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Comparison of Losses and Costs between AC and MVDC Connections for New DC Resources

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Abstract—The proliferation of direct current (DC) resources (loads, generation, and storage) presents opportunities for new medium voltage DC (MVDC) networks that should be compared against standard alternating current (AC) connections. In this paper, we provide a point-to-point transmission analysis of AC vs. MVDC, and determine the distance at which MVDC prevails over AC in terms of total losses, and, most importantly, total costs. We further provide insights on the connection of new DC resources to existing networks with different distances, accounting for network-related costs (e.g., upgrades required or avoided), and highlighting the impact that an MVDC connection of a flexible DC resource could have on the main AC/DC converter rating, by lowering the MVDC network peak load. Our work is motivated by an application of a train MVDC network, with the possibility of connecting a solar power plant potentially equipped with a battery. We thus provide numerical illustrations centered around this application; nevertheless, our analysis remains general, and applicable to the connection of any DC resource.

Index Terms—Direct Current, Medium Voltage, Break-Even Distance.

I. INTRODUCTION

Direct current (DC) resources, namely loads (e.g., data centers and electrolysis), generation (e.g., solar power plants), and flexibility devices (e.g., storage) are expected to be increasingly present in power networks. Several CIGRE Technical Brochures [1], [2] highlight the opportunities provided by medium voltage DC (MVDC) networks thanks to the recent progress of power electronic power devices. This expansion raises new questions about the connection of DC resources to the existing networks, and the opportunities to create new dedicated MVDC networks that could host these new resources and prevail over standard point-to-point connections to alternating current (AC) networks. Thus, cost-benefit analysis (CBA) methodologies that compare the AC and DC connections become particularly relevant.

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Detailed results on the point-to-point transmission between AC and DC technologies exist in the CBA-related literature. For example, [3] presents a general methodology on the comparison for high voltage applications, whereas project-specific literature considers small scale high voltage connections for rural villages [4], and MVDC connections of offshore wind farms [5], [6]. A somewhat more general comparison for MVDC point-to-point transmission is presented in [7], which defines a break-even distance according to power loss criteria, henceforth referred to as “loss break-even distance” (LBED), i.e., the distance beyond which the power losses of an MVDC connection become lower than those of an AC connection. However, although [7] presents useful results, arguably, a general cost and benefit comparison framework for MVDC applications is still missing.

In this work, we extend the LBED in [7] to account for time-varying load profiles and costs of equipment (converters, lines) and electricity. Thus, we introduce the “cost break-even distance” (CBED), i.e., the distance beyond which the DC connection prevails in terms of total costs, and we compare against the LBED. Interestingly, under certain conditions, the CBED could be several times higher than the LBED for load profiles with small utilization of the line capacity. We further consider connections of new DC resources to existing networks, with different distances, and quantify the impact on the connection decision of network-related costs, e.g., upgrades required or avoided, impact on network losses, etc. We also highlight the impact that an MVDC connection of a flexible DC resource could have on the main AC/DC converter rating, by lowering the MVDC network peak load, which could make MVDC connections more attractive. Our analysis is motivated by an application of a train MVDC network, with the possibility of connecting a solar power plant potentially equipped with a battery. Hence, our numerical illustrations are centered around this application; nevertheless, our analysis

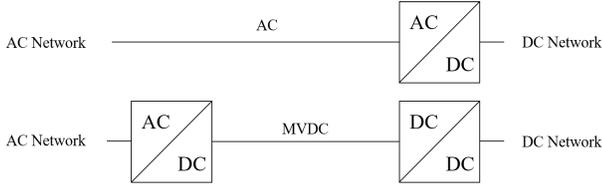


Fig. 1. AC and DC point-to-point transmission configurations.

remains general, and applies to the connection of any DC resource. Unsurprisingly, a flexible DC resource (solar plus battery) connected to the train MVDC network can reduce its peak load and the rating of its main AC/DC converter.

Our main contribution is two-fold. First, we extend existing results on the point-to-point transmission for MVDC applications to account for total costs, apart from losses, arguably providing an improved metric on the AC vs. DC point-to-point transmission comparison. Second, we provide formal insights on the connection of new DC resources to existing networks in terms of network-related costs and particularly the MVDC network main converter rating.

The remainder of the paper is organized as follows. Section II presents the point-to-point transmission analysis and derives the LBED and CBED. Section III quantifies the impact of new DC resources connections to existing networks. Section IV presents a numerical demonstration of the analysis, and Section V concludes and provides further research directions.

II. POINT-TO-POINT TRANSMISSION

In this section, we compare AC vs. DC point-to-point transmission, and compute the LBED (in Subsection II-A) and the CBED (in Subsection II-B). The AC and DC point-to-point transmission configurations are shown in Fig. 1. The AC network (left) is connected to the DC network (right) either through AC (see the AC transmission line and AC/DC converter at the top) or through DC (see the AC/DC converter, MVDC line, and DC/DC converter at the bottom).

Our analysis accounts for dynamic power flow profiles over time, which we assume to be independent of the type of transmission and constant along the line and converters for a specific time period t (considering that the impact of losses on the power flow is small). For time period t , the power flow is denoted by $P_t = k_t \bar{P}$, where k_t is a load factor taking values between 0 and 1 (without considering the direction of the flow), and \bar{P} is the maximum power along the line. The AC phase-to-phase RMS voltage is denoted by U_{AC} (with a phase between voltage and current of ϕ), and the DC pole-to-pole voltage by V_{DC} , for the AC and MVDC lines, respectively, (considering that the voltage drop along the line is small and hence neglected). Converter efficiencies are denoted by $\eta_{AC}^{AC/DC}$ for the AC transmission, and $\eta_{DC}^{AC/DC}$, $\eta_{DC}^{DC/DC}$, for the DC transmission. The resistances per km of line are denoted by R_{AC} and R_{DC} , for the AC and MVDC lines, respectively, and the distance of the line is denoted by D .

A. Loss Break-Even Distance (LBED)

In this subsection, we compute the LBED accounting for the following two types of losses (relevant for small losses): (i) losses due to the converters, and (ii) losses due to the Joule effect in the lines.

A 3-phase AC line has a nominal current at time period t on each phase that is equal to $\frac{k_t \bar{P}}{\sqrt{3} U_{AC} \cos \phi}$. A pole-to-pole MVDC line has a nominal current at time period t that is equal to $\frac{k_t \bar{P}}{V_{DC}}$. For line loss computations, we consider a factor of 3 for the AC line accounting for the 3 phases, and a factor 2 for the DC line accounting for the fact that the Joule effect applies to both poles. Hence, the losses at time period t , $L_{AC,t}$ and $L_{DC,t}$, for the AC and DC transmissions, respectively, are given by:

$$L_{AC,t} = \underbrace{\ell_{AC}^{\text{Conv}} k_t \bar{P}}_{\text{Converter losses}} + 3 \underbrace{\left(\frac{k_t \bar{P}}{\sqrt{3} U_{AC} \cos \phi} \right)^2 R_{AC} D}_{\text{Joule effect line losses}}, \quad (1)$$

$$L_{DC,t} = \underbrace{\ell_{DC}^{\text{Conv}} k_t \bar{P}}_{\text{Converter losses}} + 2 \underbrace{\left(\frac{k_t \bar{P}}{V_{DC}} \right)^2 R_{DC} D}_{\text{Joule effect line losses}}, \quad (2)$$

where $\ell_{AC}^{\text{Conv}} = 1 - \eta_{AC}^{AC/DC}$, and $\ell_{DC}^{\text{Conv}} = 2 - \eta_{DC}^{AC/DC} - \eta_{DC}^{DC/DC}$, denote the converter loss coefficients for the AC and DC connections, respectively. Summing (1) and (2) over time periods, the total losses, L_{AC} and L_{DC} , are given by:

$$L_{AC} = \ell_{AC}^{\text{Conv}} \bar{P} \sum_t k_t + \left(\frac{\bar{P}}{U_{AC} \cos \phi} \right)^2 R_{AC} D \sum_t k_t^2, \quad (3)$$

$$L_{DC} = \ell_{DC}^{\text{Conv}} \bar{P} \sum_t k_t + 2 \left(\frac{\bar{P}}{V_{DC}} \right)^2 R_{DC} D \sum_t k_t^2. \quad (4)$$

The loss break-even distance (LBED) is the distance, D , at which L_{AC} in (3) equals L_{DC} in (4), and is given by:

$$\text{LBED} = \frac{(\ell_{DC}^{\text{Conv}} - \ell_{AC}^{\text{Conv}}) \left(\sum_t k_t \right)}{\bar{P} \left[\frac{R_{AC}}{(U_{AC} \cos \phi)^2} - \frac{2 R_{DC}}{(V_{DC})^2} \right]}. \quad (5)$$

Several comments can be made on the LBED in (5). First, the LBED is linearly related to the difference in the loss coefficients of the converters; the smaller the difference, i.e., the closer the DC transmission converter losses are to the AC transmission converter losses, the lower the LBED. Second, the LBED is inversely proportional to the maximum power \bar{P} ; hence, DC breaks even faster in terms of losses for high values of maximum power. Third, the denominator could be negative, if $\frac{R_{AC}}{R_{DC}} < 2 \cos^2 \phi \left(\frac{U_{AC}}{V_{DC}} \right)^2$, in which case the DC transmission will always exhibit higher losses compared to the AC transmission. Unsurprisingly, the lower the resistance R_{DC} compared to R_{AC} and the higher the V_{DC} compared to $U_{AC} \cos \phi$, the faster DC catches up with AC in terms of losses. Fourth, the LBED is proportional to the ratio $\frac{\sum_t k_t}{\sum_t k_t^2}$ that represents the utilization of the line capacity. This ratio, whose minimum value is 1 (for a line that is loaded at 100%) can be very high for loads that are often significantly at a

small power compared to \bar{P} (for instance solar photovoltaic installation or train substations), which in turn reduces the benefits of a DC transmission in terms of losses.

B. Cost Break-Even Distance (CBED)

In this subsection, we compute the CBED accounting for the following three types of costs: (i) costs of converters (including CAPEX and fixed OPEX throughout the lifetime, i.e., not including costs of losses); (ii) costs of transmission lines, and (iii) costs of power losses. Equipment (converter and lines) are assumed to be appropriately sized for the maximum power \bar{P} .

Let C_{AC}^{Conv} and C_{DC}^{Conv} denote the costs of converters (including their respective interface transformers) for the AC and DC transmission, respectively. Let c_{AC}^{Line} and c_{DC}^{Line} denote the costs per km of AC (including shunt compensation) and MVDC transmission line, respectively. Let c_t^E denote the electricity cost (e.g., the hourly electricity spot price), which affects the cost of losses.

The total costs for the AC and DC transmission, C_{AC} and C_{DC} , are given by:

$$C_{AC} = \underbrace{C_{AC}^{\text{Conv}}}_{\text{Converters costs}} + \underbrace{c_{AC}^{\text{Line}} D}_{\text{Line costs}} + \underbrace{\sum_t c_t^E L_{AC,t}}_{\text{Losses costs}}, \quad (6)$$

$$C_{DC} = \underbrace{C_{DC}^{\text{Conv}}}_{\text{Converters costs}} + \underbrace{c_{DC}^{\text{Line}} D}_{\text{Line costs}} + \underbrace{\sum_t c_t^E L_{DC,t}}_{\text{Losses costs}}, \quad (7)$$

where $L_{AC,t}$ and $L_{DC,t}$ are given by (1) and (2), and the losses cost essentially weighs the losses with the electricity cost c_t^E .

The cost break-even distance (CBED) is the distance, D , at which C_{AC} in (6) equals C_{DC} in (7), and is given by:

$$\text{CBED} = \frac{C_{DC}^{\text{Conv}} - C_{AC}^{\text{Conv}} + (\ell_{DC}^{\text{Conv}} - \ell_{AC}^{\text{Conv}}) \bar{P} \sum_t c_t^E k_t}{c_{AC}^{\text{Line}} - c_{DC}^{\text{Line}} + \bar{P}^2 \left[\frac{R_{AC}}{(U_{AC} \cos \phi)^2} - \frac{2R_{DC}}{(V_{DC})^2} \right] \sum_t c_t^E k_t^2}. \quad (8)$$

Obviously, the CBED in (8), is affected by the difference in converter costs, line costs, and losses cost. For example, higher converter costs for DC transmission (in the numerator) could potentially be compensated by lower DC line costs (in the denominator). We elaborate further on this remark, by relating the CBED in (8) to the LBED in (5).

Example 1. Consider a constant electricity cost, i.e., $c_t^E = c^E$. Then, (8) yields:

$$\text{CBED} = \text{LBED} \left(\frac{1 + \frac{C_{DC}^{\text{Conv}} - C_{AC}^{\text{Conv}}}{c^E (\ell_{DC}^{\text{Conv}} - \ell_{AC}^{\text{Conv}}) \bar{P} \sum_t k_t}}{1 + \frac{c_{AC}^{\text{Line}} - c_{DC}^{\text{Line}}}{c^E \bar{P}^2 \left[\frac{R_{AC}}{(U_{AC} \cos \phi)^2} - \frac{2R_{DC}}{(V_{DC})^2} \right] \sum_t k_t^2}} \right). \quad (9)$$

A closer look at (9) shows that the numerator contains the ratio of the difference of the converter costs to the difference of the costs of the converter losses; the higher this ratio, the longer the CBED compared to the LBED. Similarly, the denominator contains the ratio of the difference of the line costs to the difference of the costs of the line losses; the smaller the AC costs the longer the CBED compared to the LBED. The CBED

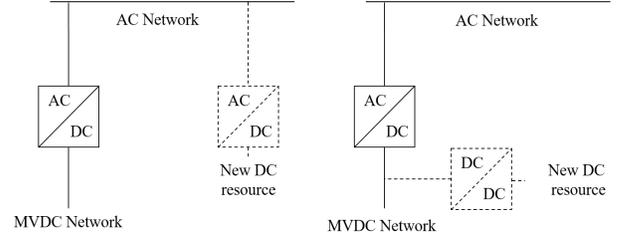


Fig. 2. Options of connection for a new DC resource to existing networks.

will be equal to the LBED when the two ratios are equal. Note that, if we further assume equal costs of lines, the denominator becomes 1, and the ratio will be higher for load profiles with small utilization of the line capacity (i.e., low $\sum_t k_t$ values).

III. CONNECTION TO EXISTING NETWORKS

In this section, we extend our analysis to account for AC and DC connections to existing networks, as displayed in Fig. 2. For instance, a mid-sized solar (photovoltaic) power plant located near an MVDC train line could be connected either to the closest AC network or directly to the train MVDC network.

A. Comparison of Losses and Costs

The total losses and cost for the configurations of Fig. 2 should be adapted to consider (i) the different distances to the existing networks, (ii) the AC/DC converter that was saved in the MVDC connection (compared to the extra DC/DC converter), and (iii) the impact of the new DC resource on the network losses (due to the change of the power flows) and additional costs (e.g., due to the need of additional maintenance or equipment upgrade).

Let D_{AC} and D_{DC} denote the distances of the new DC resource to the AC and DC existing network, respectively. Let $L_{AC,t}^{\text{Net}}$ and $L_{DC,t}^{\text{Net}}$ denote the AC and DC network losses, respectively, at time period t , due to the connection of the new DC resource, where time dependency is related to the injection of the new resource $k_t \bar{P}$. Then, losses $L_{AC,t}$ and $L_{DC,t}$ in (1) and (2), respectively, become:

$$L_{AC,t} = \ell_{AC}^{\text{Conv}} k_t \bar{P} + \left(\frac{k_t \bar{P}}{U_{AC} \cos \phi} \right)^2 R_{AC} D_{AC} + L_{AC,t}^{\text{Net}}, \quad (10)$$

$$L_{DC,t} = \ell_{DC}^{\text{Conv}} k_t \bar{P} + 2 \left(\frac{k_t \bar{P}}{V_{DC}} \right)^2 R_{DC} D_{DC} + L_{DC,t}^{\text{Net}}, \quad (11)$$

where $\ell_{DC}^{\text{Conv}} = 1 - \eta^{\text{DC/DC}}$ is the converter loss coefficient for the DC connection that considers only the DC/DC converter. Hence, the losses comparison of the two connections involves the comparison of the summation over time of (10) and (11).

Let C_{AC}^{Net} and C_{DC}^{Net} denote the AC and DC network costs, respectively, to support the new DC resource connection. Using (10) and (11), the total costs in (6) and (7) become:

$$C_{AC} = C_{AC}^{\text{Conv}} + c_{AC}^{\text{Line}} D_{AC} + \sum_t c_t^E L_{AC,t} + C_{AC}^{\text{Net}}, \quad (12)$$

$$C_{DC} = C_{DC}^{\text{Conv}} + c_{DC}^{\text{Line}} D_{DC} + \sum_t c_t^E L_{DC,t} + C_{DC}^{\text{Net}}, \quad (13)$$

where C_{DC}^{Conv} refers to the cost of the DC/DC converter, and losses $L_{AC,t}$ and $L_{DC,t}$ are given by (1) and (2), respectively. Hence, the costs comparison of the two connections involves (12) and (13). Notably, each connection may also affect the power flows (k_t) of the DC resource (flexible resources such as batteries may be utilized differently depending on the connection), which can be assessed on a case by case basis.

Example 2. Consider a solar power plant as a new DC resource. Using the summation over time of (10) and (11) and/or (12) and (13), one can determine conditions where the MVDC connection of a new solar power plant prevails in terms of total losses and/or costs, respectively.

Furthermore, the connection may also affect the rating of the AC/DC converter between the AC and the MVDC networks, i.e., of the left converter in both Fig. 2(a) and Fig. 2(b). We discuss this issue next.

B. Converter Rating

In this subsection, we elaborate on the rating of the AC/DC converter that connects the AC and the MVDC networks depending on the net load of the MVDC network.

In Fig. 2(a), the AC/DC converter (left) should be rated for the peak load of the MVDC network, denoted by:

$$\bar{P}_{AC}^{\text{MVDC}} = \max_t \{|P_t^{\text{MVDC}}|\},$$

where P_t^{MVDC} is the load of the MVDC network at time period t . For the sake of simplicity, we ignore losses, and from Fig. 2(b), the peak load on the AC/DC converter would be:

$$\bar{P}_{DC}^{\text{MVDC}} = \max_t \{|P_t^{\text{MVDC}} - p_t|\}, \quad (14)$$

where p_t is the DC resource net injection, with $|p_t| = k_t \bar{P}$. Obviously, $\bar{P}_{DC}^{\text{MVDC}}$ can be higher or lower than $\bar{P}_{AC}^{\text{MVDC}}$ depending on the value of p_t . For instance, considering the (non-flexible) solar power plant of Example 2, the peak load can be obtained by evaluating directly (14), which, in turn, might affect the rating of the AC/DC converter. In fact, the AC/DC converter rating would be reflected in the network-related costs, C_{AC}^{Net} and C_{DC}^{Net} , introduced in (12) and (13), respectively. These could be direct costs for upgrades, or avoidable costs, e.g., by rating the converter lower than the MVDC network peak, or by providing the capability to serve higher MVDC network loads avoiding/deferring the need for upgrades.

Let us now consider a flexible DC resource whose output can be modulated to reduce the peak load on the AC/DC converter of Fig. 2(b). In this case, the potential for the reduction in the converter rating cannot be obtained by evaluating directly (14) but would rather be the outcome of an optimization problem. In a simple implementation, this problem would consider the converter cost and the cost of electricity for the MVDC network, as follows:

$$\min_{\bar{P}_{DC}^{\text{MVDC}}, p_t} C_{AC/DC}^{\text{Conv}}(\bar{P}_{DC}^{\text{MVDC}}) + \sum_t (P_t^{\text{MVDC}} - p_t) c_t^E \quad (15)$$

$$\text{subject to: } (14) \quad \text{and} \quad p_t \in \mathcal{P}, \quad \forall t, \quad (16)$$

where $C_{AC/DC}^{\text{Conv}}(\bar{P}_{DC}^{\text{MVDC}})$ is the cost function of the converter that depends on its size, and \mathcal{P} represents the set of constraints for the flexible DC resource.

Example 3. Consider a hybrid power plant that includes a solar power plant and a battery as a new DC resource. Assuming hourly periods for t , \mathcal{P} includes the following constraints:

$$p_t = p_t^{\text{Solar}} - p_t^{\text{Bat, ch}} + p_t^{\text{Bat, dis}}, \quad \forall t, \quad (17)$$

$$0 \leq p_t^{\text{Solar}} \leq \bar{P}_t^{\text{Solar}}, \quad \forall t, \quad (18)$$

$$0 \leq p_t^{\text{Bat, ch}}, p_t^{\text{Bat, dis}} \leq \bar{P}^{\text{Bat}}, \quad \forall t, \quad (19)$$

$$e_t^{\text{Bat}} = e_{t-1}^{\text{Bat}} + \eta^{\text{Bat, ch}} p_t^{\text{ch}} - \frac{1}{\eta^{\text{Bat, dis}}} p_t^{\text{dis}}, \quad \forall t, \quad (20)$$

$$E_{\min}^{\text{Bat}} \leq e_t^{\text{Bat}} \leq E_{\max}^{\text{Bat}}, \quad \forall t. \quad (21)$$

Briefly, constraint (17) defines the hybrid power plant net injection at hour t , combining the solar production p_t^{Solar} and the battery charging and discharging, $p_t^{\text{Bat, ch}}$ and $p_t^{\text{Bat, dis}}$, respectively. Constraints (18) and (19) impose solar and battery power limits, \bar{P}_t^{Solar} and \bar{P}^{Bat} , respectively. Constraint (20) defines the battery state of energy e_t^{Bat} , with charging/discharging efficiency $\eta^{\text{Bat, ch}}$ and $\eta^{\text{Bat, dis}}$, respectively. Constraint (21) imposes the minimum and maximum energy limits, E_{\min}^{Bat} and E_{\max}^{Bat} , respectively, on the battery state of energy.

IV. NUMERICAL RESULTS

In this section, we present numerical results to illustrate the point-to-point transmission analysis (in Subsection IV-A), the connection to existing networks with different distances (in Subsection IV-B) and the impact of the MVDC connection on the converter rating (in Subsection IV-C).

A. Point-to-Point Transmission Results (Example 1)

In this subsection, we consider Example 1, with three load types: (i) a constant full power load as reference; (ii) a solar plant, and (iii) a train substation, with generally low average load factor.

The pole-to-pole DC voltage is set as the double of the AC phase-to-phase RMS voltage as suggested in [1], [7]. All converter efficiencies are set to 0.99. The annualized difference between the DC and AC converter costs is 12,151 €/MW, and the electricity cost is assumed to be constant and equal to 100 €/MWh. AC and DC line resistances are 0.0273 and 0.0211 (Ohm/km), respectively; line costs are supposed to be equal. The AC line power factor is set at 0.95.

Table I presents the LBED and the ratio $\frac{\text{CBED}}{\text{LBED}}$ given by (9) for four combinations of maximum power and voltages. Given the assumptions for this example, this ratio is independent of the power and voltages — see (9) and note that for equal line costs the denominator of the ratio is equal to 1. Lower utilization of the line results in higher $\frac{\text{CBED}}{\text{LBED}}$ ratio; for example, the train substation has a ratio of 12.7. Notably, the LBED values, for this particular example, span a very large range, from 2 km (for the reference constant full power load at 100 MW with $U_{AC} = 20$ kV and $U_{DC} = 40$ kV) to 509 km (for the train substation at 20 MW with $U_{AC} = 63$ kV and $U_{DC} = 126$ kV).

TABLE I
RESULTS FOR THE POINT-TO-POINT TRANSMISSION

Case	P [MW]	U_{AC} [kV]	V_{DC} [kV]	LBED [km]	CBED LBED
Constant full power	20	20	40	10	2.39
$\langle k_t \rangle$		63	126	101	
$\langle k_t^2 \rangle$		20	40	2.0	
$\sum_t k_t / \sum_t k_t^2$		63	126	20	
Solar power plant	20	20	40	23	10.47
$\langle k_t \rangle$		63	126	225	
$\langle k_t^2 \rangle$		20	40	4.5	
$\sum_t k_t / \sum_t k_t^2$		63	126	45	
Train substation	20	20	40	51	12.70
$\langle k_t \rangle$		63	126	509	
$\langle k_t^2 \rangle$		20	40	10	
$\sum_t k_t / \sum_t k_t^2$		63	126	102	

B. Connection to Existing Networks (Example 2)

In this subsection, we consider Example 2, with a new solar power plant of $\bar{P} = 1$ MW and load factor as per Example 1, which could be connected to an AC network ($U_{AC} = 20$ kV phase-to-phase RMS) or to an MVDC train power network (e.g., [8], at $V_{DC} = 9$ kV pole-to-pole). Converter efficiencies, AC and DC line data are as per Example 1. The annualized difference between the converter costs is 5,316 €/MW, and the annualized AC and DC line costs are equal to 10,919 €/km.

Using the summation of (10) and (11) over a year, and neglecting the network-related terms, the connection to the MVDC network prevails in terms of total losses when

$$D_{DC} < 0.145 D_{AC}.$$

Since the converter losses are the same (equal efficiencies), the trade-off between the connection to the MVDC and the AC network in terms of losses depends on the ratio between the MVDC (annual) line losses (300 kWh/km) and the AC (annual) line losses (44 kWh/km, i.e., about 7 times smaller than the respective MVDC losses). Hence, the distance to the MVDC network would need to be about 7 times smaller compared to the AC network, to justify an MVDC connection in terms of losses.

Using (12) and (13), and neglecting the network-related terms, the connection to the MVDC network prevails in terms of total costs when

$$D_{DC} < 0.998 D_{AC} - 0.486 \quad [\text{in km}].$$

Since the costs of the lines are equal, the per km cost only depends on the difference in the cost of the line losses, which is higher in the MVDC line, but the combined effect is small (e.g., 1 km of AC line is as costly as 0.998 km of DC line). Given the difference in the converter costs, the MVDC connection prevails in terms of total costs, when the AC network is about 0.5 km farther than the MVDC network.

C. Converter Rating (Examples 2 and 3)

In this subsection, we assess the impact of the new DC resource connection on the rating of the AC/DC converter between the AC and the MVDC networks.

We first consider Example 2, where the MVDC network includes a non-flexible train substation load, of 5-MW maximum instantaneous load, and load factor as per Example 1. Because the peak load of the train substation occurs on a summer evening, the connection of the solar power plant to the train MVDC network does not affect the converter rating.

We then consider Example 3, where the 1-MW solar power plant is also equipped with an 1-MW, 2-MWh battery, with an 85% cycle efficiency. The connection to the MVDC network uses a unidirectional converter. We assume the annualized AC/DC converter cost to be equal to 6,835 €/MW, and the electricity cost as per Example 1. The solution of the optimization problem (15)–(16), using the constraint set (17)–(21), yields a rating for the AC/DC converter of 4 MW, i.e., 1 MW lower than the rating considering only the train substation (and/or Example 2). The outcome implies that the battery power capacity is fully utilized (the cost of the efficiency losses being smaller than the benefit from the lower converter rating). Hence, increasing the battery capacity could further reduce the converter rating; for example, a 2-MW, 2-MWh battery could further reduce the peak load to about 3.203 MW.

V. CONCLUSION

In this work, we compared AC and MVDC connections for new DC resources, in terms of total losses and costs. Our analysis included results on break-even distances of point-to-point connections, as well as insights on the connection of new DC resources to existing networks with different distances, accounting for network-related costs (e.g., upgrades required or avoided). We also illustrated the impact that a flexible DC resource could have on the peak load of an MVDC network, thus allowing for lower ratings of the main AC/DC converter.

Future work is directed to integrating the network impact (e.g., network losses) and the opportunity for a lower converter rating in the optimization problem, also taking into account the uncertainty of the MVDC network load combined with new DC resources, and further refining costs (e.g., for shunt compensation) and benefits (e.g., from the provision of ancillary services).

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