,ext}$ and Eq. 6 may no longer hold. Otherwise, it is preferable to build a direct line from that substation in Germany to Switzerland. Simulations and more concrete examples are provided in Section IV-A.

If we now assume that the long direct line should be based on the AC-750 kV technology, while the internal reinforcements should be carried out on the AC-400 kV level, then the effectiveness of the direct lines is even more apparent, as the following difference becomes even larger (due to the fact that $Z'_{400} > Z'_{750}$):

$$\frac{Z'_{int}}{Z'_{new,int,400}} \leq \frac{Z'_{int} + Z'_{ext}}{Z'_{new,int,750} + Z'_{new,ext,750}}. \tag{11}$$

In conclusion, we have shown that if we want to increase the transmission capacity of weakly interconnected meshed networks and allow for higher power transfers over longer distances, installing long transmission lines can be more effective than carrying out several local reinforcements. In such a case, the concept of a Supergrid increases the utilization of transmission assets, resulting in a smaller footprint for the line installation, while increasing social welfare.

III. OVERLAY GRID: AC VS. DC

In this section, we deal with the question if the overlay grid should use alternating current (AC) or direct current (DC). Several concepts for an overlay HVDC grid exist, but there are also ideas on an Ultra High Voltage AC overlay network, at a voltage level of 750 kV. Here, we derive an upper bound that could be achieved in terms of line utilization when we add a single AC overlay line along an interconnection. In compliance with Section II, we assume that through the existing grid a current of I_{NTC} can maximally flow, which is equivalent to the NTC capacity of the interconnection. From Eq. 6 and Eq. 1, we can derive an upper bound for the flow I_{OL}, according to the following equation:

$$I_{OL} \leq \frac{Z'_{ext}}{Z'_{new,ext}} \cdot I_{NTC}. \tag{12}$$

A similar length l_{ext} is assumed for both impedances. As already mentioned, most interconnections in Europe comprise of at least one 400 kV line. If an AC-400 kV line has Z'_{400kV} Ohms per length unit, and since Z'_{ext} aggregates the existing interconnecting lines of an interface, it will hold $Z'_{ext} \leq Z'_{400kV}$.

Therefore, if we add a long AC-400 kV line, according to Eq. 12, the power flow on the new line will not exceed the

NTC value. Since $Z'_{ext} \leq Z'_{400kV}$, the total power flow will be upper-bounded at twice the NTC value:

$$I_{new,OL-400kV} \leq 2 \cdot I_{NTC}. \tag{13}$$

Based on [3], a single-circuit AC-750 kV/3900 MVA line has an impedance equal to $Z'_{750kV} = 0.65 \cdot Z'_{400kV}$, where the AC-400 kV is a double-circuit 3000 MVA line. Hence, for an AC-750 kV line, this bound will be:

$$I_{new,OL-750kV} \leq 2.6 \cdot I_{NTC}. \tag{14}$$

It should be noted that our calculations are in per unit in order to be able to compare between different voltage levels. All our considerations hold true for the power transfers in absolute values[3].

In fact, the more parallel lines exist along a certain interconnection, the less power will flow along the new direct line. As we will see in Section IV, this can significantly limit line utilization. On the other hand, an HVDC line, due to its capability to control the power flow, can be loaded up to its thermal limit. This stresses the need for power flow controllability, which becomes stronger as the underlying network becomes more meshed. In Section IV-B, we demonstrate these results with simulations on a simplified pan-European grid.

IV. CASE STUDIES

A. RTS-96 Two-Area system

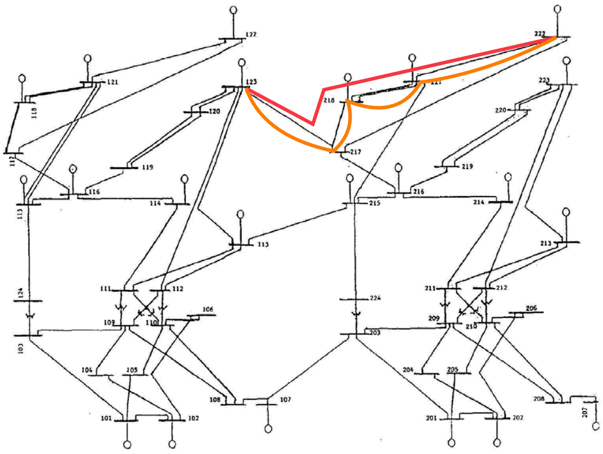

Fig. 4: RTS-96 two-area system [4]. The added overlay line is shown in red and the local reinforcements in orange.

Figure 4 illustrates the RTS-96 two-area network [4], which is used to test the theoretical results derived in the previous sections. The goal is to identify the maximum transmissible power from bus 222 in Area 2 to bus 123 in Area 1. In doing so, we set bus 222 as the slack bus and increase the active power consumption on bus 123 in steps of 50 MW. Bus 222 should compensate for this load increase. After each step, a DC power flow is executed, and the line flows inside Area 2 are compared against their limits. The maximum power transfer is defined as the amount of power injected in bus 222 at the step which the first line inside Area 2 gets overloaded.

TABLE I: RTS-96 – Maximum Power Transfer from Bus 222 (in MW)

Interconnecting Lines	No Expansion	Local Reinforc.	Overlay	Overlay Higher Volt.
123-217	951.40	1501.40	1551.40	3201.40
123-217 107-203	951.40	1451.40	1501.40	3001.40
123-217 107-203 113-215	901.40	1451.40	1301.40	2501.40

As described in Ref. [4], the upper part of the system operates on a voltage level of 230 kV, while the lower part is operating on 138 kV. The flow from bus 222 has two main routes to follow inside Area 2, both on 230 kV, one arriving at bus 217 and the other arriving at bus 215. We study three different "levels" of interconnection: (a) line 123-217 (230 kV) is the sole interconnecting line between Areas 1 and 2, (b) Areas 1 and 2 are connected with lines 123-217 and 107-203 (138 kV), and (c) all three lines, i.e. 123-217, 107-203 and 113-215 (230 kV) are connecting the two areas. In case (a), the external "network", comprising line 123-217, is clearly less "meshed" than the internal network in area 2. In case (b), as line 107-203 is on a lower voltage level, still the interconnections should appear as a less meshed network than the two parallel paths on 230 kV which emanate from bus 222. The same can probably not be argued for case (c), where the power at bus 222 is injected on two parallel paths, while the interconnection network comprises three lines.

TABLE II: RTS-96 – Line Loadings: Overlay vs. Local Reinforcements (in MW) for $P_{222} = 1301.40$ MW

Interconnecting Lines	Overlay	Local Reinforcements			
	123-222	123-217	217-218	218-221	221-222
123-217	494.36	577.20	426.28	261.68	445.94
123-217 107-203	469.24	533.01	409.40	250.43	447.86
123-217 107-203 113-215	402.46	401.18	345.66	207.98	454.84

Except for the base case, where no expansion measures are undertaken, we define three further expansion scenarios along the path 123-222, as shown on Fig. 4: (i) local reinforcements, i.e., 230 kV parallel lines along the existing ones, connected at the buses along the route, (ii) overlay line, i.e., one direct 230 kV line connecting buses 123 with 222, and (iii) a similar overlay line, but on a higher voltage[4] (400 kV; line data taken from Ref. [3]). It should also be noted that the two overlay options have length equal to the sum of the length of the line segments in the local reinforcements.

Table I presents the results for the maximum power transfer from bus 222. In general, expansion measures allow more power to be transferred than in the base case. As already derived in Section II, the overlay option leads to a higher power transfer, as long as the external network is less meshed than the internal. This is when Areas 1 and 2 are interconnected by one or two lines. When all three lines connect the two

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[3] With the same base value for power on the whole network, a comparison of currents in the per unit system can be directly transferred to a comparison of power in absolute values with V=1 p.u. and $S = V \cdot I^*$, $|S|_{pu} = |I|_{pu}$.

[4] At least for Europe, an AC overlay network is expected to operate on 750 kV level. Still, as RTS-96 is operating on 138/230 kV, we selected appropriate voltage levels for a fair comparison.

areas, the internal network, as seen from bus 222, is not more meshed than the external, and therefore, local reinforcements are more effective than the overlay line. The last column of Table I presents the maximum power transfer achieved when the overlay line is operating on a voltage level higher than the rest of the network. As it can be observed, for all levels of interconnection studied, overlay lines on higher voltage levels have an advantage against other expansion options with respect to network utilization.

Table II assumes a fixed power injection of 1301.40 MW at bus 222 and compares the loadings of the *additional* lines in the case of local reinforcements and in the case of the overlay line. All lines are on the 230 kV level, as the rest of the network. As already shown in Section III, the loading of the parallel interconnecting line, i.e., 123-217, should be higher than of the overlay line, as long as the internal network is more meshed than the external. At the same time, the loading of the overlay line is higher than the loading of any of parallel lines added in the internal network. Both effects can be observed in the first two rows of Table II. In the third case, where all three interconnecting lines are assumed connected, the external network can no longer be assumed less meshed than the internal, and, therefore, the obtained relationships in Sections II and III would not hold.

An additional effect mentioned in Section III, that can be observed in Table II, is that with increasing the number of interconnecting lines, the utilization of the overlay line is decreased.

As a closing remark, concerning the necessary line-kilometers in the case of local reinforcements, it could be argued that not all line segments might need to be reinforced, and, therefore, less line-kilometers might need to be built. Although this may be less probable for higher power transfers, still, it could be equally argued that a direct line might be able to follow a shorter route and, thus, also result in need for less line-kilometers.

B. European network - single node per country system

In this section, we present simulation results on a simplified European network. The studies have been carried out within the framework of the EU FP7 Project IRENE-40 (www.irene-40.eu). IRENE-40 aims to identify appropriate transmission expansion measures in order to achieve a more secure, sustainable, and competitive European power system. Within this context, simulations based on different future generation scenarios were made. Hourly generation and load data for the years 2010, 2020, 2030, 2040, and 2050 for each EU-27 member state, Norway, and Switzerland were taken from [5]. The studies were performed with a single-node per country model, comprising 32 nodes and 104 branches. The model includes the former UCTE area, Nordel, UK and Ireland, and the Baltic States. Each interconnection (except for the submarine cables) was modeled as two identical AC lines. The line data were aggregations of real data provided by UCTE (now ENTSO-E) (www.entsoe.eu). The used network model is illustrated in Fig. 5.

For the case studies presented in this paper, the generation and load data are taken from the so-called RES scenario, which projects a high share of renewable generation in Europe (80 %) by the year 2050. In this paper, the focus is on the line utilization and the associated costs for different expansion technologies.

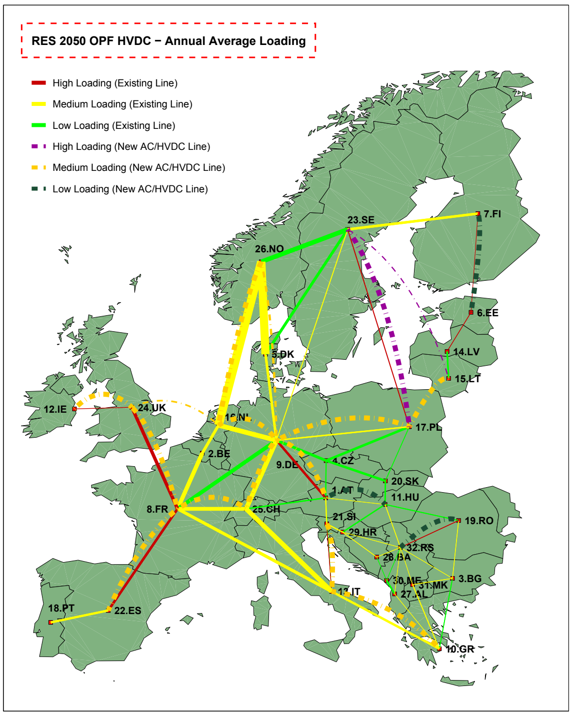

Fig. 5: Annual average line loadings in the HVDC expansion scenario. High Loading: >85 %. Medium Loading: 50 %-85 %. Low Loading: <50 %. The line width is proportional to the line capacity.

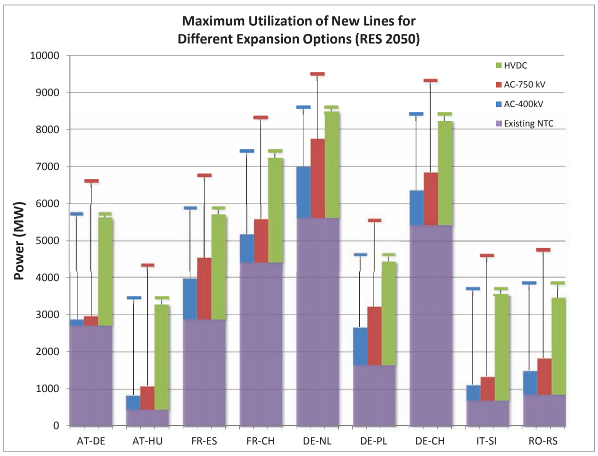

Fig. 6: Maximum Utilization of New Lines for Different Expansion Options in the RES 2050 Scenario.

Three expansion technologies have been considered: double circuit AC-400 kV/3000 MVA, single-circuit AC-750 kV/3900 MVA, and VSC-HVDC 3000 MVA[5]. In all cases we assume that we add *one* parallel line along interconnections which are congested (i.e., 100 % loaded) over 50 % of the time

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[5] Currently, VSC-HVDC lines of 3000 MVA are not available. Such capacities can be achieved at the moment by connecting converter stations in parallel. We have assumed a 3000 MVA capacity in order to carry out a fair comparison with the rest of the AC technologies. Nevertheless, from the results we see that incorporating the losses of the parallel converter stations would not have had a significant effect on the resulting network utilization. In any case, it is foreseeable that the VSC-HVDC capacity of a single line will increase in the future and has certainly the potential to reach such values.

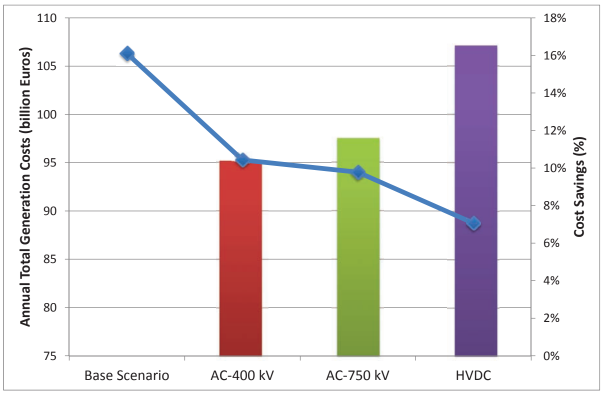

Fig. 7: Annual Total Generation Costs (line) and Cost Savings (bars) in different Transmission Expansion Scenarios.

during the year. Figure 5 graphically illustrates the average line loadings resulting in the case of HVDC, after carrying out hourly Optimal Power Flow simulations for a whole year. The algorithm is based on a standard AC Optimal Power Flow formulation, as described in [6]. The modelling of the VSC-HVDC lines was based on [7]. The average loading of the AC expansion options result in a lower average line loading (not shown here due to space limitations).

In both AC scenarios, all submarine interconnections are assumed to be VSC-HVDC cables. In Fig. 6, we focus only on the lines we added on land. We present the maximum loading, achieved during a year, of the three used technologies. In order to account for the best possible case in the AC scenarios, we have assumed that the long AC lines are sufficiently series compensated (i.e., up to 50 %), so that Eq. 12 is an equality.

The purple semi-transparent bars in Fig. 6 represent the assumed NTC values of the existing interconnections, while the blue, red, and green bars on top show the *maximum* loading of the parallel line that was achieved during a year with the three different technologies. It can be observed that the maximum utilization of both AC options is low compared with their theoretical thermal limit. In all cases the upper bounds we extracted in Eq. 13 and Eq. 14 hold true. On the other hand, the HVDC lines, due to their inherent controllability, can always be loaded up to their limit.

Figure 7 presents the total generation operating costs that were incurred over a year in the European system for the RES 2050 Scenario[6]. The maximum reduction in costs is achieved when HVDC technology is used for the overlay grid. For the two AC options, costs are about 6-8 billion[7] Euros *per year* higher.

From these results it seems apparent that the European grid will need a significantly higher degree of controllability in the future. Due to the highly meshed nature of the European power system, the addition of new lines without any power flow control, will probably lead to under-utilization of the new assets. This controllability can be achieved either with the use of HVDC lines, or, alternatively, with the extensive installation of FACTS devices in the AC network.

V. CONCLUSIONS

In this paper, an analytical approach has been developed in order to deal with network planning questions for meshed AC networks. First, relationships have been derived to address the question of what is more preferable as a transmission expansion measure: the building of long lines in the form of overlay grids or local reinforcements in the existing grid along the transmission path. Second, upper bounds for the maximum utilization of long AC lines over a meshed network have been extracted. Our results suggest the following:

- Overlay networks are preferable. Long direct lines, e.g., in the form of a Supergrid, can transfer more power for the same line-kilometers and line capacity over weakly interconnected meshed networks. An overlay grid at higher voltage levels could be the preferred option even over stronger interconnected networks.
- An upper bound for the maximum utilization of one additional (long) AC line along an interconnection is extracted. For highly meshed systems, this upper bound can become significantly limiting.
- The derived relationships have been confirmed through simulations on the two-area RTS-96 system and on a simplified European network. Controllable power flows, either in the form of HVDC lines, or AC lines coupled with FACTS devices, seem necessary.
- Simulation results on the simplified European network show that HVDC lines, by offering this controllability, can save up to 8 billion Euros/year in comparison with the non-controllable AC technologies.

In general, our results show that the concept of a controllable Supergrid has the potential to increase the utilization of transmission assets, to result in smaller footprint for the line installation, and to increase social welfare.

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[6] The generation capital costs are assumed as given and are the same for the base case and all three expansion options. The focus here is on the amount of cost savings that can be achieved through the use of different technologies during transmission expansion.

[7] 1 billion €= 10^9 €