# Evaluation of the risk of failure due to switching overvoltages of a phase to phase insulation

A. Xemard, J. Michaud, A. Guerrier, I. Uglesic, G. Levacic, M. Mesic

***Abstract*-- The upgrade of an overhead line (i.e. the use of an overhead line at a voltage higher than the voltage for which the line was initially designed) requires generally a careful consideration of the switching overvoltages both phase to ground and phase to phase. This last type of overvoltages is posing a specific problem because, for systems belonging to the second range of the IEC, the phase to phase switching withstand voltage of a self restoring insulation depends on the repartition of the voltage between the electrodes.**

**When estimating the risk of failure of a specific air insulation due to switching overvoltages, an EMTP-like software is usually used to evaluate the constraints. Events causing switching over-voltages are chosen randomly and, for each of them, the over-voltages are calculated with EMTP. The risk of failure is deduced from the knowledge of the probability of these events (usually the switching time of a breaker), from the level of overvoltage obtained for each event, and from the withstand of the insulation.**

**This approach is quite simple to implement for phase to ground self restoring insulation but it is less straightforward for phase to phase insulation because for each event considered, the over-voltages calculated with EMTP correspond to a different repartition of overvoltages between both electrodes. Therefore overvoltages due to different events are not directly comparable.**

**In this paper we present an approach for the calculation of the risk of failure of a phase to phase self restoring insulation due to slow front overvoltages compatible with the use of an EMTP like software. The approach is illustrated by a practical example related to the upgrade of an overhead line from 245 kV to 362 kV.**

***Keywords*: phase to phase insulation, upgrade of overhead line, risk of failure, EMTP-RV.**

## I. Introduction

The upgrade of an overhead line requires generally to carefully consider the phase to phase slow front over-voltages caused by line energizing and re-energizing. These overvoltages are posing a specific problem because the withstand voltage of phase to phase air insulation depends on the repartition of the overvoltage components between the electrodes. This phenomenon might be sometimes neglected with standard lines but this cannot be the case for an upgraded line because its distances between phases are smaller than the ones of a standard line at the same voltage level. In this paper we are proposing a method to evaluate the representative overvoltage of a phase to phase air insulation at a tower when considering line energizing or re-energizing which are usually the most severe causes of overvoltages .

A method is proposed in the IEC 60071-2 (see annex D) to calculate this risk of failure, but it relies on a simplified approach which does not give the full benefit of EMTP calculations for the evaluation of the overvoltages.

The paper initially provides some insights in the approach proposed by the European standard EN 50341-1 for the calculation of tower clearances and then presents some information on the characteristics of the phase to phase air insulation having an impact on the determination of tower clearances. In the following part of the paper a method proposed to evaluate the representative phase to phase slow front overvoltage is detailed. The last part of the paper is devoted to an application of this method in the case of the upgrade of an overhead line from 245 kV to 362 kV.

## II. Origin and Characteristics of Slow Front Overvoltages

Slow Front Overvoltages [SFO] have a front time ranging from a few tens of milliseconds to a few thousands of milliseconds. The duration of their tail is of the same order [1]. SFO usually originate from the following phenomena :

- line energizing and reclosing;
- fault and fault clearing;
- load shedding;
- interruption of capacitive or inductive current;
- remote lightning stroke on an overhead line.

The most severe ones are due to line energizing and re-energizing except if some special means are used to reduce SFO. This is the case for instance of ultra high voltage systems for which the most severe SFO might be due to faults or faults clearing.

When dealing with air clearances calculations, the representative overvoltage is usually chosen, according to [1], as a frequency distribution of values that characterize the service conditions. This distribution is evaluated based on EMTP simulations.

## III. The Approach Proposed by EN 50341-1 for the Calculation of Line Clearances

EN 50341-1 is an European standard covering the general specifications of overhead lines exceeding 45 kV. In its appendix E, it is recommended to calculate the withstand voltage of phase to phase clearances against SFO using the following approach : the probability distribution is defined by

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$V_{2\%sf}$ corresponding to the crest value of the overvoltage having a probability of 2% to be exceeded. Then the representative overvoltage $V_{rp}$ is chosen such as :

$$V_{rp} = K_{cs} \times V_{2\%sf} \quad (1)$$

where $K_{cs}$ is the statistical coordination factor. A value of 1.05 is proposed in [4].

The withstand voltage of the insulation is chosen such as :

$$\boldsymbol{U_0 \geq V_{rp}} \quad (2)$$

where $U_0$ is the withstand voltage for which the insulation has a probability of withstand of 90% (namely the statistical withstand voltage [1]).

## IV. Generalities about The estimation of the stress due to SFO

This paragraph deals mainly with the overvoltages due to line energizing and reenergizing. Each of these events is at the origin, on a circuit, of phase to ground overvoltages on the three phases and also three overvoltages between phases. As indicated above, the Cumulative Distribution Function (cdf) of the amplitude of overvoltages is usually estimated with an EMTP-like package, based on the calculation of the crest value of the overvoltages for a huge number of combinations of breakers closing times chosen randomly by using a Monte-Carlo method.

Regarding the choice of the number of overvoltages to consider per event (i.e. per combination of breaker closing time) two methods are proposed in [5] :

- phase-peak ; for each switching, the higher value of overvoltage is considered for each phase and between each phase. In other words, each switching contributes in the cumulative distribution function of the phase to ground and phase to phase insulation with 3 values. These cumulative distributions are considered identical for each insulation ;
- case-peak ; for each switching event, the highest value of the phase to ground and phase to phase overvoltage is taken into account respectively in the phase to ground and phase to phase cdfs. This method is equivalent to considering that one component between the 3 components of stress contributes more significantly to the risk of failure. This method, generally considered as more precise than the previous one, has been used in this study.

The withstand voltage of phase to phase insulation depends on the repartition of the overvoltage components between phases. The negative component of the overvoltage has generally less influence on the insulation than the positive component [3], as the positive withstand voltage of the insulation is lower than the negative one. For this reason, [5] has proposed two possible instants for the selection of the value of the overvoltage corresponding to a switching event :

- the instant of phase to phase overvoltage peak ; this approach can be applied when dealing with air insulations for which the withstand voltage does not depend significantly on the repartition of the components between both electrodes. This is the case for instance of insulations belonging to the range 1 of IEC ;
- the instant of the phase to earth overvoltage peak ; this instant is usually more critical for air insulation of range 2 of the IEC. This instant has been selected in this study.

## V. The withstand voltage of phase to phase air insulation

### A. Generalities

When estimating the risk of failure caused by SFO of a phase to phase air insulation, as indicated previously, it is required to take into account the fact that the effect on the insulation of the stress depends on the repartition of the components between the electrodes and does not depend only on the overvoltage applied between both electrodes.

If $V^+$ is the positive voltage applied to one electrode and $V^-$ is the absolute value of the negative voltage applied to the other electrode, the phase to phase voltage $V_p$ is expressed by :

$$V_p = V^+ + V^- \quad (3)$$

The withstand voltage $U_{50}^+$ (50% discharge voltage of the insulation [1]) for the positive component is approximated as an affine function of the negative component [3], as illustrated in Fig. 1. below.

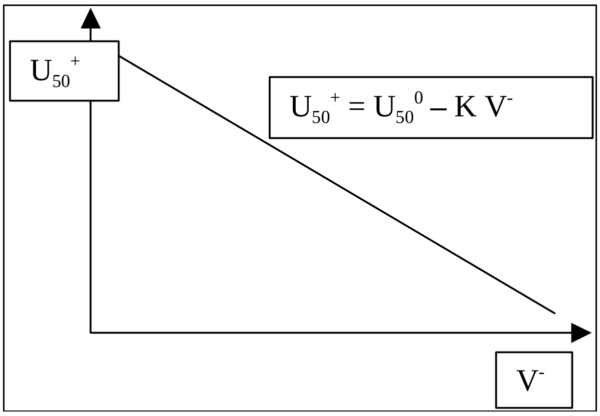


Fig. 1. Withstand voltage $U_{50}^+$ of the electrode stressed by the positive component, versus the negative component $V^-$ applied to the second electrode. K is a constant defined experimentally [2][3].

In accordance to [5], the ratio α is usually used to express the proportion of negative component within the total over-voltage between electrodes. It is given by :

$$\alpha = \frac{V^-}{V^+ + V^-} \quad (4)$$

Usually the phase to phase withstand voltage is measured only for two values of $\alpha$ corresponding to 0.5 and 0.33.

### B. The calculation of the phase to phase withstand voltage

The document [2] proposes formula (5) below to evaluate the withstand voltage between two phase conductors along a span, taking into account the height of the conductors above ground.

$$\left(U^{+}+U^{-}\right)_{50}=\frac{640d^{0.6}(1-0.25\frac{d}{H})}{1-\alpha(0.14+0.54\frac{d}{H})} \quad (5)$$

$(U^{+}+U^{-})_{50}$ (kV), $d$ (m) and $H$ (m) are respectively the value of the 50 % withstand voltage of the air insulation (for a given value of $\alpha$, $d$ and $H$), the distance between both conductors and the height from the ground of the conductors.

This formula is considered valid for $d$, $d / H$ and $V^{-}/V^{+}$ belonging respectively to the following intervals [5m,10m], [0.2,1] and [0,1]. The Fig. 2. below illustrates the influence of $\alpha$ on $(U^{+}+U^{-})_{50}$.with the configuration of phase conductors considered in the second part of the paper. $(U^{+}+U^{-})_{50}$ increases of 17% when α changes from 0.2 to 0.9.

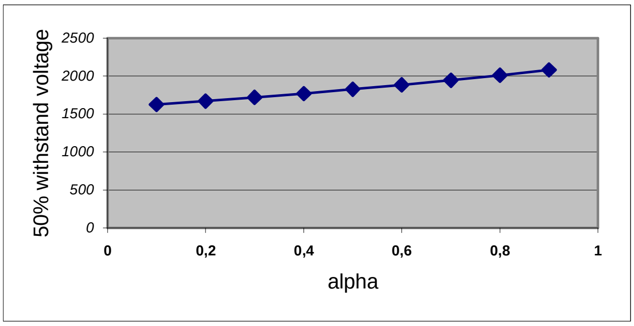


Fig. 2. : Conductor to conductor $(U^{+}+U^{-})_{50\%}$ versus α calculated with the formula 5 above, for d = 5 m and h = 21.5 m.

The statistical withstand voltage $U_O$ of the insulation (corresponding to a probability of discharge of 10%) can be estimated according to [4] by :

$$(U^{+}+U^{-})_{0}=(U^{+}+U^{-})_{50}-1.3Z \quad (6)$$

where $Z$ is the standard deviation of SFO, expressed by [4] :

$$Z=0.06(U^{+}+U^{-})_{50} \quad (7)$$

## VI. The Determination of the Representative Phase to Phase SFO Due to Line Energization and Re-Energization

### A. Introduction

It is indicated in section III. that the method proposed by the standard EN 50341-1 to estimate the representative overvoltage stressing the insulation is based on the knowledge of $V_{2\%SF}$ representing the stress experienced by the insulation. Both $U_{0\%}$ and $V_{2\%SF}$ depend on $\alpha$ for phase to phase insulation.

If the case of the phase to ground insulation of an overhead line, $V_{2\%sf}$ is determined by using a Monte-Carlo method and by considering the SFO due to line energizing and reclosing. The cdf is approximated using an EMTP-like software and by simulating the electromagnetic transient appearing for different configurations of closing instants of the breakers at the entrance of the line.

In mathematical terms a series of samples of closing instants $(x_1, x_2,...,x_N)$ of the breakers is chosen randomly. N is high enough to cover all possible cases of closing instants.

For each sample $x_i$ a simulation is performed and the stress $v_i$ at a given tower is determined according to the method "case-peak" (see section IV. ). As the closing instants of the breakers are random variables, the maximum value of the SFO applied to the phase to ground insulations at the tower is also a random variable V. The probability p to have a stress U higher than a given value $U_0$ can be calculated approximately by :

$$p(V>U_{0})=\frac{card\left(x_{i}/x_{i}\geq U_{O}\right)}{N} \quad (8)$$

Therefore the value of $U_{2\%SF}$ is such as :

$$p(V>U_{2\%sf})=0.02 \quad (9)$$

This method cannot be applied directly because the stress $V_{phasephasei}$ due to a closing instant $x_i$ depends on the repartition of the components of the overvoltages among the electrodes and not only on the value $V_{phasephasei}$. In the next paragraph we are proposing some improvements of the method presented in this paragraph in order to adapt it for phase to phase self-restoring insulation.

### B. Method to calculate the cdf of phase to phase SFO

When the cdf of the phase to phase SFO applied to a conductor to conductor is estimated using a Monte-Carlo method we suggest for each closing time configuration of the breakers $x_i$ to transform the stress $(v_i^{+}+v_i^{-})$ into an equivalent stress corresponding to a standard value of $\alpha$, $\alpha_{st}$.

The series $(v_1^{+}+v_1^{-},v_2^{+}+v_2^{-},$ ----$,v_N^{+}+v_N^{-})$ is transformed into a series $((v_1^{+}+v_1^{-})_{std},(v_2^{+}+v_2^{-})_{std},$ ----$,(v_N^{+}+v_N^{-})_{std})$ in which all elements get standardized and can be compared to the same value of withstand voltage.

The following approach is applied to perform the transformation.

We consider a 2-dimension space with a cartesian coordinate $(V,\alpha)$ system where the series $(v_1^{+}+v_1^{-},v_2^{+}+v_2^{-},$ ----$,v_N^{+}+v_N^{-})$ and $(\alpha_1,\alpha_2,...,\alpha_N)$ are represented.

with :

$$\alpha_{i}=\frac{v_{i}^{-}}{v_{i}^{+}+v_{i}^{-}} \quad (10)$$

The variation of the withstand voltage $(U^{+}+U^{-})_{50}$ of the conductor insulation is approximately linear versus α, according to (5). This property is illustrated in Fig. 2..

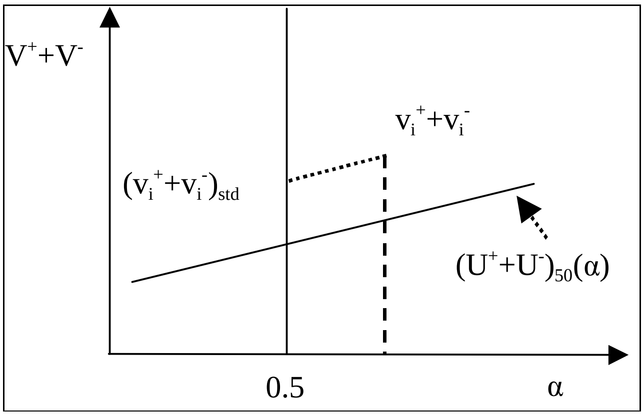

Fig. 3. : Projection of the sample $(v_i^+ + v_i^-)$ on the straight line $\alpha=0.5$ in order to obtain $(v_i^+ + v_i^-)$.

Therefore $(v_i^+ + v_i^-)_{std}$ is obtained by projecting $(v_i^+ + v_i^-)$ on the straight line α = 0.5, as shown in Fig. 3. below.

The direction of the projection is parallel to the straight line $(U^+ + U^-)_{50}(\alpha)$.

Based on this approach it is possible to evaluate the $V_{2\%}$ of the phase to phase SFO cdf and then to apply the approach presented in section III. to evaluate the $U_o$ required for the insulation.

It should be noted that this approach is a simplification in the sense that it does not consider simultaneously on a circuit of a tower the 3 phase to phase and the 3 phase to ground insulations (annex D of [5] proposes such a method but it includes various hypothesis whose validity is difficult to assess). One can logically expect that its application leads to some conservative results, compared to a method considering all the insulations at the same time.

## VII. Practical Study of the Phase to Phase SFO when Upgrading a 245 kV Transmission Line

### A. Introduction

As indicated previously, when upgrading an overhead line of range 2 of the IEC, the phase to phase air distances have to be carefully checked because it may be necessary to use some special technique in order to reduce the amplitude of the SFO.

This paragraph describes an application of the method presented in §VI. B. . The elements presented here, related to the study of the phase to phase SFO due to line energization and re-energization, are part of a more general study devoted to the upgrade of 245 kV overhead lines to a higher voltage.

### B. Configuration

A double circuit 245 kV line is upgraded to 362 kV. The characteristics of the line are the followings: the span length is 400 m and the line is 90 km long. The position of the conductors is given in the appendixes (section IX. A. ). The phase conductors are constituted of bundles of 2 sub-conductors.

The substation at the entrance of the line is represented by a Thevenin Equivalent. Several configurations are considered as detailed in the table below.

TABLE 1
DIRECT AND HOMOPOLAR INDUCTANCE OF THE THEVENIN EQUIVALENT OF THE SUBSTATION

| Configuration | homopolar inductance (mH) | direct mode inductance (mH) |
|---|---|---|
| Configuration 1 low short circuit current | 110 | 110 |
| Configuration 2 – medium short-circuit current | 53.6 | 36.7 |
| Configuration 3 – high short-circuit current | 13.8 | 13.8 |

The fig. 4. below gives the notations used to specify the position of the phase conductors on a tower.

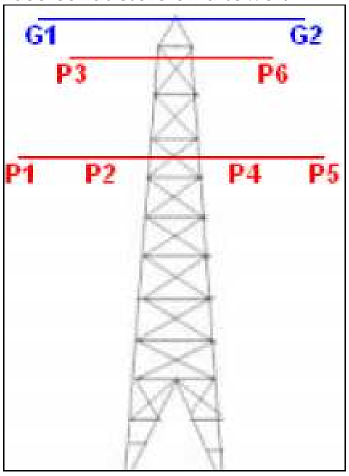

Fig. 4. : Position of the phase conductors on the tower.

The surge arresters used in some configurations of the study have a rated voltage of 342 kV and a residual voltage of 775 kV for a lightning current of 10 kA.

In the calculations 1 p.u. = 296 kV.

### C. Approach used for the study

The statistical function of the software EMTP-RV is used. It allows to determine automatically the cdf of the SFO, due to breaker switching, based on a Monte-Carlo approach by selecting randomly the closing time of breakers. The modeling used to represent the system follows the recommendation given by [6].

The line is represented by a succession of 10 km long line segments modeled with the FD-line model in order to measure the phase to phase SFO stressing the insulation at the end of each segment. The substation is represented by a Thevenin equivalent whose characteristics are given in Table 1. The breakers are modeled as ideal switches. The closing time of the main breaker is supposed to be uniformly distributed and the closing time of the other breakers is supposed to be around it with a Gaussian law of probability with a medium value equal to zero and, with a standard deviation of 3 ms.

A module was developed in EMTP-RV, based on “MACS” (control part of EMTP-RV), to evaluate for each simulation and each phase to phase insulation $(V_i^+ + V_i^-)_{std}$ from $(V_i^+ + V_i^-)$ (see section VI. B. ). This module is built with classical control functions like comparators, sums, select functions, etc. In the study three configurations were considered for the substation regarding its short-circuit current (see Table 1) .

### *D. Study of the re-energization of the line without mean to reduce SFO*

We suppose in this sub-paragraph that the line is not equipped with arresters at its terminals and we calculate the phase to phase SFO when re-energizing the line. The crest values given in the tables were measured at the open end of the line.

TABLE 2
PHASE TO PHASE OVERVOLTAGES WITHOUT MEANS TO REDUCE OVERVOLTAGES CONFIGURATION 1

| Type of energizing | 2% value of the cpf – kV (p.u.) |
|---|---|
| Re-energizing of one circuit, the other one disconnected. Trapped charges are 1p.u., 1p.u., -1p.u., 1.p.u., 1p.u., -1p.u. | P1-P2 : 1463 kV (4.9 p.u.) |
| | P1-P3 : 1600 kV (5.4 p.u.) |
| | P3-P2 : 1594 kV (5.4 p.u.) |
| Re-energizing of one circuit, the other one being connected. The trapped charges are 1p.u., 1p.u., -1p.u. | P1-P2 : 1347 kV (4.6 p.u.) |
| | P1-P3 : 1500 kV (5.1 p.u.) |
| | P2-P3 : 1410 kV (4.8 p.u.) |
| Re-energizing of one circuit, the other one being connected. The trapped charges are 1.6 p.u., 1.6 p.u., 0. Case of a fault leading to temporary overvoltages. | P1-P2 : 1524 kV (5.1 p.u.) |
| | P1-P3 : 1743 kV (5.9 p.u.) |
| | P3-P2 : 1768 kV (6.0 p.u.) |

TABLE 3
PHASE TO PHASE OVERVOLTAGES WITHOUT MEANS TO REDUCE OVERVOLTAGES CONFIGURATION 2

| Type of energizing | 2% value of the cpf – kV (p.u.) |
|---|---|
| Re-energizing of one circuit, the other one disconnected. Trapped charges are 1p.u., 1p.u., -1p.u., 1.p.u., 1p.u., -1p.u.) | P1-P2 : 1575 kV (5.3 p.u.) |
| | P1-P3 : 1644 kV (5.6 p.u.) |
| | P3-P2 : 1733 kV (5.9 p.u.) |
| Re-energizing of one circuit, the other one connected. The trapped charges are 1p.u., 1p.u., -1p.u. | P1-P2 : 1200 kV (4.5 p.u.) |
| | P1-P3 : 1240 kV (5.2 p.u.) |
| | P2-P3 : 1275 kV (5.3 p.u.) |
| Re-energizing of one circuit, the other one being connected. The trapped charges are 1.6 p.u., 1.6 p.u., 0. Case of a fault leading to temporary overvoltages. | P1-P2 : 1425 kV (5.5 p.u.) |
| | P1-P3 : 1510 kV (6.6 p.u.) |
| | P3-P2 : 1545 kV (6.5 p.u.) |

TABLE 4
PHASE TO PHASE OVERVOLTAGES WITHOUT MEANS TO REDUCE OVERVOLTAGES CONFIGURATION 3

| Type of energizing | 2% value of the cpf – kV (p.u.) |
|---|---|
| Re-energizing of one circuit, the other one disconnected. Trapped charges are 1p.u., 1p.u., -1p.u., 1.p.u., 1p.u., -1p.u.) | P1-P2 : 1425 kV (4.8 p.u.) |
| | P1-P3 : 1600 kV (5.4 p.u.) |
| | P3-P2 : 1625 kV (5.5 p.u.) |
| Re-energizing of one circuit, the other one connected. The trapped charges are 1p.u., 1p.u., -1p.u. | P1-P2 : 1365 kV (4.6 p.u.) |
| | P1-P3 : 1540 kV (5.2 p.u.) |
| | P2-P3 : 1510 kV (5.3 p.u.) |
| Re-energizing of one circuit, the other one being connected. The trapped charges are 1.6 p.u., 1.6 p.u., 0. Case of a fault leading to temporary overvoltages. | P1-P2 : 1595 kV (5.4 p.u.) |
| | P1-P3 : 1770 kV (6.4 p.u.) |
| | P3-P2 : 1700 kV (6.4 p.u.) |

### *E. Study of the re-energizing of the line equipped with arresters at both ends*

We suppose that the line is equipped with arresters at both ends. Because of that, the crest values presented in the tables below have been found on towers located in the vicinity of the middle of the line.

TABLE 5
PHASE TO PHASE OVERVOLTAGES WITH ARRESTERS AT BOTH ENDS CONFIGURATION 1

| Type of energizing | 2% value of the cpf – kV (p.u.) |
|---|---|
| Re-energizing of one circuit, the other one disconnected. Trapped charges are 1p.u., 1p.u., -1p.u., 1.p.u., 1p.u., -1p.u.) | P1-P2 : 1120 kV (3.8 p.u.) |
| | P1-P3 : 1250 kV (4.2 p.u.) |
| | P3-P2 : 1235 kV (4.2 p.u.) |
| Re-energizing of one circuit, the other one connected. The trapped charges are 1p.u., 1p.u., -1p.u. | P1-P2 : 1110 kV (3.8 p.u.) |
| | P1-P3 : 1130 kV (3.8 p.u.) |
| | P2-P3 : 1165 kV (3.9 p.u.) |
| Re-energizing of one circuit, the other one being connected. The trapped charges are 1.6 p.u., 1.6 p.u., 0. Case of a fault leading to temporary overvoltages. | P1-P2 : 1155 kV (3.9 p.u.) |
| | P1-P3 : 1205 kV (4.1 p.u.) |
| | P3-P2 : 1205 kV (4.1 p.u.) |

TABLE 6
PHASE TO PHASE OVERVOLTAGES WITH ARRESTERS AT BOTH ENDS CONFIGURATION 3

| Type of energizing | 2% value of the cpf – kV (p.u.) |
|---|---|
| Re-energizing of one circuit, the other one disconnected. Trapped charges are 1p.u., 1p.u., -1p.u., 1.p.u., 1p.u., -1p.u.) | P1-P2 : 1140 kV (3.8 p.u.) |
| | P1-P3 : 1172 kV (4 p.u.) |
| | P3-P2 : 1100 kV (3.7 p.u.) |
| Re-energizing of one circuit, the other one connected. The trapped charges are 1p.u., 1p.u., -1p.u. | P1-P2 : 1120 kV (3.8 p.u.) |
| | P1-P3 : 1120 kV (3.8 p.u.) |
| | P2-P3 : 1155 kV (4 p.u.) |
| Re-nergizing of one circuit, the other one being connected. The trapped charges are 1.6 p.u., 1.6 p.u., 0. Case of a fault leading to temporary overvoltages. | P1-P2 : 1145 kV (3.9 p.u.) |
| | P1-P3 : 1205 kV (4.1 p.u.) |
| | P3-P2 : 1085 kV (3.7 p.u.) |

### F. *Analysis of the results*

Using (5)(6) and (7), $U_0$ is calculated for each insulation and then the maximum $V_{2\%sf}$ that each insulation can withstand, according to the approach presented in section III. , with a statistical coordination factor $K_{cs} = 1.05$. The results are presented in Table 7 below. Their comparison with the values of overvoltages given in section VII. D. and VII. E. indicates that the air distances are sufficient to withstand the phase to phase overvoltages for an upgrade of the line from 245 kV to 362 kV. However care should be taken that the reduction of insulation due to altitude and to the insulations in parallel are not taken into account (see [5]).

TABLE 7
$U_0$ AND MAXIMUM VALUE OF THE $V_{2\%SF}$ ACCEPTABLE FOR THE INSULATION

| Insulation | $U_0$ (kV) | $V_{2\%sf}$ max kV (p.u.) |
|---|---|---|
| P1P2 | 2050 | 1950 (6.6 p.u.) |
| P2P3 | 2750 | 2600 (8.8 p.u.) |
| P1P3 | 2900 | 2750 (9.3 p.u.) |

Regarding the impact of the major parameters on the amplitude of the overvoltages the following conclusions can be made.

The influence of the short circuit current of the power source does not appear to be major. A slight decrease of the $(V^{+}+V_{-})_{std2\%}$ versus the short circuit of the source can however be detected in most of the cases. Trapped charges are an important factor. We can see that the most severe overvoltages appear in the case with strong trapped charges on two phase conductors (1.6 p.u.) and no trapped charges on the other phase conductors.

The presence of arresters at the ends of the line leads to a significant decrease of the overvoltages. This decrease is related to the characteristics of the arresters and especially their level of protection. In this case the level of protection corresponds to 775 kV / 296 kV = 2.6 p.u.

## VIII. CONCLUSIONS

This paper is mainly devoted to the problem of the dimensioning of the phase to phase insulation of overhead lines against SFO caused by switching operations. This dimensioning is a specific concern for systems belonging to the range 2 of the IEC

In this paper we propose a method to take into account the influence of the overvoltage component on each phase, when studying the phase to phase overvoltages on an overhead line due to line energizing and re-energizing, with an EMTP-like software. This method allows to determine easily the representative overvoltage and streamlines the application of the standard EN 50341 for the determination of the required withstand voltage of the phase to phase air insulations [1].

This method is applied to study some aspects of the upgrade of an overhead line from 225 kV to 362 kV. The influence of some parameters like the short-circuit current of the source, the configuration of trapped charges and the presence or not of arresters at both ends of the line is analyzed.

We can conclude that the presence of arresters leads to a significant decrease of the phase to phase overvoltages, even in the most severe configurations of trapped charges.

## IX. APPENDIX

### A. *Configuration of the line*

The table below gives the position of phase conductors and sky wires.

TABLE 8
POSITION OF THE CONDUCTORS ALONG THE LINE

| Conductor | Height at tower (m) | Height at mid-span | Horizontal distance from the middle of the tower |
|---|---|---|---|
| Circuit 1, phase 1 | 21.5 | 8.5 | -9.5 |
| Circuit 1, phase 2 | 21.5 | 8.5 | -4.5 |
| Circuit 1, phase 3 | 29 | 16 | -6.3 |
| Circuit 2, phase 1 | 21.5 | 8.5 | 4.5 |
| Circuit 2, phase 2 | 21.5 | 8.5 | 9.5 |
| Circuit 2, phase 3 | 29 | 16 | 6.3 |
| Sky wire 1 | 34.2 | 21.2 | -8.4 |
| Sky wire 2 | 34.2 | 21.2 | 8.4 |

## X. BIBLIOGRAPHY


[1] IEC 60071-1, “Insulation co-ordination Part 1: Definitions, Principles and rules”, 1992.

[2] CIGRE, “Guidelines for the evaluation of the dielectric strength of external insulation”, CIGRE technical Brochure N°72.

[3] A.R. Hileman, “Insulation Coordination for Power Systems”, Marcel Dekker, 1999.

[4] European Standard, “EN 50341 – Overhead electrical lines exceeding AC 45 kV – Part 1 : General requirements – Common specifications – February 2002.

[5] IEC 60071-2, “IEC 60071-2 – Insulation co-ordination – Part 2: Application guide”.

[6] IEC 60071-4, “Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modelling of electrical networks” , 2003.

[7] L.W. Marks, “Line discharge by potential transformers”, IEEE Transactions on PAS, Vol PAS-88, N°4, April 1969

[8] C. Csida, L.I. Kromer, “An improved method for determining line discharge through potential transformers”, IEEE Transactions on PAS, VOL PAS-97, N°1, January/February 1978.

[9] www.emtp.com - EMTP-RV WEB site.