INDUCED DISTURBANCE VOLTAGES IN ISOLATED CONDUCTORS SITUATED IN CLOSE VICINITY OF A INDUCING HIGH VOLTAGE CABLE LINE

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ABSTRACT

Mutual inductive interferences occur between electrical systems that are located in close vicinity over a certain distance so that the low frequent electromagnetic field can interact between the galvanic isolated systems. Especially in urban regions so-called energy corridors are built where high voltage power lines are often situated close to information and telecommunication lines, other power lines, gas pipes, low voltage lines etc. With increasing operation- and fault-currents the determination of the effects and consequences of inductive coupling have to be considered and should be taken into account. With the help of calculations it's possible to determine the effects of inductive interferences and disturbances in advance to set measures against negative influences in the face of personal safety and the operation of the power systems. It's also possible to get more information for dimensioning of earthing systems to reduce the potential in case of touch and step voltages and provide additional information's for the determination of resistive influences.

For calculations of the interference and disturbing the usage of reduction factors, especially in the case of interference in close vicinity of earth wires, cable shields and additional reduction conductors, have to be taken into account.

In this paper the authors present different line configurations and positioning of the reduction conductors on the induced voltage of an isolated conductor (ICT-lines, pipelines etc.) in close vicinity of the inducing power line system.

INTRODUCTION

Interference and disturbance calculations can be performed with the help of simplified models – using spare conductors for the inducing power line system – and standard reduction factors that are only applicable for standard interference diagram configurations. If there is no standard configuration the usage of reduction factors known in literature are not applicable.

Generally the reduction factor of conductors or cable shields depends on several parameters like the geometric position, impedance (cross section), grounding conditions, the physical presence of other reducing conductors in addition to the overhead grounding wire(s) and cable shields. The coupling impedances of the circuit configuration have an impact on the reduction factor.

With the help of computer-assisted calculation tools the opportunity is given to consider flexible circuit configurations which allow calculating the major interference configurations that will appear in praxis. These models can also be used for calculating the effects caused by normal operation or operation during a fault in the inducing power system.

Interference calculations can be performed with the help of matrix calculations [1], [2]. To reduce the complexity and calculation time the configurations today for the practical use are simplified and reductions factors for standard configurations have been developed. Also simplifications like the introduction of spare conductors for the inducing power line will be performed.

Since the demands on the accuracy of the calculations will be higher and the limits are exhausted these simplifications are not particularly applicable in respect of the complex inductive interference configuration appearing in praxis (complex situation: considering several grounding wires, cable shields and reduction conductors). Especially if the induced conductor will be in the near of the inducing power line the standard reduction factor is not usable. New ways for the determination of accurate results und consideration additional influences have to be found.

REDUCTION FACTORS

As a basic requirement for the investigations the self-impedances and coupling impedances of the circuit configuration have to be calculated with the well-known formulas (e.g. [1], [2], with the help of Carson's [3] or Pollaczek's [4] formulas, [5], [6]).

The limits of the impedance and coupling impedances calculation (distance between the lines, inaccuracy, data, etc.) have to be taken into account. For an accurate calculation every active conductor or passive reduction conductor (e.g. earth wire(s), cable shields etc.) that take part in the interference system has to be considered.

In complex systems the application of the standard reduction factor r is not enough the calculation must performed in detail (e.g. if cross bounding occur) so using real reduction factors will lead to better and accurate calculation results. Also the right arrangement of reduction conductors in case of inductive interferences has to be

discovered to get the best effect for the reduction.
Especially in the near of the inducing power system the positioning and the number of reduction conductors have a strong impact on the reduction factor respectively the reduced resulting induced voltages and currents.
After the full impedance matrix of a circuit configuration is calculated the impedance matrix of the system can be separated into active (conducting) and passive (not conducting, grounded) conductors (1).

$$\begin{vmatrix} \underline{\mathbf{U}}_p \\ \mathbf{0} \end{vmatrix} = \begin{vmatrix} \underline{\mathbf{Z}}_{pp} & \underline{\mathbf{Z}}_{pq} \\ \underline{\mathbf{Z}}_{qp} & \underline{\mathbf{Z}}_{qq} \end{vmatrix} \cdot \begin{vmatrix} \underline{\mathbf{I}}_p \\ \underline{\mathbf{I}}_q \end{vmatrix} \qquad (1)$$

$\underline{\mathbf{U}}_p$ Phase voltages of the active conductors

$\underline{\mathbf{Z}}_{pp}$ Part of the impedance matrix with the impedances and coupling impedances of the line conductors

$\underline{\mathbf{Z}}_{qq}$ Part of the impedance matrix with the impedances and coupling impedance of the earth wire(s)

$\underline{\mathbf{Z}}_{pq}$ Part of the impedance matrix with the coupling impedances between the line conductors and earth wire(s)

$\underline{\mathbf{Z}}_{qp}$ Part of the impedance matrix with the coupling impedances between earth wire(s) and the line conductors

$\underline{\mathbf{I}}_p$ Currents in the active conductors (phases)

$\underline{\mathbf{I}}_q$ Currents in the passive conductors (e.g. earth wire)

For every single conductor there exists a different reduction factor, because of the fact that the reduction factor is depending on the geometry of the system. The reduction factors for the line configuration can be written in matrix notation. The matrix $\underline{\mathbf{K}}$ is defined by (2) and includes the reduction factors for every conductor.

$$\underline{\mathbf{K}} = \underline{\mathbf{Z}}_{pq} \cdot \underline{\mathbf{Z}}_{qq}^{-1} \cdot \underline{\mathbf{Z}}_{qp} \qquad (2)$$

The reduced impedance matrix of the active conductors can be calculated with (3).

$$\underline{\tilde{\mathbf{Z}}}_{pp} = \underline{\mathbf{Z}}_{pp} - \underline{\mathbf{K}} \qquad (3)$$

The induced voltage in the active conductors $\underline{\mathbf{U}}_p$ or in the passive conductors $\underline{\mathbf{U}}_q$ can be determined with (4) or (5).

$$\underline{\mathbf{U}}_p = \underline{\tilde{\mathbf{Z}}}_{pp} \cdot \underline{\mathbf{I}}_p \qquad (4)$$

$$\underline{\mathbf{U}}_q = \underline{\mathbf{Z}}_{qp} \cdot \underline{\mathbf{I}}_p \qquad (5)$$

If the passive conductors are grounded on both sides ($\underline{U}_q = 0$) a current path exists and with the help of the induced voltage in this reduction conductor the induced current can be derived with the equation (6).

$$\underline{\mathbf{I}}_q = -\left(\underline{\mathbf{Z}}_{qq}\right)^{-1} \cdot \underline{\mathbf{Z}}_{qp} \cdot \underline{\mathbf{I}}_p \qquad (6)$$

To get the residual induced voltage in an isolated conductor, the sum of all operation currents and compensating currents in the reduction conductors have to be taken into account.

$$\underline{\mathbf{U}}_i = \sum_{k=1}^{n} \underline{\mathbf{I}}_k \cdot \underline{\mathbf{Z}}_{ik} \qquad (7)$$

$\underline{\mathbf{U}}_i$ Voltage that is induced into an isolated conductor

$\underline{\mathbf{I}}_k$ Inducing current, compensating current, etc.

$\underline{\mathbf{Z}}_{ik}$ Coupling impedance between the respective isolated conductor and the current-carrying conductor

n Number of the inducing conductors (active and passive)

RESULTS

An example will be chosen to demonstrate the calculation results. The induced voltages in isolated conductors (ICT-lines) are calculated considering different positions and numbers of reduction conductors (see Fig. 1).
For the inducing currents in the power lines the following currents are chosen:

- **Normal operation**
  Symmetrical currents in all phases with an amplitude of 500 A

- **Short time operation during a fault**
  Cross country fault: asymmetrical two phase fault current over earth with an amplitude of 20 kA, current flow in one single phase (L1)

For the cable type, a standard 110-kV single-core cable was used (1x800 RM/70).
All the results are calculated for a line length of 1 km, so the results will be easy to compare and applying for other line lengths.

Example

For this demonstration example a 110-kV cable line with two symmetric systems (Sys 1, Sys 2) is chosen. Fig. 1 shows the dimensions of the power lines, the reduction conductors (A … D) and the positioned isolated conductors (1 … 7) as they were chosen for the characteristic example.

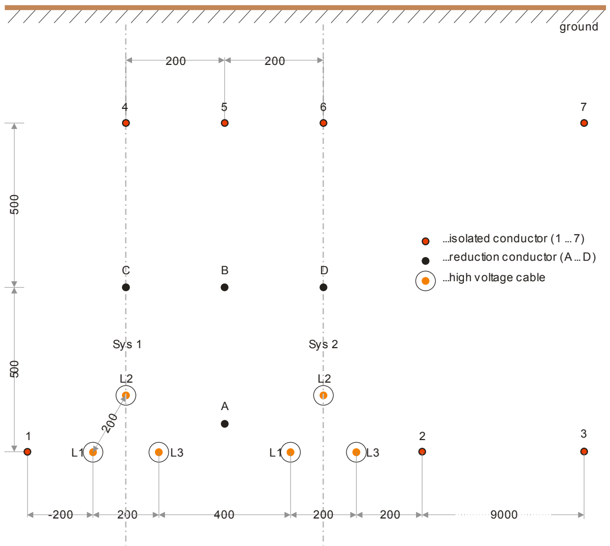

Figure 1 Example: high voltage three phase cable lines with both side earthed shields, reduction conductors (A … D) and isolated conductors (1 … 7). All dimensions in mm

To demonstrate the results of the investigations the reduction factor or the effectiveness of the reduction the reduction factors r will be expressed by the quotient of the induced voltage $\underline{U}_i$ with consideration of the reduction effects and the induced voltage $\underline{U}_{i0}$ without considerations of any reduction effects (reduction conductors) into the isolated conductors – see equation (8).

$$r_i = \frac{U_i}{U_{i0}} \qquad (8)$$

r_i … Reduction factors

U_i … Induced voltage with consideration of reduction factors

U_{i0} … Induced voltage that would be induced in the isolated conductors under consideration of the reduction factor that is given through both side earthed cable shields without any additional consideration of any other reduction conductors

Normal Operation

For the label in the head of the following tables, that describes the chosen investigated configuration (see Fig. 1) the following cases are investigated:

Case 1: no reduction conductors installed (only consideration of the cable shields)
Case 2: reduction conductor A is additionally installed
Case 3: reduction conductor B is additionally installed
Case 4: reduction conductors C and D are additionally installed
Case 5: reduction conductors A, C and D additionally installed to the cable shields

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	V	Degree	V	Degree		V	Degree		V	Degree		V	Degree	
U_{i1}	21,80	53,2	21,59	52,9	0,990	23,33	57,3	1,070	24,11	61,1	1,106	23,51	60,9	1,078
U_{i2}	23,06	-157,9	23,17	-157,4	1,005	22,75	-163,4	0,987	22,73	-168,2	0,986	23,08	-166,9	1,001
U_{i3}	1,00	-117,3	1,15	-113,5	1,143	1,41	152,8	1,406	2,76	138,2	2,748	2,63	145,5	2,627
U_{i4}	11,17	-36,3	11,34	-37,2	1,015	7,48	-33,1	0,669	4,73	-32,6	0,423	4,88	-38,0	0,437
U_{i5}	11,25	-46,2	11,45	-46,9	1,018	7,27	-49,3	0,646	4,67	-53,3	0,415	4,97	-57,7	0,442
U_{i6}	10,38	-56,8	10,60	-57,3	1,021	6,82	-64,4	0,657	4,24	-76,0	0,409	4,66	-79,0	0,449
U_{i7}	1,04	-111,2	1,19	-108,3	1,144	1,31	154,2	1,265	2,66	138,4	2,565	2,54	146,0	2,451

Table 1 Induced voltages and reduction factors in the isolated conductors; both cable systems in operation, symmetrical inducing currents 2x3x500 A, 1 km line length

In Tab. 1 it can be seen, that the reduction factors for each isolated conductors is different and mainly depending from the positioning and number of the reduction conductors. The positioning of the reduction or guarding conductors have to be optimized in dependence of the distance between the isolated conductor (e.g. ICT-line) and the inducing power system.
Reduction factors r < 1 can be explained trough a current shift that results from the reduction conductor(s) and will lead to another additional asymmetry.

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	V	Degree	V	Degree		V	Degree		V	Degree		V	Degree	
U_{i1}	19,08	62,8	21,22	55,0	1,112	20,90	64,0	1,095	21,56	67,1	1,130	22,34	61,9	1,171
U_{i2}	5,87	-143,1	1,48	-140,4	0,253	5,32	-167,5	0,907	5,56	179,6	0,948	3,39	158,5	0,578
U_{i3}	0,53	-136,6	2,02	19,6	3,832	1,29	116,1	2,455	2,15	118,0	4,087	2,23	79,9	4,231
U_{i4}	5,88	-45,9	7,85	-19,4	1,336	3,63	-25,9	0,618	1,95	-21,1	0,331	3,65	-7,7	0,621
U_{i5}	5,47	-61,0	6,68	-26,3	1,222	2,59	-50,7	0,473	1,24	-60,4	0,228	2,57	-17,4	0,470
U_{i6}	4,64	-75,5	5,16	-29,5	1,111	1,79	-83,8	0,385	0,87	-125,6	0,186	1,39	-13,1	0,299
U_{i7}	0,52	-130,8	2,04	18,3	3,904	1,25	115,2	2,385	2,11	117,6	4,027	2,20	79,0	4,201

Table 2 Induced voltages and reduction factors in the isolated conductors; only system 1 is installed and in operation, symmetrical inducing currents 1x3x500 A, 1 km line length

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	V	Degree	V	Degree		V	Degree		V	Degree		V	Degree	
U_{i1}	5,87	51,3	1,57	68,2	0,268	5,65	75,5	0,964	6,18	79,8	1,053	3,55	98,9	0,606
U_{i2}	19,08	-154,6	22,51	-156,0	1,180	19,73	-159,8	1,034	19,76	-163,5	1,036	22,17	-162,4	1,162
U_{i3}	0,56	-136,6	3,01	-146,5	5,363	1,75	169,0	3,128	2,34	154,7	4,174	3,34	-179,7	5,950
U_{i4}	4,64	-16,4	4,05	-68,4	0,873	1,77	-20,1	0,380	1,06	8,2	0,228	1,41	-112,2	0,303
U_{i5}	5,47	-30,8	5,41	-71,8	0,990	2,78	-49,0	0,508	1,46	-45,7	0,266	2,48	-103,6	0,454
U_{i6}	5,88	-45,9	6,44	-80,3	1,095	3,73	-67,2	0,635	2,19	-82,2	0,373	3,67	-111,2	0,625
U_{i7}	0,56	-130,5	2,99	-145,4	5,368	1,71	170,1	3,063	2,29	155,2	4,110	3,30	-179,1	5,920

Table 3 Induced voltages and reduction factors in the isolated conductors; only system 2 is installed and in operation, symmetrical inducing currents 1x3x500 A, 1 km line length

Tab. 2 and 3 shows that under consideration of the same reduction conductors (as mentioned for the both system installation) especially for isolated conductors that are positioned away from the inducing power line the situation of the reduction factors changes. For some configurations cases the induced voltage in the isolated conductors are increased because of the additional current shift resulting from the reduction conductor(s) that lead to an increased asymmetry.

Short-time operation during a fault

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	kV	Degree	kV	Degree		kV	Degree		kV	Degree		kV	Degree	
U_{i1}	1,86	33,5	1,85	37,9	0,994	1,82	37,2	0,975	1,74	39,7	0,935	1,73	42,5	0,929
U_{i2}	0,70	-22,0	0,58	-15,6	0,827	0,58	-19,6	0,825	0,48	-18,1	0,691	0,40	-13,2	0,577
U_{i3}	0,63	4,6	0,58	11,4	0,911	0,54	8,4	0,858	0,47	10,8	0,741	0,44	16,0	0,689
U_{i4}	1,01	8,4	0,92	14,5	0,908	0,80	10,0	0,792	0,65	8,5	0,638	0,60	13,2	0,591
U_{i5}	0,95	4,4	0,85	10,4	0,891	0,72	4,2	0,760	0,58	3,1	0,612	0,53	7,7	0,556
U_{i6}	0,88	0,8	0,78	7,0	0,880	0,67	0,3	0,760	0,53	-0,7	0,600	0,48	4,1	0,538
U_{i7}	0,63	4,5	0,58	11,3	0,911	0,54	8,4	0,857	0,47	10,6	0,740	0,44	15,8	0,687

Table 4 Induced voltages and reduction factors in the isolated conductors; both systems installed, fault in phase L1 system 1, 1 km line length

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	kV	Degree	kV	Degree		kV	Degree		kV	Degree		kV	Degree	
U_{i1}	0,79	-16,4	0,62	-14,3	0,785	0,67	-13,5	0,845	0,59	-10,6	0,737	0,46	-9,9	0,585
U_{i2}	1,22	5,5	1,08	10,0	0,880	1,13	9,4	0,919	1,04	12,0	0,850	0,93	15,3	0,761
U_{i3}	0,64	-1,1	0,54	2,5	0,836	0,55	1,6	0,850	0,47	3,8	0,738	0,40	6,4	0,628
U_{i4}	0,89	-3,5	0,72	-1,7	0,811	0,68	-5,8	0,759	0,54	-6,3	0,603	0,44	-5,8	0,497
U_{i5}	0,93	-1,5	0,76	0,4	0,818	0,70	-4,0	0,753	0,57	-4,4	0,607	0,47	-3,8	0,504
U_{i6}	0,96	0,0	0,80	2,4	0,827	0,75	-1,1	0,775	0,60	-2,3	0,622	0,50	-1,1	0,524
U_{i7}	0,64	-1,2	0,54	2,4	0,835	0,55	1,5	0,849	0,47	3,7	0,736	0,40	6,2	0,627

Table 5 Induced voltages and reduction factors in the isolated conductors; both systems installed, fault in phase L1 system 2, 1 km line length

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	kV	Degree	kV	Degree		kV	Degree		kV	Degree		kV	Degree	
U_{i1}	2,27	23,0	2,07	31,7	0,910	2,06	30,1	0,904	1,90	34,4	0,835	1,82	39,2	0,799
U_{i2}	1,67	7,0	1,19	10,6	0,711	1,22	9,2	0,734	0,96	10,1	0,573	0,74	11,4	0,443
U_{i3}	1,13	6,9	0,88	13,2	0,772	0,86	10,5	0,756	0,69	12,5	0,606	0,58	16,7	0,512
U_{i4}	1,69	8,3	1,31	14,5	0,775	1,18	9,2	0,698	0,88	8,2	0,524	0,75	12,4	0,445
U_{i5}	1,66	7,4	1,26	12,9	0,758	1,12	6,7	0,671	0,83	5,5	0,502	0,69	9,0	0,416
U_{i6}	1,63	7,1	1,22	12,2	0,747	1,10	6,5	0,673	0,80	4,7	0,493	0,66	7,8	0,403
U_{i7}	1,13	6,8	0,87	13,2	0,772	0,86	10,4	0,755	0,68	12,4	0,604	0,58	16,6	0,511

Table 6 Induced voltages and reduction factors in the isolated conductors; only system 1 installed, fault in phase L1 system 1, 1 km line length

	Case 1		Case 2			Case 3			Case 4			Case 5		
	Magnitude	Angle	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r	Magnitude	Angle	r
	kV	Degree	kV	Degree		kV	Degree		kV	Degree		kV	Degree	
U_{i1}	1,80	14,9	1,21	13,7	0,673	1,33	17,7	0,742	1,07	19,9	0,598	0,78	16,4	0,437
U_{i2}	1,85	2,5	1,40	7,1	0,758	1,51	7,3	0,819	1,32	10,7	0,713	1,09	13,3	0,588
U_{i3}	1,15	7,0	0,82	8,4	0,714	0,86	9,3	0,749	0,70	11,2	0,606	0,54	11,1	0,472
U_{i4}	1,68	10,5	1,16	9,9	0,692	1,12	8,4	0,667	0,83	7,0	0,495	0,62	4,4	0,372
U_{i5}	1,69	9,5	1,18	9,2	0,698	1,12	6,7	0,663	0,84	5,8	0,498	0,64	3,6	0,379
U_{i6}	1,69	8,3	1,19	8,6	0,707	1,15	6,4	0,684	0,86	5,2	0,512	0,66	3,9	0,395
U_{i7}	1,15	6,9	0,82	8,4	0,713	0,86	9,3	0,748	0,69	11,1	0,604	0,54	10,9	0,471

Table 7 Induced voltages and reduction factors in the isolated conductors; only system 2 installed, fault in phase L1 system 2, 1 km line length

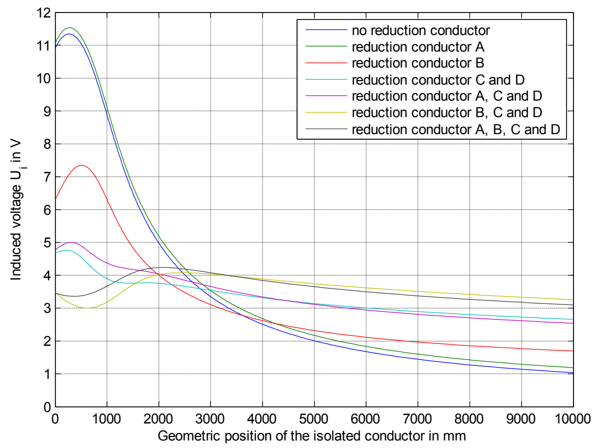

Figure 2 Calculated induced voltage in a single isolated conductor (4, see Fig. 1) if this conductor will be moved from the left to the right side; normal operation mode.

Fig. 2 shows the induced voltage in a single isolated conductor (4, see Fig. 1) if this conductor will be moved along a horizontal plane from the left to the right side under consideration of a different reduction factor configurations.

CONCLUSSION

In practice reduction and guarding conductors will be installed in close vicinity to inducing power lines. For standard installations (e.g. high voltage overhead lines with earth wires and cable lines etc.) standard reduction factors are given in literature, but the applicability of those factors is limited to the standard configurations and to the circumstance that the induced conductor will have a certain distance to the inducing power line.

For non-standard configurations and close situated inducing and induced conductors (e.g. energy corridors in urban regions) the positioning of reduction and guarding conductors in normal operation will have a significant impact on the reduction effects so that standard reduction factors cannot apply.

The reducing effect is mainly depending on the positioning and the conductivity of the reduction or guarding conductors. The cross-section for all cable shields, reduction and guarding conductors have to consider the maximum induced currents in case of the short-time operation during a fault (e.g. cross country fault) of the inducing power system.

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