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SHUNT COMPENSATION DESIGN OF EHV DOUBLE-CIRCUIT MIXED OHL-CABLE CONNECTIONS

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Abstract

This paper deals with the shunt compensation design of long 380kV-50Hz XLPE cables by simulating a double-circuit partially cabled connection with the transmission length of 80 km in the Dutch transmission system. The proposed procedure for shunt compensation sizing is fully elaborated in this paper. Four sizing criteria are used to find the minimum required size of compensation. All simulations are performed for different cable lengths. Moreover, different compensation arrangements including line-end and distributed arrangements are compared in terms of minimum required compensation size. Finally, the influence of mixed-line configuration, i.e. the number and the location of cable sections, on the minimum required compensation size is investigated by simulating five mixed-line configurations. All simulations are performed for two load-flow scenarios representing two extreme situations in the future planning of the Dutch transmission grid.

1 Introduction

The utilization of partial cable-based EHV network expansions has recently increased among transmission system operators (TSOs). Partial undergrounding is a favourable option mainly because of public opposition as well as governmental policies against construction of new overhead lines (OHLs) at least in densely populated areas and sensitive locations. However, underground cable application for transport of large amounts of power in transmission networks has its own difficulties and it is not yet a well-practiced technology from the system point of view. This is mainly due to the large cable capacitance compared to OHL. Many operational aspects need to be investigated beforehand to get assured that the system reliability will not be jeopardized.

This paper deals with the shunt compensation design of long 380kV-50Hz XLPE cables by simulating a double-circuit connection consisting of series connected OHL and cable sections, which is known as a mixed-line, in the future Dutch transmission system. Reactive power compensation by means of shunt reactors (SRs) has to be applied for long EHV cables to consume reactive power surplus of cable and to keep system voltage within acceptable margins. It is crucial to have sufficient size of shunt compensation because both undercompensation and overcompensation can lead to undesirable system operation like overvoltage (and generator self-excitation in extreme situations) and zero-missing phenomenon, respectively [3,8].

The present paper proposes a shunt compensation sizing approach based on the requirements addressed in [1,2,4,7,8]. This approach is according to the practical and theoretical concerns related to the operation of long EHV cables. The study is performed for two load-flow scenarios representing two extreme situations, which are considered for the future planning of the Dutch grid. All simulations are performed for different cable lengths in percentages of the total transmission length. This is needed to determine the influence of increasing cable length on the shunt reactor allocation. Moreover, different compensation arrangements including line-end and distributed arrangements are compared in terms of the minimum required compensation size. The minimum required size of compensation is also compared for five mixed-line configurations with different number of cable sections at different locations. The results of these comparisons are important in the planning stages of a mixed OHL-cable connection because they can indicate the best mixed-line configuration(s) related to the compensation degree for a given cable length. The steady-state calculations are based on the positive sequence representation of the Dutch transmission system in the DIgSILENT PowerFactory environment. This model includes all interconnections and a simplified representation of European transmission grids and can therefore represent realistic load-flows and short-circuit levels.

The paper is structured as follows: Basic considerations are presented in section 2; Section 3 deals with the shunt compensation sizing requirements; Simulation results are presented in Section 4; The influence of distributed compensation and mixed-line configuration on compensation sizing are treated respectively in Sections 5 and 6; Finally the most important conclusions are summarized in Section 7.

2 Basic considerations

This study is performed for the case study of a hypothetic project that will connect the western part of the Dutch 380 kV ring to the eastern part of the ring. This project is assumed to have two identical circuits with the transmission length of around 80 km and it is expected to have a significant role in reducing future bottlenecks in the grid.

2.1 Electrical characteristics of OHL and cable

Table 1 presents the electrical parameters for 400kV-50Hz OHL and cable. The OHL is composed of a bundle of four sub-conductors with a continuous current rating (ampacity) of 4 kA in total. The continuous current rating of a single cable is 1500 A, but this value can be increased to 2 kA for 24 hours.

2.2 Default mixed-line configuration

It is necessary to introduce a proper illustration for the mixed-line in terms of the number and location of cable sections. Different configurations may represent a mixed-line. A practical approach is to locate sensitive areas along the connection route where the importance of undergrounding is highlighted, such as cities and national parks. Based on this approach, three cable and four OHL sections are considered for each circuit. This is the default representation of the mixed-line for this project, which is also shown in Fig. 1. Because the standard transmission capacity of a three-phase OHL circuit is about 2635 MVA (380 kV/4000 A), each cable section needs two parallel cables per phase to have the same transmission capacity as the OHL.

The next important step is to determine the possible locations for the shunt reactors. Three shunt reactor arrangements, which are known as Line-End Compensation (LEC), are studied as default arrangements. In all arrangements, compensation sizes of two circuits are not necessarily equal (i.e. SR1≠SR2 for arrangements A1S and A1R; SR1+SR2≠SR3+SR4 for the arrangement A2). In the arrangement A2, reactors of each circuit are equal, namely SR1=SR2 and SR3=SR4. Moreover, the size of each shunt reactor (SR) unit is adjustable.

2.3 Load-flow scenarios

System impact studies require different load-flow scenarios like high wind power generation or high conventional power generation. According to the TenneT quality and capacity plan of 2013, two distinct load-flows can be determined for the year 2020: (1) *Load-flow A (West-East)*: In this case, a large transport of power from west to east is expected. The short-circuit powers for the sending-end (substation KIJ380) and the receiving-end (substation DOD380) are 29.7 GVA and 20.4 GVA, respectively. (2) *Load-flow B (East-West)*: In this case, a large transport of power from north-east to west and south-west is expected. The short-circuit powers for the sending-end (substation DOD380) and the receiving-end (substation KIJ380) are respectively 21GVA and 20.1GVA.

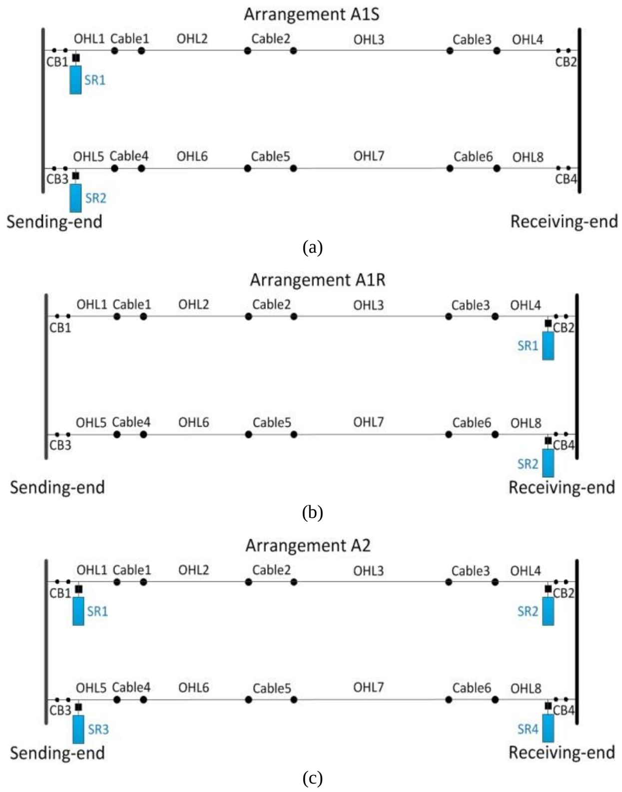

Figure 1: Single-line representation of the default double-circuit mixed-line with three different LEC arrangements: (a) reactors at the sending-end, (b) reactors at the receiving-end, (c) reactors at both line ends.

2.4 Cable length

The influence of increasing cable length on shunt reactor allocation is investigated by simulating different cable lengths presented in Table 2. The cable portion is increasing from zero to 100% of total transmission length in five steps, which means in total six cases: fully OHL (0% cable), 15% cable, 25% cable, 50% cable, 75% cable and fully cable (100% cable). In this research when it is mentioned “L” km cable, as an example, it means that each phase is composed of 2×L km

Case	OHL length (km)	Cable length (km)
Fully OHL	80	0
15% Cable	68	12
25% Cable	60	20
50% Cable	40	40
75% Cable	20	60
Fully Cable	0	80

Table 2: Simulated cable lengths (transmission length 80km).

Type	Cross-section (mm^2)	R+jX (Ω/km)	C (nF/km)	SI (Ω)	SIL [b] (MVA)	I_n [c] (A)	S_n [d] (MVA)
OHL conductor [a]	2483.6	0.0148+j0.232	15.3	219.7	657.3	4000	2635
XLPE Cable	2500	0.0227+j0.1712	231.5	48.5	2976.2	1500[e]	987.27

[a] Bundle of 4 sub-conductors. [b] Surge impedance loading for a three phase system calculated at U_n=380kV. [C] Ampacity/Rated Current.
[d] Apparent power at ampacity I_n (thermal power limit); $S_n = \sqrt{3}U_nI_n$. [e] This value can be increased to 2 kA just for 24 hours.

Table 1: Electrical parameters for 400kV-50Hz OHL/cable lines.

cable (there are two cables per phase) and each circuit 3×2×L km cable. In total, the double-circuit includes 12×L km cable.

3 Sizing requirements

In [1,2,4,6,7,8], several operational constraints are proposed for shunt compensation sizing of long cables. These constraints are mainly based on no-load open-end operation, which is the most onerous reactive power balance. The four criteria used for the sizing of shunt reactors in this paper are:

(1) *Sudden voltage jump (or rapid voltage change (RVC)) at the supply node*: Sudden voltage change at the supply node of the mixed-line associated with no-load energization or line disconnection should be less than 3% (according to the Dutch grid code) to reduce the disturbance to the customers. In addition, the sending-end final voltage should be less than 1.1pu too.

(2) *Voltage along the mixed-line*: Another constraint is the voltage change along the mixed-line following no-load energization or load rejection. The voltage must be less than 1.1pu to allow line reclosure and avoid damages to line connected devices. Protection equipment like surge arrestors must be checked in terms of temporary overvoltage (TOV) capability. The voltage has to be measured at all OHL-cable transition points (cable terminations) and receiving open-end. It is worth noting that the receiving open-end voltage is the highest voltage along the mixed-line during no-load energization when shunt compensation is not applied. However, by making use of shunt compensation, the highest voltage along the mixed-line could be at a point different than the receiving open-end. Therefore, in this study the attention is given to the voltage of all points along the mixed-line and not only the receiving open-end voltage.

(3) *Line-charging breaking current of line circuit-breakers*: When a large TOV occurs, line fast switching-off at the energizing-end is an option, under the condition that the capacitive current breaking capability of the circuit-breaker is sufficient. When shunt compensation is applied, it must be sure that the no-load current of the mixed-line is not larger than the type tested capacitive breaking current of the circuit-breaker. This is an important requirement in order to avoid circuit-breaker failures. For the sake of this study, 400 A is selected as the most strict limit as well as the preferred value according to [9], although higher limits can also be used. It is always highly recommended to consider the worst case situations for sizing of reactors.

(4) *Cable current*: In situations where the length of cable is longer than the critical length (i.e. the length at which the capacitive current reaches to the ampacity of the cable [4,5]), shunt compensation by means of installing shunt reactors at appropriate intermediate locations must ensure that the cable current stays below the thermal limit (ampacity) of the cable, which is 2 kA per cable in this study.

4 Simulation results

The mixed-line representation includes four line circuit-breakers. This theoretically leads to 24 possibilities in terms of switching sequence of circuit-breakers to connect both circuits to the grid. However, the switching sequence should comply with three practical and theoretical rules. Firstly, line connection switching should start from the terminal with higher short-circuit power (sending-end). In fact, the idea of best-end switching, i.e. operating line energization only from the terminal with higher short-circuit power, could lead to further savings on shunt reactors as well as a lower sudden voltage jump[1]. Secondly, shunt reactors have to be connected prior to the energization of their corresponding circuit. In advance connection of shunt reactors leads to better current and voltage profiles as well as significant improvement in the dynamic behaviour of the system [6]. Thirdly, energization of the second circuit occurs after complete connection of the first circuit. These three conditions lead to only two acceptable switching sequences for the double-circuit mixed-line connection, CB1-CB2-CB3-CB4 and CB3-CB4-CB1-CB2.

Tables 3 and 4 present the minimum required size of shunt compensation for different cable lengths. The results are categorized for two modes of operation, namely single-circuit operation and double-circuit operation. The reported sizes for double-circuit operation are the total size of both circuits (SR1+SR2 for arrangements A1S and A1R, SR1+SR2+SR3+SR4 for the arrangement A2). The values in parenthesises are compensation degrees calculated as follows:

$$K_{sh}\% = \frac{Q_{SR}}{N \times \omega\, C\, L\, {U_n}^2} \times 100 \qquad (1)$$

Where Q_{SR} is the total shunt compensation size in Mvar, C is the cable capacitance in F/km, L is the cable length in km, and U_n is the system nominal voltage, which in this study is 380 kV. The factor N denotes the number of cables. The value of N is 6 and 12 respectively for the single-circuit operation and the double-circuit operation.

The green cells show the best compensation for each specific case. Let's assume that the mixed-line includes 60 km cable and operates in the load-flow B. When the operation mode is single-circuit, according to Table 4 the arrangement A1R with the size of 1058 Mvar is the best option. However, when the connection is going to operate in double-circuit mode, then the arrangement A2 with the total size of 2380 Mvar is the best option according to Table 4. This means that in the case of double-circuit operation with 60 km cable, the first energized circuit should be compensated by the arrangement A2 and size of 1160 Mvar, and the second energized circuit should be compensated with the arrangement A2 and size of 1220 Mvar (2380 Mvar -1160 Mvar =1220 Mvar). Obviously, as an alternative option but not the best one, compensation can be with the arrangement A1R and size of 1058 Mvar for the first energized circuit and 1397 Mvar for the second energized circuit (2455 Mvar -1058 Mvar =1397 Mvar).

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[1] In the case of mixed-line disconnection, switching should start from the weak-end (receiving-end) in order to minimize sudden voltage changes.

Load-flow A						
Cable length (km)	Single-circuit operation Q_{sh} [Mvar] (K_{sh} [%])			Double-circuit operation Q_{sh} [Mvar] (K_{sh} [%])		
	A1S	A1R	A2	A1S	A1R	A2
12	51 (20.2%)	49 (19.5%)	50 (19.8%)	104 (20.6%)	100 (19.8%)	102 (20.2%)
20	218 (51.9%)	212 (50.5%)	214 (50.9%)	438 (52.1%)	426 (50.7%)	430 (51.2%)
40	633 (75.4%)	628 (74.8%)	620 (73.8%)	1269 (75.5%)	1260 (75%)	1245 (74.1%)
60	1051 (83.4%)	1043 (82.8%)	1030 (81.7%)	2106 (83.6%)	2091 (83%)	2062 (81.8%)
80 (fully cable)	1473 (87.7%)	1455 (86.6%)	1440 (85.7%)	2948 (87.7%)	2915 (86.7%)	2883 (85.8%)

Table 3: Minimum required shunt compensation size for single-circuit and double-circuit operation in the load-flow A.

Load-flow B						
Cable length (km)	Single-circuit operation Q_{sh} [Mvar] (K_{sh} [%])			Double-circuit operation Q_{sh} [Mvar] (K_{sh} [%])		
	A1S	A1R	A2	A1S	A1R	A2
12	314 (124.6%)	122 (48.4%)	176 (69.8%)	504 (100%)	290 (57.5%)	366 (72.6%)
20	617 (147%)	269 (64%)	356 (84.8%)	962 (114.5%)	611 (72.7%)	722 (86%)
40	1118 (133.1%)	641 (76.3%)	750 (89.3%)	1862 (110.8%)	1555 (92.6%)	1560 (92.9%)
60	1665 (132.1%)	1058 (84%)	1160 (92.1%)	2805 (111.3%)	2455 (97.4%)	2380 (94.4%)
80 (fully cable)	2120 (126.2%)	1470 (87.5%)	1600 (95.2%)	3655 (108.8%)	3300 (98.2%)	3226 (96%)

Table 4: Minimum required shunt compensation size for single-circuit and double-circuit operation in the load-flow B.

According to Tables 3 and 4, the required compensation degree increases by increasing the cable length for almost all of cases. There is also a meaningful difference between the results of the two load-flows (despite the high short-circuit power levels in both load-flows) with higher compensation degrees for the load-flow B. The main reason is the high voltage profile in the region of the project in this load-flow, which is already around 1.08 pu before mixed-line energization. Moreover, high voltage profile in combination with low efficiency of the arrangement A1S to control the voltage along the mixed-line leads to the need of overcompensation up to 150% for this arrangement. Therefore, compensation with the arrangement A1S due to the need of extreme overcompensation is never recommended for operation in the load-flow B. Besides, shunt reactor contingencies which lead to arrangements similar to the arrangement A1S should be treated carefully in this load-low.

The simulation results prove the considerable influence of load-flow on the compensation requirements (location and size). Therefore, if a transmission system is expected to experience several load-flow scenarios with considerable variations of the voltage levels and the active power flow, it will be crucial to allocate an appropriate global compensation in terms of shunt reactors location and size which will be capable of satisfying sizing constraints in all expected load-flow scenarios. As an example, let's assume that the Dutch transmission system in the year 2020 will operate in both load-flow A and load-flow B (and probably next to that many other load-flow situations). The global compensation of this project is therefore with the arrangement A2 because the location of reactors in arrangements A1S and A1R is either at the sending-end or receiving-end of the mixed-line whilst the sending and receiving ends are not the same in two load-flows. In this global compensation, for each cable length, the installed shunt reactor capacity has to be the largest one for the arrangement A2 in Tables 3 and 4, which are sizes for the load-flow B. By having enough installed capacity of shunt compensation, the appropriate size can be adjusted depending on the load-flow situation.

The most decisive sizing criterion:

Figure 2 shows the minimum required shunt compensation degree versus cable length calculated based on the first three sizing constraints (see Section 3) to illustrate the most decisive sizing criterion. The results are plotted for double-circuit operation and the compensation arrangement A2. The cable current is the less decisive sizing criterion in this study and it never exceeds the limit of 2 kA for cable lengths up to 103 km in the load-flow A and 92 km in the load-flow B. According to Fig. 3, the line-charging breaking current of line circuit-breaker is decisively the most determinant criterion for the load-flow A. This means that the size of compensation is dictated by this criterion and any further savings on shunt reactors can be achieved with the use of higher rated circuit-breakers. However, in contrast to the load-flow A, the voltage along the mixed-line is the most decisive sizing criterion for the load-flow B despite of decreasing difference between

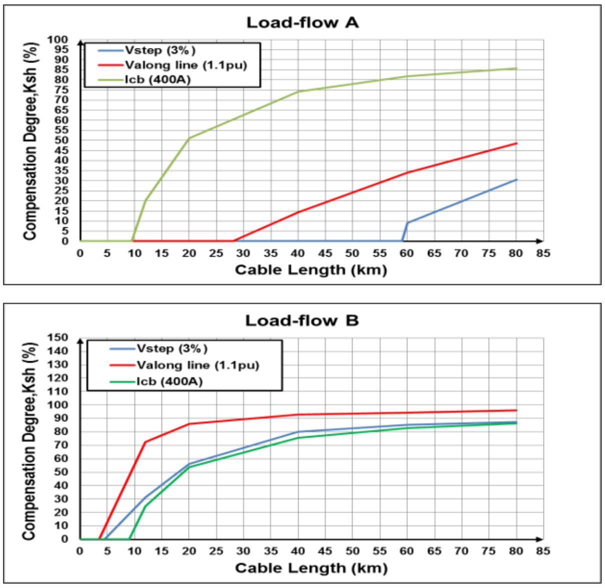

Figure 2: Minimum required shunt compensation degree vs. cable length calculated based on different sizing criteria for double-circuit operation and the arrangement A2.

constraint requirements with the increasing cable length. It should be noted that for the studied project and 80 km transmission length, the most decisive sizing criterion is not dependent on the mixed-line configuration, compensation arrangement, and operation mode (single-circuit or double-circuit) in both load-flows.

Figure 3 shows the results of sensitivity analysis on the circuit-breaker capacitive current breaking capability. The minimum required compensation degree is plotted versus cable length for two rated values, 400 A and 500 A, when operating in the load-flow A. The utilization of 500 A rated circuit-breaker, compared to 400 A, results in up to 20% saving in the compensation size, which can be a considerable value for long cable lengths.

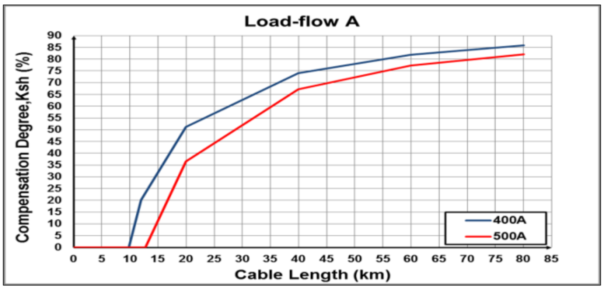

Figure 3: Minimum required shunt compensation degree vs. cable length for 400 A and 500 A circuit-breaker capacitive current braking ratings.

5 Distributed compensation

Different shunt compensation arrangements may have different impacts on the system operation like the steady-state operation, transient behaviour and dynamic behaviour. The investigation regarding the performance of line-end compensation was presented in the previous sections. The line-end compensation is easy to be realized in practice and well-known for TSOs. There are also some less-practiced compensation arrangements with distributed shunt reactors along the mixed-line. The realization of these arrangements in practice is certainly harder than line-end compensation due to the higher costs and the need to construct more facilities. However, the options of distributed compensation should not be ignored because in some situations they may improve the system operation and consequently increase the possibility of installing longer cable lengths.

In this section, the performance of distributed compensation in terms of required compensation degree is investigated by considering three types of distributed arrangement. These distributed arrangements have different number of shunt reactors and different compensation locations. These three distributed arrangements are compared with two lined-end compensation arrangements, A1R and A2. The studied distributed arrangements are: (1) *Arrangement A3:* In this arrangement, two reactors are allocated at the sending and receiving ends (same as the arrangement A2), plus an additional shunt reactor at the fourth OHL-cable transition point of each circuit. In the case of 80 km cable (fully cable), since there is no OHL-cable transition point, the additional reactor is located at the middle of cable. (2) *Arrangement A6:* This arrangement is called as Cable-End Compensation (CEC). In CEC, six reactors are located at six OHL-cable transition points of each circuit. In case of 80 km cable (fully cable), reactors are placed at six equally distributed intermediate points along the cable with distance of 11.43 km from each other leading to a symmetrical distribution. (3) *Arrangement A8:* This arrangement has eight reactors per circuit. It is similar to the arrangement A6, but with two more shunt reactors at the sending and the receiving end of each circuit right before circuit-breakers. It should be noted that for each arrangement, the reactor sizes in each circuit are equal, however the compensation size of two circuits are not necessarily equal (same as arrangements A1R and A2).

Figures 4 shows the minimum required shunt compensation degree versus cable length for different compensation arrangements for double-circuit operation in the load-flows A and B. The sizes are calculated according to the most decisive sizing criteria, which are circuit-breaker capacitive current breaking capability and voltage along the mixed-line respectively for the load-flow A and the load-flow B. For the load-flow A, distributed compensation in comparison with the traditional types of compensation at line-ends decreases the minimum required size of compensation for long cable lengths (longer than about 20 km) up to 1.6%. However, in the load-flow B, distributed compensation can decrease the minimum required compensation degree up to 8.8% only for cable lengths longer than 34 km; for cable lengths shorter than 34 km, distributed compensation increases the minimum required size while the arrangement A1R has the lowest compensation degree.

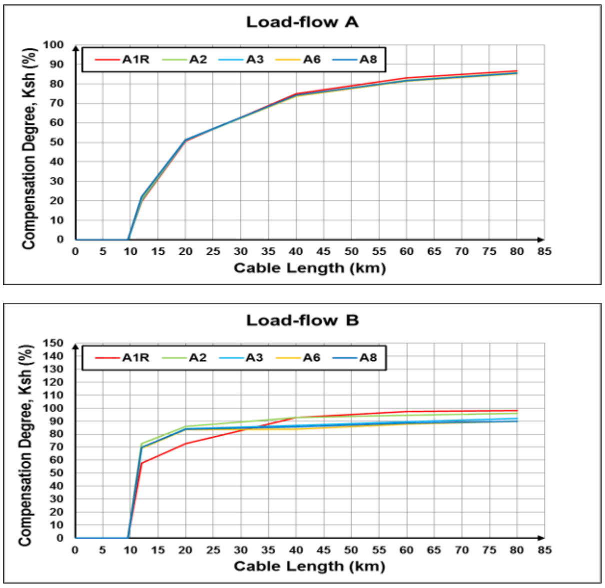

Figure 4: Minimum required shunt compensation degree vs. cable length for double-circuit operation with distributed and line-end compensation arrangements.

6 Influence of mixed-line configuration

The studied mixed-line configuration in the previous sections consists of three cable and four OHL sections. However, since the studied project is a future project and the number and location of cable sections are not determined yet, it will be possible to have a mixed-line with different number of cable sections at different locations. Therefore, it looks interesting to study the possible influence of mixed-line configuration, i.e. the number and the location of cable sections, on the shunt compensation design. For this purpose, five mixed-line configurations are compared together in terms of the minimum required size of compensation. These five configurations are: (1) OHL-Cable, (2) Cable-OHL, (3) OHL-Cable-OHL, (4) OHL-Cable-OHL-Cable-OHL, (5) OHL-Cable-OHL-Cable-OHL-Cable-OHL (default configuration). It is assumed that all these configurations are compensated by the shunt compensation arrangement A2 and sized according to the most decisive sizing criterion in each load-flow (see Section 4).

The minimum required compensation degree for five mixed-line configurations versus cable length is shown in Fig. 5. For the load-flow A, there is a negligible difference between different configurations in terms of compensation degree; however, the difference is considerable for the load-flow B where the difference can be up to 60% in some case. This means hundreds of Mvar difference in the total size of compensation. The configuration OHL-Cable has the worst results mainly because of higher overvoltages along the mixed-line comparing to the rest of configurations. In contrast, the configuration Cable-OHL requires the lowest compensation degree. The difference between configurations is however decreasing with increasing portion of cable, which was predictable due to the decreasing dissimilarities between configurations with increasing length of cable after 40 km.

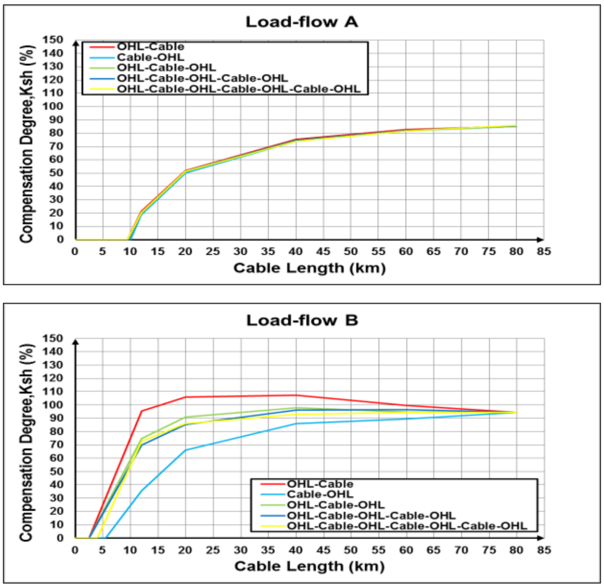

Figure 5: Minimum required shunt compensation degree vs. cable length for different mixed-line configurations during double-circuit operation.

7 Conclusions

The paper addressed the most important issues regarding the shunt compensation design of long EHV underground cables. According to the simulation results, it is crucial to investigate the influence of different load-flow scenarios on the allocation of shunt reactors. In addition to the short-circuit power levels, voltage levels prior to the mixed-line energization are significantly affecting the sizing results. For a robust network, like the Dutch transmission system, the most decisive sizing criterion is very likely to be either line-charging breaking current of line circuit-breaker or voltage along the mixed-line after no-load energization. The minimum required compensation degree increases by increasing the cable length in almost all of the cases. Moreover, applying compensation at both ends of the mixed-line is not always necessary. Shunt compensating only at the receiving side can lead to a smaller compensation degree in the case of a high voltage profile prior to the no-load energization. This can however only be applied if the power flow is never reversed and the receiving side is always the same. Distributed compensation in comparison with the traditional type of compensation at line-ends can decrease the minimum required size of compensation up to 8.8% for cable lengths longer than 20 km. Finally, the number and the location of cable sections can influence the minimum required compensation degree considerably, especially when the voltage profile in the operation load-flow is high.

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