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P. L. Metayer, J. Paez, S. Toure, *et al.*

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POWER ELECTRONICS LABORATORY
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Break-even distance for MVDC electricity networks according to power loss criteria

Pierre Le Métayer[1], Juan Paez[1], Sellé Touré[1], Cyril Buttay[2], Drazen Dujic[3], Eric Lamard[4], Piotr Dworakowski[1]

[1]SUPERGRID INSTITUTE
23 Rue Cyprian
69100 Villeurbanne, France
+33 7 63 66 19 15
pierre.lemetayer@supergrid-institute.com
https://www.supergrid-institute.com

[2]Univ Lyon, CNRS, INSA Lyon,
Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, Ampère, UMR 5005,
69621 Villeurbanne, France
http://www.ampere-lab.fr

[3]Power Electronics Laboratory (PEL)
École Polytechnique Fédérale de Lausanne
1015 Lausanne, Switzerland
https://www.epfl.ch/labs/pel/

[4]Compagnie nationale du Rhône (CNR)
2 rue André Bonin
69004 Lyon, France
https://www.cnr.tm.fr/

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Keywords

«DC collector network», «Medium voltage», «Efficiency», «Power transmission», «Photovoltaic»

Abstract

The medium voltage direct current (MVDC) technology is emerging in electricity networks including point-to-point transmission, distribution networks and collection networks for renewable energy sources. In this article the MVDC break-even distance (with respect to AC distribution) is calculated according to the overall energy efficiency criteria. The break-even distance is found to vary from less than 10 km to several tens of kilometres depending on power and voltage ratings and network topology.

Introduction

In recent years, the electrical power system has started to evolve from a centralized architecture, with large power plants, to a more distributed architecture integrating many smaller power sources, mainly wind and photovoltaic (PV). The power transmission and distribution systems have to face this evolution and adapt accordingly.

The high voltage direct current (HVDC) technology is expanding in the transmission grids. It offers an economically viable solution for long-distance transmission of bulk power, especially when underground or underwater cables are used. Similar reasons that have made the HVDC technology gain momentum in power transmission networks are now causing the medium voltage direct current (MVDC) technology to emerge for power distribution. Recently, Siemens has proposed a product for MVDC links, offering among other advantages lower overall losses and power flow controllability [1]. ABB makes a similar analysis in [2]. The "Angle DC" project in United Kingdom is an example of converting two existing MVAC circuits to operate as MVDC circuits [3], with, as a result, an expected 23% increase in transmitted power capacity. Moreover, the converter stations supplied by General Electric will provide reactive power control capability on both AC networks, which will improve the power quality in the local region and hence reduce the operating losses in the networks. CIGRÉ has provided some

foundations for the MVDC grid development in [4] and the efforts continue in the ongoing working group C6/B4.37.
In large offshore wind farms the distance between the wind turbines and the HVDC converter station may exceed tens of kilometres. Since underwater cables are used, then MVDC may be considered [5], [6]. Large solar power plants, some of which spread over kilometres may also benefit from MVDC, especially because PV modules are inherently producing DC power [7], [8]. The electrified railway infrastructure may see a new standard of MVDC power supply at 9 kV [9]. Ships are also getting more electric and the standards include the MVDC power distribution networks up to 35 kV [10].
All the above clearly shows that MVDC technology have advantages for some specific applications. The criteria for an application to switch to DC will depend strongly on the result of a cost-benefit analysis. One of the important performance indicators is the energy efficiency which is a component of the operational expenditure (OPEX). Power losses in DC cables are lower than in AC cables, as there is no circulation of reactive current in DC and therefore no corresponding Joule losses in the conductors. However, considering that the DC system has to be connected at some point to an existing AC system, a DC-AC converter station is required. This station comes at a given cost and adds power losses. For high voltage links, it has been demonstrated that a break-even-distance exists, where HVDC becomes advantageous over HVAC. The HVDC/HVAC break-even-distance is approximately 50 km in case of submarine cables [11].
In this paper, an MVDC/MVAC break-even distance is calculated according to the overall energy efficiency criteria. The power losses in underground cables and DC-AC converter stations are considered, assuming some hypotheses, in particular regarding the equivalent voltage and power between AC and DC. This study strictly focuses on the efficiency criteria, as accurate cost estimations are not within the scope of the authors' work.
Three case studies are presented. The first one is a point-to-point transmission, the elementary block of electricity networks. The second one is a distribution network, a common type of network in today's grid. Third one is a collection network for a large PV installation, to give an example of a network with a particular production profile.
The novel aspects of this work are as follows:

- The calculation of break-even distances for MVDC, with clear underlying hypotheses,
- The study of the effect on the break-even distance of the power repartition in a multi-terminal network,
- The study of the effect of the production profile on the break-even distance.

Methodology

The DC electricity networks are expected to develop together with AC networks following similar principles. The elementary electricity interconnection unit is the point-to-point (P2P) transmission line and it can be realised in AC or DC as presented in Fig. 1a. In the current AC grid, a distribution network is commonly realised as a ring where the individual loads are supplied from a ring main unit (RMU) [12]. A normally open point (NOP) separates the system into two radial networks as presented in Fig. 1b. The same ring network architecture can be considered for the collection network of renewable energy sources such as PV or wind.

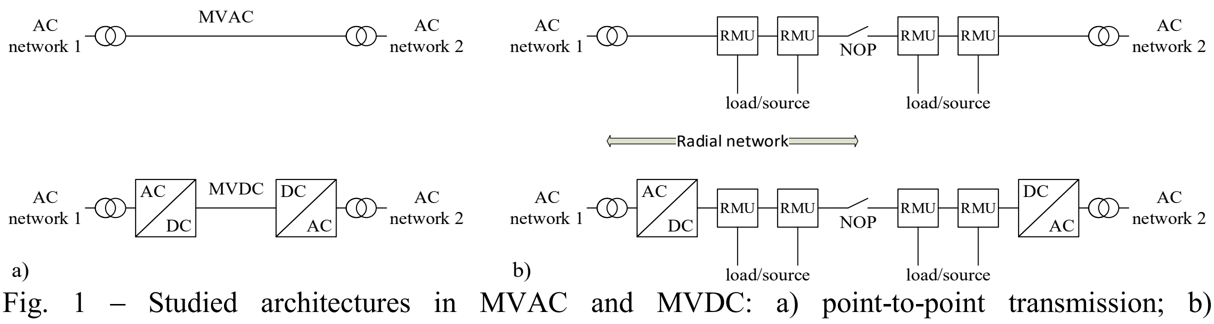

Fig. 1 – Studied architectures in MVAC and MVDC: a) point-to-point transmission; b) distribution/collection ring network (two radial networks)

A symmetric monopole line configuration with high impedance grounding is selected for the MVDC line. It offers a good robustness to fault events while reducing isolation constraints. Considering voltage source converter (VSC) AC-DC stations with sinusoidal pulse width modulation, the MVDC voltage is defined as:

$$U_{DC} > 2\sqrt{\frac{2}{3}}U_{AC} \approx 1.6U_{AC} \tag{1}$$

where U_{DC} is the DC line-line voltage and U_{AC} is the 3-phase AC line-line RMS voltage. Then, for the comparative analysis of AC and DC, the transmission voltages equivalence between both options can be assumed to be described by (1). A complementary approach to define the equivalence on voltages is to consider the DC voltage that a cable insulation can withstand compared to its AC ratings. In [13] a 12/20 kV MVAC cable was reported to pass a 55 kV DC test. The conclusion of [4] is that a MVAC cable rated for X kV AC nominal voltage is recommended for ±X kV DC. The authors follow this recommendation for the choice of the voltage levels.
The comparative analysis of power losses takes into account the cable and AC-DC stations. Other elements of the network are not considered in this analysis. In particular, the transformers (Fig. 1) are assumed to have the same efficiency in both AC and DC systems. The same cables are considered for the DC and AC lines assuming that the MVDC market demand will not allow the development of specific technologies in the short term. One should note that three conductors are used in AC systems while only two are used in DC. This fact should be taken into account when analysing the cost. The cable parameters are presented in Table I, according to [14]. For both AC and DC, it is considered the use of single-core, unarmoured copper cables. For the AC case the resistance is calculated taking into account the skin effect [15]. The cable temperature is assumed to be 70°C. Cable losses calculations are performed based on load flow analysis [16].

Table I: Cable parameters

Network nominal voltage	Cable rating	Section [mm²]	DC resistance @ 20°C [Ω/km]	DC resistance @ 70°C [Ω/km]	AC resistance @ 70°C [Ω/km]	Inductance [mH/km]	Capacitance [µF/km]	Capacitive current [A/km]
10 kVac / ±10 kVdc	12 kV	1000	0.0176	0.0211	0.0273	0.268	0.904	1.80
20 kVac / ±20 kVdc	22 kV	1000	0.0176	0.0211	0.0273	0.283	0.584	2.33
33 kVac / ±33 kVdc	36 kV	1000	0.0176	0.0211	0.0273	0.290	0.380	2.52

The nominal power of the network for each voltage level is calculated according to the maximum cable current. In this analysis a value of I_{max} = 1 kA is retained. The value of 1 A/mm^2 is a typical current density according to [14]. Therefore, the nominal power is calculated as the minimal power between DC and AC transmission that gives the maximal current per cable as expressed in (2). Table II presents the nominal power obtained for each voltage level.

$$P_{nom} = min\left(\sqrt{3}U_{AC}I_{max}, U_{DC}I_{max}\right) \tag{2}$$

Table II: Nominal power at different voltages

U_{AC}	U_{DC}	P_{nom}
10 kV	±10 kV	17.3 MW
20 kV	±20 kV	34.6 MW
33 kV	±33 kV	57.2 MW

The AC-DC converter stations are only required in the MVDC systems. The efficiency of each AC-DC station is assumed to be that presented in [17]. The reported efficiency of the studied 24 MW 3-level neutral point clamped (NPC) inverter based on IGCTs is approximately 99.1% at low fractions of the nominal power. In this article, the conservative value of efficiency at 99% is considered in the entire power range of the AC-DC converter station.

In the distribution or collection network, if the load or the energy source requires a power conversion equipment then it is assumed that this equipment has the same efficiency in both AC and DC. For example, considering a PV source, the PV inverter and transformer required for the MVAC network is assumed to have the same efficiency as the step-up DC-DC converter needed for the MVDC network.

Point-to-point transmission

In this section the break-even distance for a point-to-point transmission is studied. In order to calculate it, the power losses in the cables are calculated for the different voltage levels defined in Table II.

The power losses are calculated for different distances using the nominal power defined for each voltage level (Table II) and cable parameters (Table I). The results are presented in Fig. 2. The figure shows the losses obtained in the cable for the AC and DC interconnection, as well as the total losses for the DC case if the AC-DC station losses are included. In this case, two AC-DC stations are considered, one at each side of the interconnection, which increases losses by 2 percentage points.

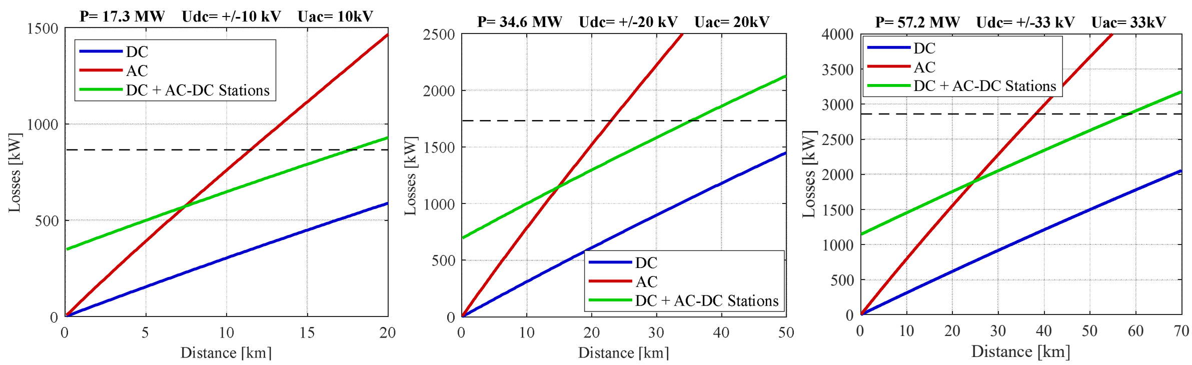

Fig. 2 – Power losses in function of the distance for the point-to-point transmission at 3 different voltages. The dashed black line represents 5% of losses related to the nominal power.

It is observed that for all the distances, the losses in the cable are lower in DC. However, because the added losses of the AC-DC stations, the overall losses in the DC installation are higher for distances shorter than the break-even distance (crossing point of red and green curves in the figure). Above this point, DC presents lower losses compared to AC. It is observed how the break-even distance changes with the voltage level. As the voltage increases, the break-even distance shifts to longer distances.

The dashed black line in the figure represents 5% of losses related to the nominal power in each case. This line is shown as reference and gives an idea of the maximum allowed distance for each configuration in terms of losses. Selecting a higher voltage level could be interesting to decrease the losses to an acceptable value. The limit of 5% is given as reference but another limit could be taken from a technical and economic analysis.

The results of Fig. 2 were obtained at the nominal power level of the line. However, according to the application, it could be expected that the line does not operate at nominal power all the time. This is the case when interconnecting renewable sources for example. Then, it is worth analysing the losses for a fixed distance in function of power. Fig. 3 shows the results of this analysis for a given case. It is observed that, for low power loads, AC offers lower losses than DC. However, above a *break-even power* point the losses in the DC installation are lower than in AC. Therefore, the load profile of the application influences as well the interest of DC transmission over AC. It is observed that the *break-even power* changes according to the length of the line.

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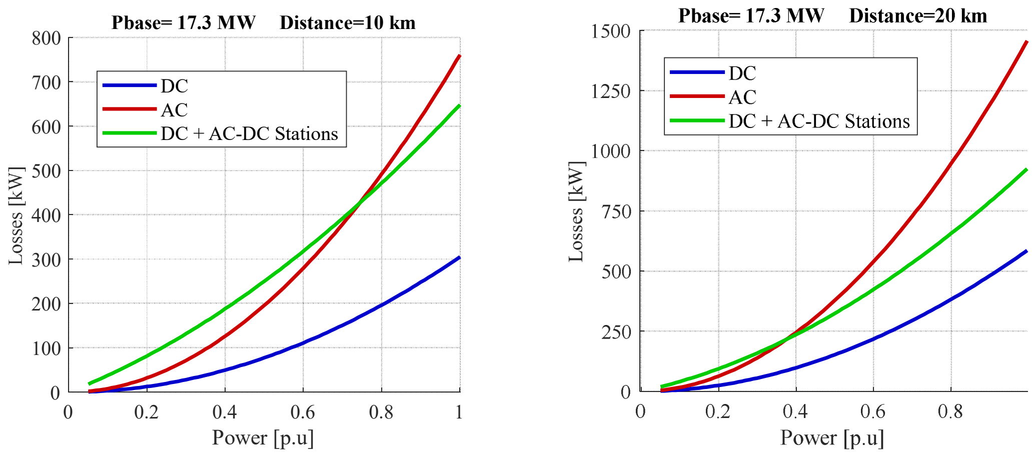

Fig. 3 – Power losses in function of the power for the point-to-point transmission at fixed distances for the voltage level of 10 kVac / ±10 kVdc.

Fig. 4 shows the *break-even distance* and *break-even power* for each voltage level. The curves represent the distances and powers for which the losses of the point-to-point transmission are the same for AC and DC. The area above each break-even curve (dashed zone) represents the zone where DC transmission gives lower losses. The area below each curve (coloured zone) represents the zone where AC transmission gives lower losses. The dashed lines for each case represent the limits of the transmission scheme. The maximal power is given for the maximal current allowed in the cable (1 kA is considered), and the maximal distances are given by a limit of 5% of losses. Above these limits the transmission should be done at a higher voltage level.

It can be observed that as the power decreases, the transmission distance becomes longer and the break-even distance increases. However, at low power the trend for the break-even curve is inversed. This is due to the predominant influence of the capacitive current in the cable (see Table I). In AC transmission at low power and long distance, the capacitive current can be of the same order of magnitude as the active current, causing the corresponding Joule power loss in the conductors to degrade efficiency noticeably.

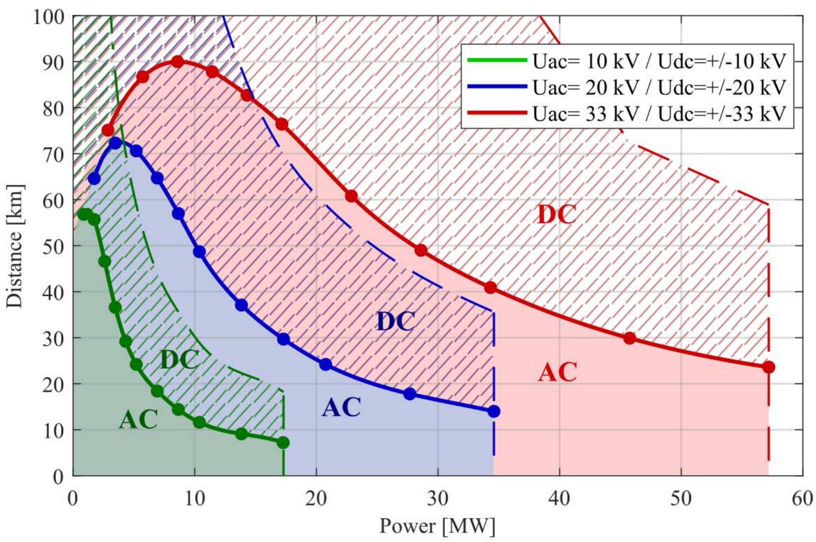

Fig. 4 – Break-even distance and power of point to point transmission in terms of losses for different voltage levels. Dashed area represents the power and distance range where DC transmission results in lower losses. The dashed line represents the limits of the transmission scheme (maximal current or maximal losses).

Distribution network at constant load

The ring or radial distribution network differs from the previous case of point-to-point transmission by the fact that the total power of the installation does not transit through the total length of the cable. Indeed, for a radial network, the power in the cable decreases at each RMU to reach its minimum in the last segment of cable. This means that the losses in the cables of a radial network, of total power P, running along a distance d, will be lower than its point-to-point counterpart. Contrary to the point-to-point configuration the distribution of loads along the line matters in the resulting power losses.
In this section only the 10 kV 17.3 MW configuration is studied according to Table II. The power of a load P_{RMU} is fixed to 250 kW giving in total 69 power loads. A constant-in-time power load is considered. In order to have representative values, a stochastic approach is taken. The power losses in the cables are calculated based on load flow analysis [16] for different total network length. For each total network length, 1000 random RMU repartitions are evaluated. Random distributions are generated while keeping a condition of minimum distance of 60 m between two RMUs.

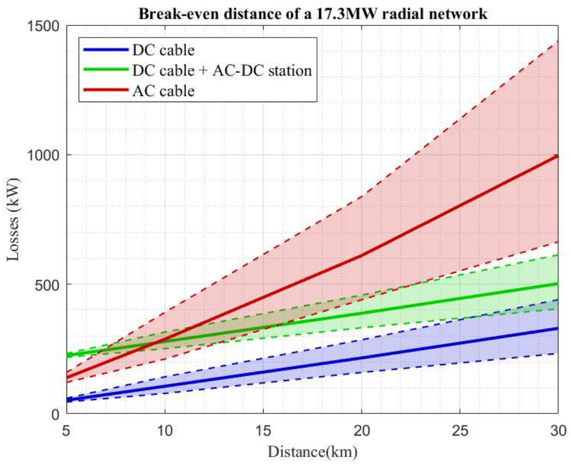

Fig. 5 – Power losses in the 10 kV distribution network over increasing distance: solid line - average power losses, dashed line - min and max power losses according to the random distribution of loads.

It can be observed that, compared with the same voltage/power than in the point-to-point case, the average break-even distance is farther away for the distribution network. This can be explained by the fact that the full power doesn't transit through the whole line. As shown in the previous section, in the case of the point-to-point transmission, the break-even distance gets farther away when the transmitted power decreases. It should be noted that the DC radial distribution network only requires one AC-DC station where two are required in the point-to-point transmission.
The dotted lines in Fig. 5 correspond to the extreme distribution cases giving the minimum and maximum losses. The extreme losses in AC and DC come from the same distribution cases respectively. Thus the break-even distance range calculated for the 1000 random distribution cases in Fig. 5 is between 7.5 km and 13 km. It can be observed that, for the extreme cases, the deviation from the mean is larger in AC than in DC. Fig. 6 illustrates this point. The efficiency of the cable transmission for AC and DC is represented for the 1000 random distribution cases, for a total network length of 30 km. The significant deviation is more noticeable with the increase of distance. The AC transmission efficiency ranges from 91.6% to 96.1% where the DC transmission efficiency ranges from 97.4% to 98.6%.

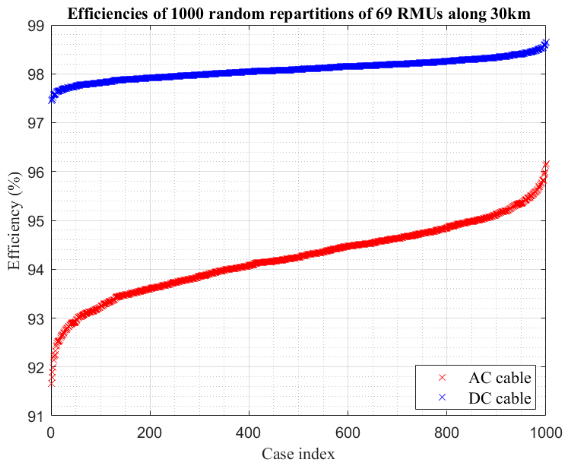

Fig. 6 – Cable transmission efficiency of the 10 kV, 30 km distribution network in function of repartition of RMUs: AC (red) and DC (blue)

It is observed again from Fig. 5 that for higher losses (low efficiency cases) the break-even distance is shorter. Fig. 7 shows the repartition of RMUs along one total network length (30 km), sorted by increasing efficiency. The density of black dots is higher at long distance and low efficiency, and at short distance and high efficiency. Indeed, when most of the RMUs are located at the other end of the distribution network, the network tends to behave more like a P2P network (with the total power transmitted through the complete distance), with higher losses and shorter break-even distance.

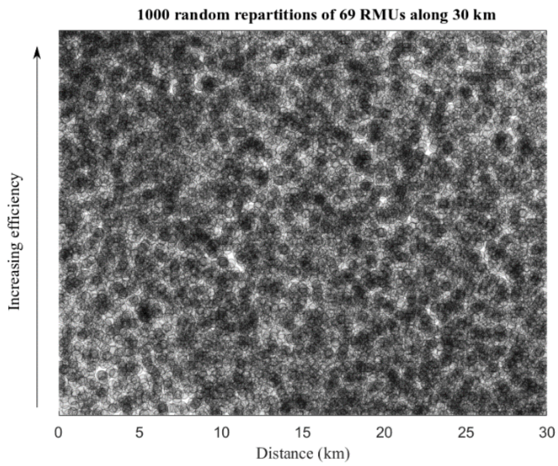

Fig. 7 – Random repartition cases of RMUs along a total network length of 30 km. Each black dot represents an RMU. The 1000 configurations are stacked along the vertical axis, ranked from lower (bottom) to higher (top) efficiency.

PV collection network with varying power production

Just as in the P2P case, the power transmitted through a distribution network is not necessarily constant over time. As seen in the point-to-point transmission section, the variation in efficiency of the cable transmission with transmitted power should be taken into account in the comparison between AC and DC networks. The previous section presented the distribution network transmitting power to loads but the same ring or radial network can be used for the collection of power from sources. The example of PV collection is taken here to illustrate a network with varying transmitted power. The nature of PV energy production is that the power varies in a wide range according to the irradiation. In order to observe the effect of the variable irradiation, the same random repartition cases of RMUs as in the previous section are considered and the losses are evaluated for different power levels delivered by the sources. All sources are considered to produce the same power.

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The statistical study of irradiance rates gave different weighted average efficiencies that can be used to evaluate the performance of a PV system depending on its geolocation [18]. The "European efficiency" [18] is used here. By applying its coefficients to the losses calculations, the "European efficiency-based" break-even distance can be found. The knowledge of the production profile enables to find a break-even distance directly accounting for variable transmitted power, contrary to the general case presented in the previous section where *break-even powers* had to be calculated.

$$\eta_{euro} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.1 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.2 * \eta_{100\%} \quad (3)$$

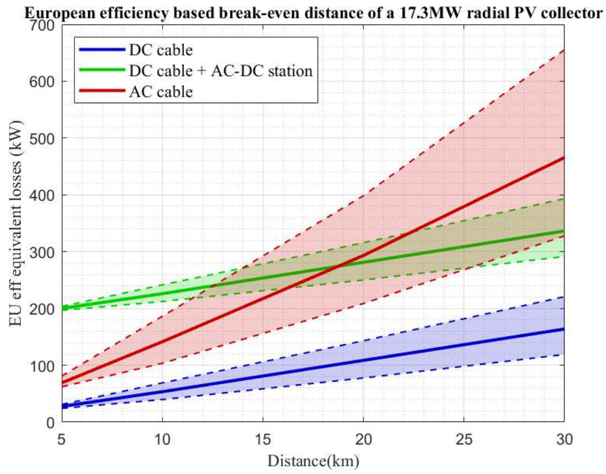

Fig. 8 – European efficiency-based efficiency of the 10 kV PV collection network over increasing distances: solid line - average power losses, dashed line - min and max power losses according to the random distribution of sources

It can be observed that taking into account the power variation of the sources results in a break-even distance farther away than in the constant power case. One should note that this procedure can be done in a similar manner for a wind energy installation by using wind speed distributions [19].

The results of this study can be used as a guideline for the design of the DC-DC converter used in the RMU of the DC architecture. The base hypothesis of the presented break-even distances is the equivalence of the RMU efficiency in both DC and AC architecture. Thus, by taking into account the efficiency of a state of the art AC RMU (in the PV example: string inverter and 50Hz transformer), one can estimate the target efficiency for the DC RMU corresponding to a target break-even distance.

Conclusion

The break-even distance for HVDC has been studied extensively in literature. This paper proposed an efficiency–based break-even distance for MVDC considering different case studies. The point-to-point case showed that the MVDC break-even distance is typically shorter than its HVDC counterpart and depends on voltage and power levels. Compared to HVDC, multi-terminal MVDC are much more commonplace. The case study of the distribution network showed that the low utilization factor of the line pushes the break-even distance farther away than in the point-to-point case. Finally it was observed that light load conditions of renewable energy applications such as PV drives away the break-even distance even more. These consideration can be used to define target efficiencies of future DC-DC converters interfacing MVDC network sources and loads. If the MVDC network was considered without any connection to AC network then the benefits of DC would be significant and the break-even distance would be much shorter. The economic study still needs to be addressed in order to have an equivalent to the existing HVDC break-even distance.

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