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Publication date
2018

Document Version
Final published version

Published in
IEEE International Conference on Power Systems Transients (IPST)

Citation (APA)
Khalilnezhad, H., Popov, M., Bos, J. A., de Jong, JPW., & van der Sluis, L. (2018). Investigation of Statistical Distribution of Energization Overvoltages in 380 kV Hybrid OHL-Cable Systems. In *IEEE International Conference on Power Systems Transients (IPST)* (pp. 1-6)

Investigation of Statistical Distribution of Energization Overvoltages in 380 kV Hybrid OHL-Cable Systems

Hossein Khalilnezhad, Marjan Popov, Jorrit A. Bos, Jan P. W. de Jong, Lou van der Sluis

***Abstract*—Switching operations in power systems can produce significant overvoltages under specific circumstances. With the increasing application of underground cables in transmission systems, the statistical distribution of energization overvoltages is expected to change substantially due to the different electrical characteristics of cables and OHLs. Therefore, it is crucial to perform an insulation coordination study by analysis of the statistical distribution of energization overvoltages. This paper presents a statistical switching analysis on a hybrid OHL-Cable circuit to investigate how such hybrid circuits can affect the distribution of overvoltages. The literature has addressed the distribution of energization overvoltages only for OHLs or cables, but such an study is not available for hybrid systems consisting of OHLs and cables combined. The study is carried out for different cable lengths in the case study to identify how an increasing cable share in the circuit influences the overvoltages distribution due to no-load energization. Moreover, the impact of symmetrical and asymmetrical circuit structures is also addressed. The study is carried out on a distributed frequency-dependent parameter model of the Dutch 380 kV grid in PSCAD/EMTDC.**

***Keywords*: Cable, energization, insulation coordination, switching overvoltage, statistical switching.**

I. INTRODUCTION

TRANSMISSION System Operators are nowadays investigating the use of long stretches of (E)HV underground cables for grid reinforcements and expansions. This is due to strong political and social oppositions against building new overhead lines (OHL). The trend in installation of longer cables leads to increasing challenges from the system technical operation aspect, mainly the system transient behavior [1]. There are significant differences in electrical characteristics of a cable and an OHL. Shunt capacitance of a cable can be up to thirty times larger and series inductance can be up to five times smaller than those of an equivalent OHL [1]. The capacitive characteristic of cables increases the concerns regarding significant switching overvoltages occurrence, especially during cable no-load energization.

The transient overvoltages caused by energization of an unloaded cable are oscillatory with frequencies up to 20 kHz and duration of several milliseconds [2]. The amplitude, frequency, and duration of energization overvoltages are determined by several parameters, mainly the short-circuit strength of the busbar from which the cable is energized, cable length, shunt compensation size, and breaker closing time.

The circuit-breaker closing time depends on the angle (point-on-wave) of the power-frequency voltage waveform where the breaker receives the close command and also on the pole closing span of the circuit-breaker. The pole closing span refers to the time difference between the first and the last pole to close (due to the different unpredictable mechanical delays) and it has a statistical behavior according to a normal distribution. Thus, the circuit-breaker closing time has a random behavior and a statistical approach, by taking into account the statistical behavior of switching time, is the most practical way to analyze the distribution of switching overvoltages [3]-[6]. Analysis of the statistical distribution of overvoltages is crucial in insulation coordination studies. Such an analysis helps to determine the optimum insulation level, to minimize the cost, and to increase system reliability by means of finding the most severe overvoltages and planning proper countermeasures when overvoltages exceed withstand voltages of system components.

This paper performs a probabilistic analysis on the transient overvoltages occurring due to no-load energization of a hybrid OHL-Cable transmission line. The statistical distribution of energization overvoltages is addressed in literature for OHL and cable individually, but it is not available for hybrid systems consisting of OHL and cable combined. The study comprises time-domain simulations in PSCAD/EMTDC, where an accurate distributed frequency-dependent parameter model of the whole Dutch 380 kV grid is developed.

The influence of the cable length on overvoltages distribution is investigated by studying different cable scenarios in a case-study hybrid OHL-Cable project with 80 km transmission length. *Mixed-line* is the term sometimes used for hybrid OHL-Cable circuits composed of solidly series connected OHL and cable sections. The effect of the mixed-line structure on the overvoltages distribution is also evaluated by modeling symmetrical and asymmetrical structures. There are four key values obtained from a statistical analysis, namely: the maximum value, mean value, standard deviation, and 2% value. These indicators are used to assess the studied scenarios.

The simulation results show that the probability of occurrence of high overvoltages decreases by increasing the cable share in the hybrid OHL-Cable circuit. In other words,

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This research is financially supported by TenneT TSO B.V., Arnhem, the Netherlands, within the framework of 380 kV cable research program.

H. Khalilnezhad, M. Popov, and L. van der Sluis are with the department of Electrical Sustainable Energy, Delft University of Technology, Mekelweg 4, 2628 CD, Delft, the Netherlands (e-mail: H.Khalilnezhad@tudelft.nl, M.Popov@tudelft.nl, L.Vandersluis@tudelft.nl).

J. A. Bos and J. P. W. de Jong are with the Grid Development and Strategy Department, TenneT TSO B.V., Utrechtseweg 310, Arnhem, the Netherlands (e-mail: Jorrit.Bos@tennet.eu, Jan.P.de.Jong@tennet.eu).

Paper submitted to the International Conference on Power Systems Transients (IPST2017) in Seoul, Republic of Korea June 26-29, 2017.

the risk of experiencing energization overvoltages higher than 2 pu in a fully OHL circuit is higher than the case in which a part or the whole of the circuit is replaced by cables.

The paper is structured as follows: Section II elaborates on the system under study and the specifications of the PSCAD model; the cable scenarios and the shunt compensation sizing are treated in Section III; the simulation results are discussed in Section IV; and finally, Section V presents the conclusions.

II. SYSTEM CHARACTERISTICS AND MODELING

A sufficiently-detailed model of the system under study is necessary to have an accurate simulation of transient switching overvoltages. Time-domain simulations are performed on a thorough frequency-dependent model of the whole Dutch 380 kV transmission system in PSCAD/EMTDC. Fig. 1 shows the single-line diagram of the Dutch 380 kV grid and the case study project.

The grid model includes detailed representations of 380 kV substations, transmission lines, and three-phase transformers. The frequency-dependent model in the phase domain is applied to model OHLs and cables by the use of actual geometry data and electrical parameters. Tables I and II show the geometry data and electrical parameters used for modeling of the OHL and cable sections of the hybrid circuit under study [7]. Shunt reactors are represented by a multi-layer model as elaborated in [8]. The 380 kV capacitor banks are also represented in the grid model by equivalent RC circuits.

Lower voltage levels, i.e. 220 kV and below, are modeled by equivalent loads. The downstream network modeling has influence on the simulated overvoltages. If it is represented by pi-models or frequency-dependent models, the total damping in the system would be higher, which results in lower overvoltages. The difference can be up to a few tens of kilovolts compared to the case in which the lower voltage levels are not sufficiently modeled. However, in this paper, the lower voltage levels are modeled by the equivalent loads and therefore the reported overvoltages are representing the worst cases.

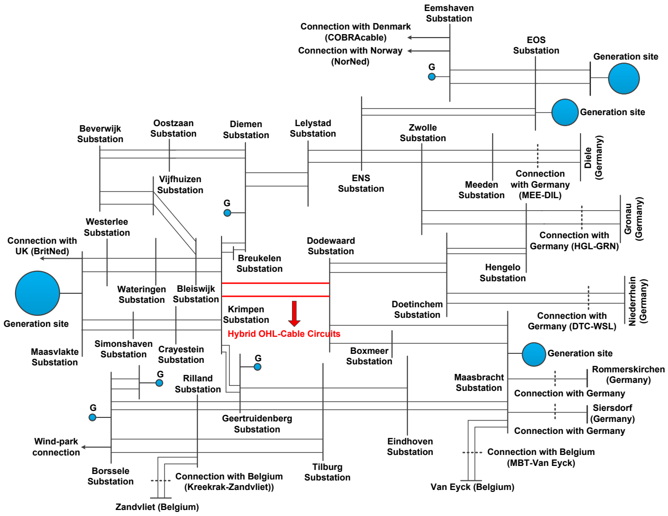

Fig. 1. Single-line diagram of the Dutch 380 kV transmission system in the reference year 2023.

Table I

GEOMETRY DATA AND ELECTRICAL PARAMETERS USED FOR MODELING OF THE OHL SECTIONS [7]

Conductor properties	
Conductor style	Solid
Outer radius	16.2 (mm)
DC resistance	0.0488 (Ω/km)
Relative permeability	1
Sag	11.1 (m)
Bundling	
Number of bundled conductors	4
Bundle configuration	Symmetrical
Bundle conductors spacing	0.5 (m)
Configuration	
Ideal transposition of circuits	Disabled
Shunt conductance	1×10^{-11} (S/m)

TABLE II

GEOMETRY DATA AND ELECTRICAL PARAMETERS USED FOR MODELING OF THE CABLE SECTIONS (CABLE TYPE: 2500 MM^2 XLPE) [7]

Cable layer	Core conductor	1st insulation	Screen conductor (sheath)	2nd insulation
Outer radius (mm)	30.65	63.1	63.7	71.5
Resistivity (Ωm)	1.98×10^{-8}	-	1.68×10^{-8}	-
Relative permeability	1	1.17	1	0.76
Relative permittivity	-	2.79	-	3.05

* Earth return approximation/ resistivity/ permeability: Saad/100 Ωm/1

Fig. 2 shows the assumed mixed-line structure for the hybrid transmission connection under study. The project has two identical parallel circuits and only one circuit is shown here. Inter-phase and inter-circuit mutual magnetic couplings are included in the model (i.e. 12 mutually coupled cables). The cable sections are composed of two parallel cables per phase to achieve the same transmission capacity as the OHL (the continuous current ratings (ampacity) for an OHL and a single-core cable are respectively 4 kA and 1.5 kA).

The three-phase shunt reactors (SRs) are connected by breakers to the circuit at the sending and receiving substations, right behind the line circuit-breakers. This is necessary in order to limit overvoltages when one side of the mixed-line is open (i.e. overvoltages at the receiving open-end) and to control the leading current through the line circuit-breaker. This could not be the case if the reactors are located at the substation busbars or at the tertiary sides of transformers.

The modeling of the cable screen cross-bondings with sufficient detail is of high importance to have an accurate simulation of switching overvoltages. In the developed PSCAD model, all cable cross-bondings are represented with full detail. It is assumed that cable sections are build-up of

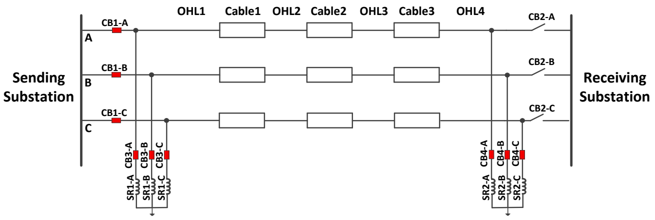

Fig. 2. Assumed structure for the mixed-line of the case study project.

minor sections with the length of 1 km each. Screen conductors are cross bonded at the end of each minor section, i.e. every 1 km, and they are grounded at the ends of each major section, which is made of three minor sections. This cross-bonding approach is already applied in commissioned cable projects in the south-west of the Dutch 380 kV grid. The values used for the cross-bonding inductances and termination resistances are according to those reported in [9].

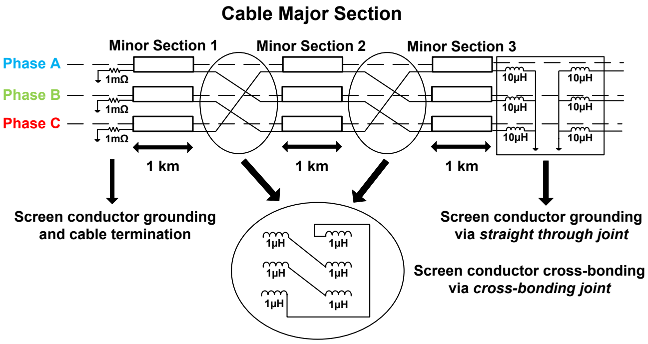

Fig. 3. Schematic of the cable screen conductors cross-bonding.

III. CABLE SCENARIOS AND SHUNT COMPENSATION

Six cable scenarios are defined to determine the cable share influence on the distribution of energization overvoltages of the hybrid OHL-Cable circuit. In each scenario, it is specified how many kilometers of the total transmission length is realized by the cables. The total transmission length of the hybrid circuit from the sending substation to the receiving substation is 80 km. In these six cable scenarios, the cable share varies from 0% (fully OHL) to 100% (fully cable) of the transmission length. The cable scenarios are presented in Table III.

Moreover, the optimum size of shunt compensation is determined for each cable scenario by an in-depth steady-state design presented in [10]. The compensation sizes are reported in Table III. SR1 and SR2 are referring to the three-phase shunt reactors at respectively sending and receiving ends and the reported value for each of them is the total three-phase size. K_{sh} is the shunt compensation degree and shows the percentage of the cable reactive power compensated by the shunt reactors.

Table IV presents the lengths of the cable/OHL sections in each cable scenario. The lengths of the cable sections as well as the OHL section lengths are unequal since an asymmetrical mixed-line structure is a more realistic assumption than a symmetrical structure in which the circuit is identical at the two sides of the mid-point. Usually, realization of a completely symmetrical mixed-line structure is practically difficult.

TABLE III
CABLE SCENARIOS AND SHUNT REACTOR SIZES FOR THE HYBRID OHL-CABLE CIRCUIT

Scenario	OHL length (km)	Cable length (km)	Compensation size (Mvar)		
			SR1	SR2	K_{Sh}
0% Cable (fully OHL)	80	0	N/A	N/A	N/A
15% Cable	68	12	88	88	69.8%
25% Cable	60	20	178	178	84.8%
50% Cable	40	40	375	375	89.3%
75% Cable	20	60	580	580	92.1%
100% Cable (fully Cable)	0	80	800	800	95.2%

TABLE IV
LENGTHS OF THE CABLE/OHL SECTIONS IN EACH CABLE SCENARIO

Scenario	Section length (km)						
	OHL 1	Cable 1	OHL 2	Cable 2	OHL 3	Cable 3	OHL 4
15% Cable	5	2	21	5	28	5	14
25% Cable	4	4	20	7	24	9	12
50% Cable	2	13	13	17	14	10	11
75% Cable	0	22	8	18	7	20	5

IV. SIMULATION RESULTS AND ANALYSIS

This section presents the obtained statistical distribution of overvoltages when energizing the unloaded hybrid OHL-Cable circuit. The overvoltages occurring during no-load energization are among the most severe switching transient overvoltages stressing power system components. Single-line-to-ground faults are also considered for evaluation of energization overvoltages in some certain types of study; however, in [5], authors have concluded that the maximum overvoltage is produced with open lines.

In this paper, from each switching operation, the highest peak value of the overvoltages of all three phases to ground at the line receiving open-end is reported. This approach is known as the case-peak method [2]. The voltage waveforms are similar to those reported in [7], in which the circuit was energized at a single switching instant. In this paper, the switching overvoltages are investigate when the switching instant is statistically varied. The overvoltages are expressed in per unit, where the base value (1 pu) is the peak value of the phase-to-ground nominal voltage $(\text{i.e. } 1\,\text{pu} = 310.27\,\text{kV})$. In all simulations, the shunt reactors are energized together with the circuit while the reactor sizes are considered as independent parameters with values presented in Table III.

A. Simulation Approach

To obtain an accurate switching overvoltage distribution and to ensure a realistic statistical representation, a sufficient number of circuit-breaker closing times over a cycle of the power-frequency voltage should be simulated [4],[5]. In general, breaker pole may close at any point of the power-frequency cycle. In this study, it is assumed that all three poles of the circuit-breakers are receiving the closing command at the same time and the pole closing span is zero (i.e. the Gaussian distribution of pole spread in not considered). Therefore, three breaker poles are connecting the phases to the voltage source at the same time. In order to deduce the required number of simulations to produce an accurate set of statistical data, two types of statistical variations for the circuit-breaker closing time are considered:

(1) Sequential distribution: The first statistical variation is a sequential distribution over a cycle of the power-frequency voltage from 0 to 360 degrees with steps of 10 degrees (≈ 0.55 ms in 50 Hz systems). This means the switching time is varied from a minimum to a maximum in equal increments

of time. 37 simulations are resulted by this statistical variation.

(2) Random distribution: This statistical variation is a uniform random distribution of the closing time over a cycle of the power-frequency voltage. 100 and 200 switchings are selected for this variation. In other words, this statistical variation considers 100 and 200 randomly selected circuit-breaker closing times along a cycle. It is clear that the evaluation of the statistical distribution of overvoltages is more accurate with a larger number of simulations, but the required process time for a larger number of runs is much longer too. In [11], 100 line energizations were performed to produce the overvoltage distribution, whilst in [3], the analysis was conducted by 200 statistical random line energization cases. Reference [4] simulated 100, 200, 300, 400, and 500 cases of transmission line energization to find out the required number of simulations to achieve the target accuracy. Authors have concluded that there is no statistically significant difference and the five switching numbers result in similar overvoltages. At least 100 simulations are recommended in literature to obtain a sufficiently accurate switching overvoltage distribution [5],[6].

Table V presents a summary of the maximum, mean, and standard deviation values of overvoltages at the receiving open-end obtained by the three statistical variations for the six cable scenarios. The results show negligible differences between overvoltages associated with the three statistical variations of the circuit-breaker closing time.

TABLE V
KEY VALUES OF THE OVERVOLTAGE DISTRIBUTIONS OBTAINED BY THE THREE STATISTICAL VARIATIONS

Scenario	Number of runs	Overvoltage (pu)		
		Max.	Mean	Standard deviation (σ)
0% Cable (fully OHL)	37 Sequential	2.309	1.756	0.369
	100 random	2.309	1.811	0.359
	200 random	2.309	1.801	0.368
15% Cable	37 Sequential	2.215	1.811	0.265
	100 random	2.216	1.776	0.271
	200 random	2.216	1.799	0.272
25% Cable	37 Sequential	2.030	1.678	0.216
	100 random	2.031	1.661	0.213
	200 random	2.031	1.677	0.215
50% Cable	37 Sequential	2.120	1.691	0.282
	100 random	2.121	1.664	0.282
	200 random	2.122	1.682	0.288
75% Cable	37 Sequential	1.964	1.589	0.248
	100 random	1.964	1.563	0.248
	200 random	1.964	1.587	0.245
100% Cable (fully Cable)	37 Sequential	1.763	1.515	0.153
	100 random	1.763	1.496	0.156
	200 random	1.763	1.510	0.154

Fig. 4 shows the probability distributions of overvoltages for the fully OHL scenario obtained by the three statistical variations. The y-axis (height of rectangle) is the frequency with which the overvoltages in the specified range (width of rectangle) have occurred. The probability distributions of random energization cases are usually compared to the normal (Gaussian) distribution [3]. However, the overvoltage distributions in Fig. 4 fail the Kolmogorov-Smirnov test at the 5% significance level. This means they are not following the normal distribution as it is evident in Fig. 4 too. This is because the Gaussian distribution of the pole spread is not simulated.

Fig. 5 shows the cumulative probabilities of overvoltages obtained by the three statistical variations. For a given voltage level, the vertical axis shows the cumulative probability of overvoltages exceeding that voltage level. The difference between the three cumulative probabilities is less than 10% and all the curves are following more or less a same trend.

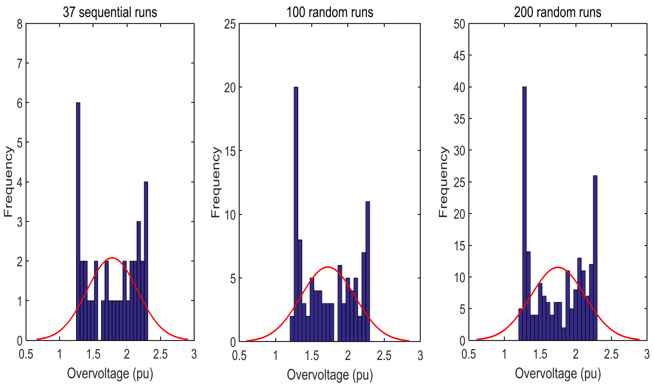

Fig. 4. Probability distributions of energization overvoltages of the fully OHL scenario obtained by the three statistical variations.

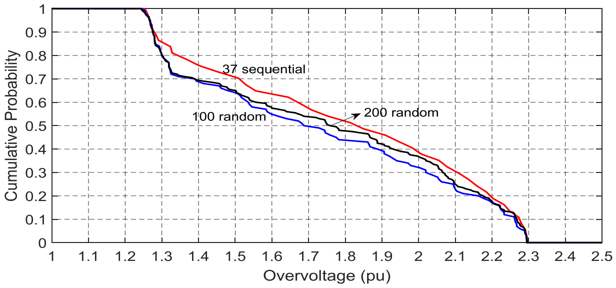

Fig. 5. Cumulative probability distributions of energization overvoltages of the fully OHL scenario obtained by the three statistical variations.

The computation time is considerably changing between the three variations. For 37 sequential runs, the simulation time is shorter than ¼ of the time required for 200 random runs. The required time for 200 random runs can last up to a few days depending on the simulated cable length. Such an extremely long simulation time is mainly caused by the small simulation time step, $\Delta T = 4.8\,\mu s$, and very detailed modeling of a big complex system.

As a conclusion, and irrespective of the required simulation time, 37 sequential runs produce accurate overvoltage values (maximum, mean, and standard deviation), but less accurate probability distributions since the number of samples are not enough. For the rest of this study, 200 random runs are used to obtain the overvoltage distributions.

B. *Effect of Cable Length*

It is crucial to determine how energization overvoltages are affected by the number of cable sections, the location of cable sections, the length of each cable section, and the total cable length in the hybrid circuit. Such a study is required to achieve an optimal design for the hybrid circuit structure with respect to the energization overvoltages and the insulation coordination.

To determine the cable length influence on the distribution of overvoltages, energization overvoltages of the six cable scenarios are compared in this section. The number and location of cable sections are the same for all cases.

Table VI presents the maximum, mean, standard deviation, and 2% values, as the four key values of statistical distributions. The 2% value is the overvoltage value that the probability of this value being exceeded is 2% [2],[3]. As it is seen, the fully OHL scenario produces the highest maximum overvoltage (2.309 pu), mean overvoltage (1.801 pu), standard deviation (0.368 pu), and 2% value (2.308 pu). All the scenarios including a share of the cable produce overvoltages lower than those of the fully OHL scenario.

Among the scenarios with the cable, all the key values decrease with the increasing share of the cable, except for the increase from 25% cable to 50% cable where all the values increase. Immediately after the breaker closure, the voltage wave propagates through the circuit producing reflection and refraction waveforms at the locations in where the conducting medium is changing (i.e. OHL-Cable transition points and cable joints). Highest overvoltages occur if the structure of the hybrid circuit provides the best condition for superimposition of the reflected and refracted waves. This can be the interpretation of higher overvoltage key values when the cable share is increased from 25% to 50%.

It can be deduced that the overvoltage peak is very likely lower when the cable share is increasing in the circuit. This conclusion coincides with the conclusion made in [3] that the overvoltages produced by energization of the cables are lower than those of OHLs. The smaller surge impedance of the cables, slower wave propagation velocity in the cables, existence of cross-bonding points for the cables, and shunt compensation of the cables can be the reasons that energization overvoltages of the cables are different than those of OHLs.

TABLE VI
KEY VALUES OF THE OVERVOLTAGE DISTRIBUTIONS OBTAINED BY 200 RANDOM CLOSING TIMES

Scenario	Overvoltage (pu)			
	Max.	Mean	Standard deviation	2% value
0% Cable (fully OHL)	2.309	1.801	0.368	2.308
15% Cable	2.216	1.799	0.272	2.215
25% Cable	2.031	1.677	0.215	2.031
50% Cable	2.122	1.682	0.288	2.121
75% Cable	1.964	1.587	0.245	1.963
100% Cable (fully Cable)	1.763	1.510	0.154	1.763

The probability distributions of energization overvoltages of the six cable scenarios with fitted normal distribution curves are shown in Fig. 6. As mentioned, the voltage distributions fail the Kolmogorov-Smirnov test at the 5% significance level. Table VII presents the skewness and kurtosis values of the overvoltage probability distributions.

The skewness is a measure describing how symmetrically the data are distributed around the mean value. The skewness of any symmetric distribution like the normal distribution is zero. A negative skewness indicates that the data are spread out more to the left side of the mean value than to the right (longer tail to the left side of the mean). A positive skewness indicates that the data are spread out more to the right side of the mean (longer tail to the right side).

According to Table VII, the overvoltage distributions of all the scenarios with the cable have positive skewnesses and are spread out more to the right side of the mean values. However, the fully OHL scenario is spread out more to the left side of the mean value with the negative skewness of -0.0284. The skewness of the fully OHL scenario is the smallest among all the scenarios indicating that the overvoltages produced by energization of the fully OHL circuit are more symmetrically distributed around the mean value than the cases in which the circuit includes a share of the cable.

The kurtosis is a measure of how outlier-prone (i.e. heavy-tailed or light-tailed) a distribution is. Higher kurtosis indicates that the distribution is more outlier-prone (i.e. has a heavier tail) and lower kurtosis indicates that the distribution is less outlier-prone (i.e. has a lighter tail). The kurtosis of the normal distribution is 3. According to Table VII, all distributions have lighter tails than the normal distribution due to a kurtosis lower than 3. The 50% cable scenario with the kurtosis of 1.4819 is the less outlier-prone scenario.

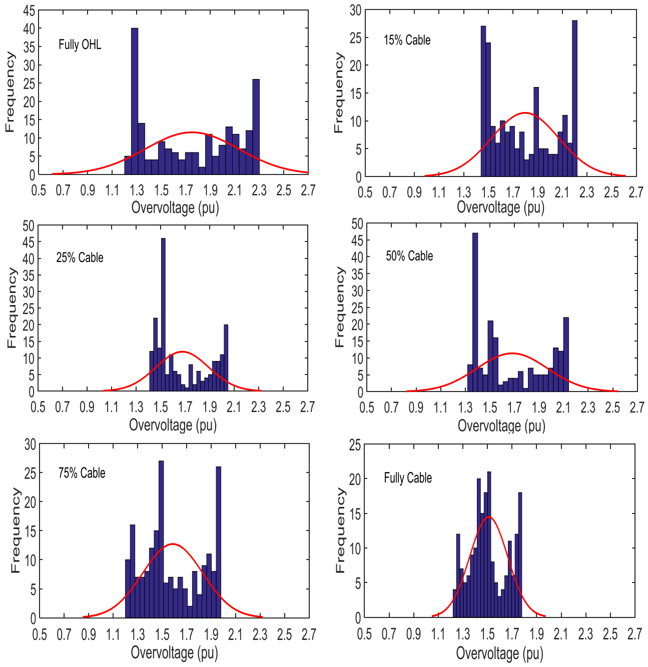

Fig. 6. Probability distributions of energization overvoltages of the six cable scenarios.

TABLE VII
SKEWNESS AND KURTOSIS OF THE PROBABILITY DISTRIBUTIONS OF ENERGIZATION OVERVOLTAGES OF THE SIX CABLE SCENARIOS

Scenario	Skewness	Kurtosis
0% Cable (fully OHL)	-0.0284	1.5173
15% Cable	0.2250	1.5436
25% Cable	0.5222	1.6363
50% Cable	0.3461	1.4819
75% Cable	0.2144	1.6957
100% Cable (fully Cable)	0.1574	2.0344

The cumulative probabilities of energization overvoltages of the six cable scenarios are plotted in Fig. 7. It is observed that the probability of high overvoltages occurrence is very likely lower when the cable share in the hybrid circuit is increased.

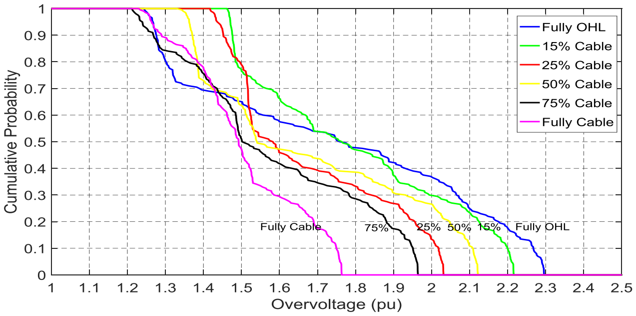

Fig. 7. Cumulative probability distributions of energization overvoltages of the six cable scenarios.

C. Effect of Mixed-Line Structure

The structure of the hybrid OHL-Cable circuit in the previous sections was asymmetrical. In practice, it may be in some situations possible to realize a hybrid circuit in a symmetrical way. A structure is symmetrical if the two sides of the circuit around the mid-point are mirroring each other. As an example, such a symmetrical structure is presented in Table VIII for the case in which the cable share is 50% (i.e. 40 km cable).

Table IX presents the key values of the overvoltage distributions of the asymmetrical and symmetrical hybrid circuits. The maximum, mean, and standard deviation values of the symmetrical structure are lower than those of the asymmetrical structure, except for the 25% cable scenario (although the difference is very small). Moreover, the maximum overvoltage always decreases by increasing the cable length when the structure is symmetrical. The cumulative probability distributions of energization overvoltages, as shown in Fig. 8, are also lower for the symmetrical structure.

TABLE VIII
LENGTHS OF THE CABLE/OHL SECTIONS IN THE ASYMMETRICAL AND SYMMETRICAL CIRCUITS (CABLE SHARE IS 50%)

Structure	Section length (km)						
	OHL 1	Cable 1	OHL 2	Cable 2	OHL 3	Cable 3	OHL 4
Asymmetrical	2	13	13	17	14	10	11
Symmetrical	10	13	10	14	10	13	10

TABLE IX
KEY VALUES OF THE OVERVOLTAGE DISTRIBUTIONS OF THE ASYMMETRICAL AND SYMMETRICAL CIRCUITS

Scenario	Overvoltage (pu)					
	Max.		Mean		Standard deviation	
	Asym.	Sym.	Asym.	Sym.	Asym.	Sym.
15% Cable	2.216	2.079	1.799	1.743	0.272	0.206
25% Cable	2.031	2.042	1.677	1.680	0.215	0.224
50% Cable	2.122	1.940	1.682	1.597	0.288	0.215
75% Cable	1.964	1.883	1.587	1.542	0.245	0.210

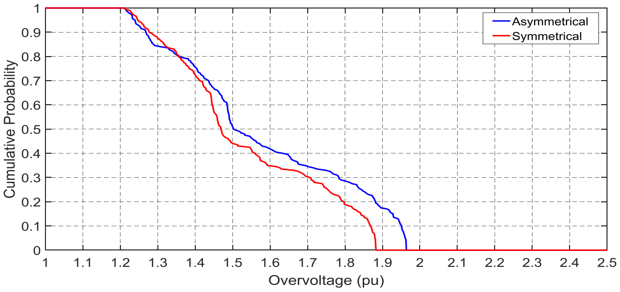

Fig. 8. Cumulative probability distributions of energization overvoltages of the asymmetrical and symmetrical hybrid circuits (75% cable scenario).

V. CONCLUSIONS

This paper studied the statistical distribution of energization overvoltages of a 380 kV hybrid OHL-Cable circuit derived from several statistical switching cases.

It has been discovered that the maximum and cumulative probability of overvoltages are lower when the circuit includes the cable. In other words, the risk of experiencing large energization overvoltages and stressing system components is higher in a fully OHL circuit than the case in which a part or the whole of the circuit is realized by the cables.

The cable length influence on the overvoltages distribution has been studied by simulating different cable shares in the hybrid circuit. With increasing the cable share, the maximum overvoltage and the probability of occurrence of high overvoltages are most likely decreasing. Moreover, for a given cable share, a symmetrical mixed-line structure has a maximum and a cumulative probability of overvoltage lower than those of an asymmetrical structure.

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