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Selection of station surge arresters for control of slow-front overvoltages on compact lines

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SUMMARY

Compact upgraded lines have shorter clearances compared to standard lines of the same voltage level, so they require the use of efficient techniques to reduce overvoltages in order to avoid phase to ground or phase to phase flashovers. The use of station arresters with a low protection level at the terminals of the line might be the best solution for the reduction of the slow-front overvoltages (SFO) due to energization or reclosing of the line. This low protection level requires the use of arresters whose rated voltage should be selected very carefully regarding the level of the temporary overvoltages (TOV) that could appear in the system. The paper is analyzing the feasibility of using station arresters subjected to TOV because of their lower rated voltage. These surge arresters are installed at both terminals of a compact line upgraded from 225 kV to 400 kV and are aiming at reducing some SFO. The energy stresses of station surge arresters were studied for different network configurations, short circuit currents, types of faults and rated voltages of arresters. These configurations combine the effect of load shedding, Ferranti effect and earth fault. The methodology and modelling of elements to perform the study is described in the paper. The parametric study was conducted analyzing the energy stressing the arrester versus: the protective level of the surge arresters; the level of TOV; the duration of TOV. Simulations were performed on simple configurations, using the EMTP-RV software, with surge arresters of rated voltages 342 kV and 330 kV, energy class 4.

KEYWORDS

TOV, Ferranti effect, earth fault, selection of station surge arrester, energy stress, compact upgraded line, EMTP-RV.

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1. INTRODUCTION

Presently the voltage rating of station surge arresters has been usually chosen higher than the amplitude of the TOV which can occur in the system. This approach leads to the use of arresters with a high protection levels, especially if the system is not solidly grounded, which do not reduce the level of SFO and fast-front overvoltages as efficiently as arresters with lower protection level would do.

In any complex electromagnetic system, a sudden change in state gives rise to transient oscillations which, in turn, can cause high overvoltages unless suitably damped. For EHV systems it has been common practice for many years now to equip circuit-breakers with closing resistors, as a mean of controlling such system transient interactions during closing or re-closing operations. The closing resistors are inserted in series with the load circuit being switched for a short period of time, before closing the main contacts of the breaker – thereby damping the transient overvoltages. Optimum overvoltage control requires correct choice of the resistor value in relation to the source impedance level, the line length and the line parameters. Although a well-proven technology, breakers equipped with closing resistors inevitably involve relatively complex mechanical constructions. In recent years several large utilities have experienced problems with the long term mechanical reliability of closing resistor mechanisms (especially in older circuit-breakers) – with adverse impact on overall system reliability – and have begun to examine alternative approaches to switching surge overvoltage control. Foremost amongst these is the installation of suitably chosen zinc oxide surge arresters at both ends of the transmission line being switched [1], [2]. Given the availability now of ZnO arresters having low protective levels and high discharge energy capabilities, this proves to be a particularly economical and very simple way of controlling transmission line switching surges – without any dependence upon complex mechanisms or sensitive timing systems.

SFO due to energization or reclosing of the line may be reduced by using various techniques like point-on-the-wave switching or breakers equipped with pre-insertion resistors, but SFO due to faults on adjacent lines, which are most of the time not of interest for standard overhead lines, might get critical in case of compact or upgraded lines. Obviously they cannot be reduced by the techniques listed above and the use of station arresters with a low protection level at the terminals of the line might be the only option. This low protection level requires the use of arresters whose rated voltage might be below the level of TOV and this issue has to be studied carefully.

2. COMPACT LINES

The biggest problem with the construction of new transmission lines is their placement in space. The main requirements are to reduce as much as possible the space occupied by the transmission line corridors and to reduce as much as possible their adverse impact on environment. This applies not only to new transmission lines, but also in the case of upgrading line to a higher voltage level. It is expected that the upgrade of existing lines to higher voltage level will often apply in the future - especially in areas where it is difficult to build new lines, in order to use the existing corridors to increase the transmission capacity. In many countries, for instance in France, significant modifications of a line design, as the change of tower heads, require the application of a very difficult administrative procedure, so it is preferred to limit as most as possible the modifications made to a line when proceeding to its upgrading. If a line is upgraded with minor changes of its design and without improvement of the grounding electrodes of towers, its lightning performance remains unchanged. The line considered in this paper is a single circuit 225 kV line equipped with 2 ground wires, upgraded to 400 kV without major modifications of the design of the towers. In this case the level of SFO can exceed the switching withstand voltage of the insulator strings. Phase conductors are bundled and consist of 2 sub-conductors separated by a distance of 0.6 m, and the line is 100 km long. The position of conductors at towers is shown in Table 1 and characteristics of conductors are shown in Table 2.

Table 1 – Position of conductors at towers

Position of conductors at towers	Horizontal position of conductors (m)	Vertical position of conductors (m)
Phase A	-10	28.8
Phase B	0	32.6
Phase C	10	28.8
Ground wire 1	-6	37.7
Ground wire 2	6	37.7

Table 2 – Characteristics of conductors

Conductors	Phase conductors	Ground wires
Type	Aster	Aster
Cross section (mm^2)	570	228
Internal diameter (mm)	0	0
External diameter (mm)	31	22
DC resistance (Ω / km)	0.0583	0.115

3. TEMPORARY OVERVOLTAGES

TOV are oscillatory phase-to-ground or phase-to-phase overvoltages (at power frequency, but in some cases the frequency may be several times smaller or higher than power frequency) at a given location, of relatively long duration and which are undamped or weakly damped. Information about the level of TOV is important when selecting surge arrester rated voltage [3] [4]. Surge arresters without gaps are continuously exposed to operating voltage, and all kinds of overvoltages (temporary, switching and lightning). Transmission networks usually operate with directly grounded neutral of power transformers. In some cases, for example, to limit excessive short circuit currents, the network may have isolated neutral. Connection of phase conductor with the ground causes a single-phase short circuit, whereby the phase voltage increases in "healthy" phases of the network.

TOV usually originates from earth faults and system faults leading to switching operations such as load rejection and/or system separation. Usually the selection of the rated voltage of surge arresters is based upon the envelope of the TOV expected, taking into account the energy capability of the surge arrester. IEC 60071.2-1996 gives some general information on the determination of the corresponding representative overvoltage in the case of earth fault and load rejection. In many cases, load flow analysis is performed in order to evaluate power frequency overvoltages and then select the rated voltage of the surge arresters which will be used in the system considered. This approach does not permit to consider TOV due to resonance and ferroresonance which may reach high values but are not normally considered when selecting the surge arrester rated voltage and for the insulation design [5]. The rated voltage of the arrester is selected based on the TOV in the system at the arrester location, considering their amplitudes as well as their durations. The basic requirement is that the power frequency voltage versus time characteristic of the arrester should be higher than the TOV amplitude versus duration characteristic of the system.

Ground fault overvoltages occur in a large part of the system. Guidance for the determination of TOV amplitudes is given in annex A of [6]. The duration of the overvoltage corresponds to the duration of the fault (until fault clearing). In earthed neutral systems it is generally less than 1 s. In resonant earthed neutral systems with fault clearing it is generally less than 10 s. In systems without ground fault clearing the duration may be several hours. Voltage rise along long line caused by Ferranti effect was also considered in calculations, as a cause of TOV. TOV due to ferroresonances should not form the basis for the surge arrester selection and should be eliminated. Sequences of causes for TOV, e.g. load rejection caused by a ground fault, need consideration, when both overvoltages have comparable severity. In such cases, however, the amount of rejected load dependent on the fault location and the arrester location has to be carefully examined. Combination of causes such as ground faults and load rejection may result in higher TOV values than those from the single events. When such combinations are considered sufficiently probable, the overvoltages for each cause have to be compounded taking into account the actual system configuration. TOV analyzed in this paper combine the effect of load shedding, Ferranti effect and ground fault.

4. NETWORKS WITH ISOLATED NEUTRAL

Advantages of networks with isolated neutral:

- during a ground fault, which statistically represents the most frequent fault, in the case of relatively low capacitive current, self extinction of the fault occurs if it is a transient fault, i.e. the faulted line does not switch off, and it positively affects the quality of the electrical power supply;
- because of the relatively low fault current, conditions for grounding implementation in substation are basically not a problem;
- simplicity and cost-effectiveness of the performance.

Disadvantages of networks with an isolated neutral:

- in networks with an isolated neutral point, intermittent overvoltages can occur, with relatively high overvoltage factors, which can cause double ground faults in different parts of the network;
- overvoltages are much greater than in earthed networks;
- fault detection is more difficult than in earthed networks;
- at higher capacitive currents there is no self extinction of currents of the transient earth faults.

Earth-fault factor is defined by following expression:

$$k = \frac{U_{\max}}{\frac{\sqrt{2}}{\sqrt{3}}U} \qquad (1)$$

where:

$U_{\max}$ – overvoltage amplitude.
U – r.m.s. phase-to-phase power frequency voltage.

Earth-fault factor k is the ratio of the voltages in the healthy phases during and prior to earth-fault conditions. It can be determined on the basis of the known (calculated) equivalent impedances of network in positive, negative and zero sequence system. In case of occurrence of single-phase to ground fault in phase A, phase to ground voltages in the other two healthy phases B and C increase (TOV occur). Figure 1 shows the earth-fault factors as families of curves applicable to particular values of R_0/X_1. The curves are valid for fault resistance values giving the highest earth-fault factors [6].

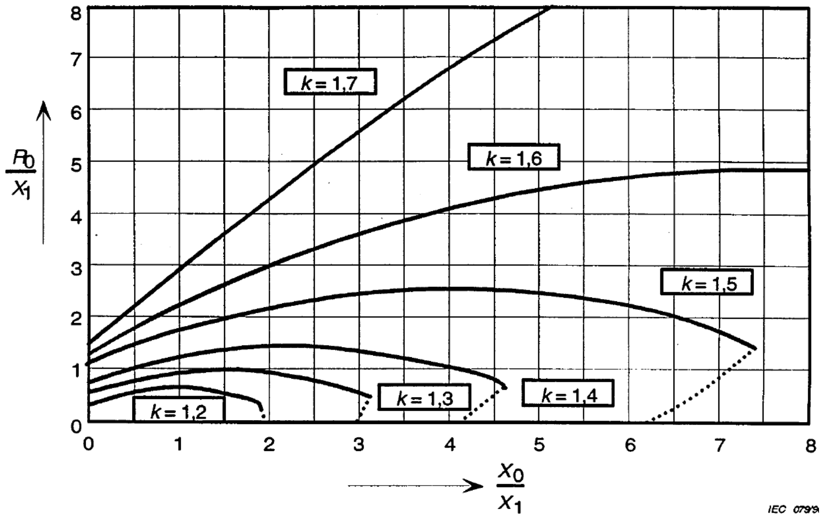

Figure 1. Relationship between R_0/X_1 and X_0/X_1 for constant values of earth-fault factor k

If these parameters are unknown, it is assumed that factor k has a value of 1.4 for earthed neutral systems and 1.73 for isolated neutral or resonant earthed systems.

5. SELECTION OF SURGE ARRESTER RATED VOLTAGE

Surge arrester is a vital piece of equipment and an insurance against damage to the other equipment in the substation. Hence, it is essential that the arrester itself is stable under all system operating conditions. This, in turn, requires that the system behaviour, especially under TOV conditions, must be known. Unfortunately this is true usually for EHV systems only. Whenever such is not the case the arrester must be selected with a sufficient safety margin. Selecting an arrester for a specific application is a compromise between protective level, TOV capability and energy capability. Increasing the TOV capability (by addition of blocks in series) increases the possibility of survival of the arrester under system voltage stresses but reduces the margin of protection provided by the arrester for a given insulation level. An arrester with a higher energy capability reduces the risk of failure. Optimization depends on how well the actual arrester stresses are known or can be estimated. The further steps will explain how to select the parameters of surge arrester.

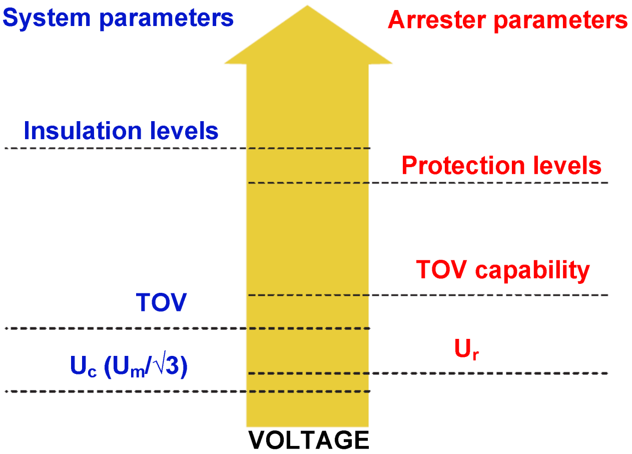

Figure 2. Comparison of system parameters and arrester parameters depending on voltage level

Temporary overvoltages are characterized with amplitude (U_{TOV}), duration (t_{TOV}) and frequency of oscillations. Rated voltage of an arrester is maximum permissible r.m.s. value of power-frequency voltage between its terminals at which it is designed to operate correctly under TOV conditions as established in the operating duty tests. It is the 10 s power frequency voltage used in the operating duty test after high current or long duration impulses. Rated voltage of surge arrester is selected on the basis of TOV that can occur in the network on site where surge arresters are installed. As a TOV have different time of duration, it is desirable to express them as the equivalent to TOV amplitudes U_{eqi} and duration of 10 seconds by the following expression derived from [6]:

$$U_{eqi} = U_{TOVi} \cdot \left(\frac{t_{TOVi}}{10} \right)^m \qquad (2)$$

where:
U_{TOVi} - amplitude of TOV; t_{TOVi} - duration of TOV; U_{eqi} - amplitude of equivalent TOV with duration of 10 s; m - exponent (0.018-0.022), usually adopted value: $m = 0.02$.

Fundamental requirement that must be satisfied in the selection of surge arrester rated voltage is:

$$U_r \geq \max(U_{eq1}, U_{eq2}, U_{eq3....}) \qquad (3)$$

Surge arrester manufacturers [7] in their instructions for the selection of surge arresters give the curve showing the TOV capability of surge arresters, depending on TOV duration, Figure 3. TOV curves show TOV strength factor (T_r) as a function of time corresponding to the fault-clearance time, $T_r = f(t_{TOV})$.

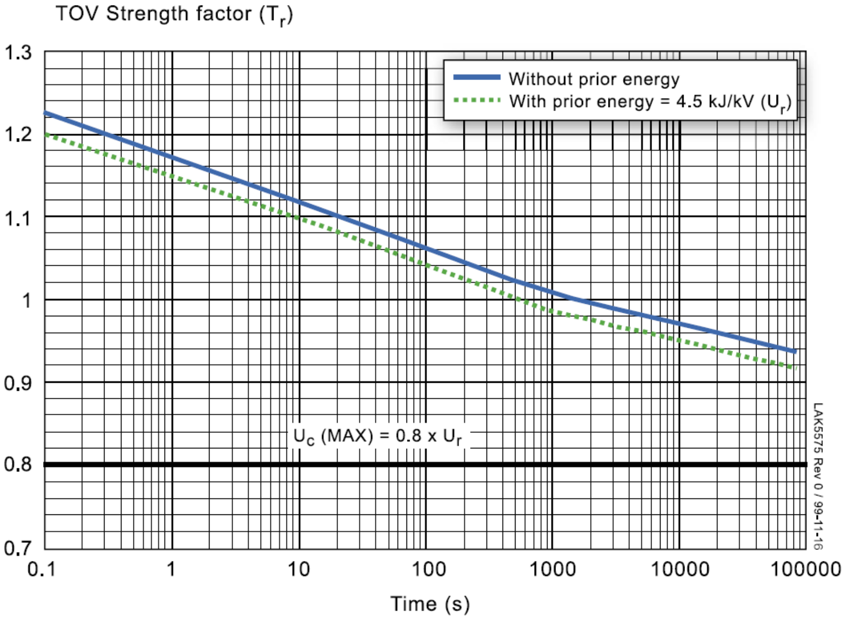

Figure 3. TOV capability curves

TOV strength factor (T_r) is defined as ratio between amplitudes of TOV and surge arrester rated voltage:

$$T_r = \frac{U_{TOV}}{U_r} \qquad (4)$$

T_r can be obtained by using the lower curve (for surge arrester with prior duty equal to the maximum single-impulse energy stress 4.5 kJ/kV (U_r)) for known durations of TOV.

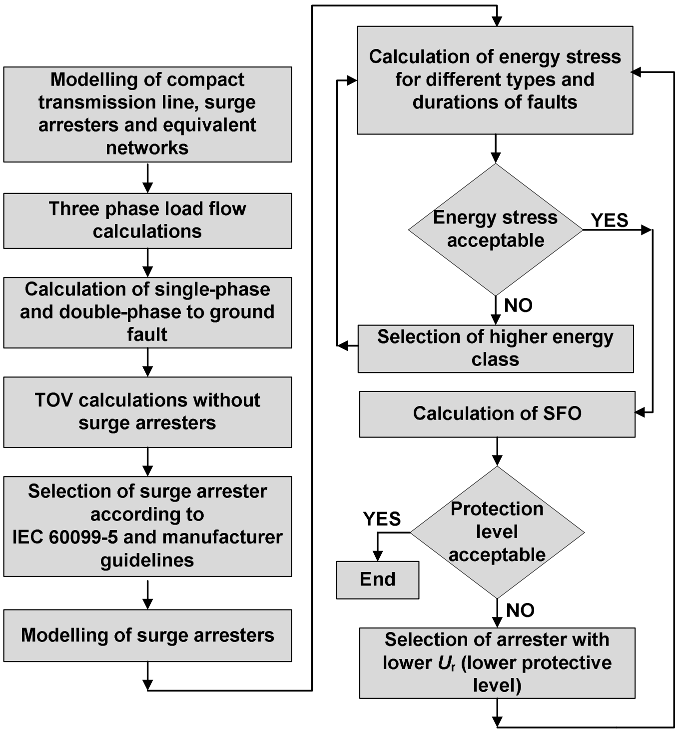

Figure 4. Procedure for selection of protective levels lower than that of the adopted arrester design

From known amplitudes of TOV U_{TOVi} rated voltages can be obtained by using the following expression:

$$U_{ri} = \frac{U_{TOVi}}{T_{ri}} \qquad (5)$$

Selection of surge arrester rated voltage must fulfil the following requirement:

$$U_r \geq \max(U_{r1,} U_{r2,} U_{r3....}) \qquad (6)$$

The rated voltage of the arrester should be equal to or higher than the highest equivalent TOV obtained. When protective levels lower than that of the adopted arrester design are desired, rated voltages below the equivalent 10 s TOV may be selected, provided the arrester is able to absorb the energy caused by system events. In this case energy absorption calculations should be carried out simulating the system events. Procedure for selection of protective levels lower than that of the adopted arrester design is shown in Figure 4. Calculations of SFO are not presented in this paper, only TOV are considered.

6. MODELLING FOR CALCULATION OF TEMPORARY OVERVOLTAGES

Substations 1 and 2 are connected with 400 kV compact line (Figure 5). Surge arresters are installed at both terminals of the line. The overhead line transmits P=300 MW and Q=130 MVAR from substation 1 to substation 2. Networks with single-phase short circuit currents I_{sc1}=5 kA and I_{sc1}=10 kA were analyzed.

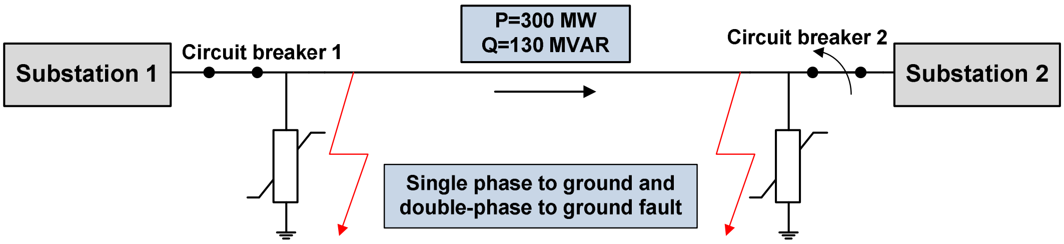

Figure 5. Model for calculation of temporary overvoltages

The following events are considered, with both short circuit currents, in order to evaluate the level of TOV and the effect on arresters:

a) A single phase to ground fault in phase A occurs at the end of the line (substation 2) and then three-phase opening of circuit breaker 2 occurs (relaying problem).
b) A double-phase to ground fault in phases B and C occurs at the end of the line (substation 2) and then three-phase opening of circuit breaker 2 occurs.
c) A single phase to ground fault in phase A occurs at the entrance of the line (substation 1) and then three-phase opening of circuit breaker 2 occurs (failure of the relaying).
d) A double-phase to ground fault in phases B and C occurs at the entrance of the line (substation 1) and then three-phase opening of circuit breaker 2 occurs (relaying problem).

6.1. Compact transmission line

Transmission line was modelled using frequency dependent model in software EMTP-RV [8] [9]. This model represents the true nature of a transmission line by modelling the line parameters as distributed and frequency dependent. The line resistance and inductance are evaluated as functions of frequency, as determined by skin effect and ground return conditions. Ground return resistivity was assumed 250 Ωm. The model is based on the approximation by rational functions of the line characteristic impedance Z_{c} and propagation function A_{p}, given by the following equations:

$$Z_c = \frac{\sqrt{R + j\omega L}}{\sqrt{G + j\omega C}} \quad (7) \qquad A_p = e^{-\gamma \cdot l} \quad (8) \qquad \gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (9)$$

6.2. Network equivalent

Parameters of equivalent network are calculated from short circuit currents by using the following expressions [10]:

$$Z_d = \frac{c \cdot U_n}{\sqrt{3} \cdot I_{sc3}} \quad (10) \qquad Z_0 = \frac{c \cdot U_n}{\sqrt{3}} \cdot \left(\frac{3}{I_{sc1}} - \frac{2}{I_{sc3}} \right) \quad (11)$$

where:

I_{sc1}, I_{sc3} – single-phase and three-phase short circuit currents; U_n – rated voltage; c – factor = 1.1.

Substations 1 and 2 are modelled with voltage sources behind Thevenin equivalent.

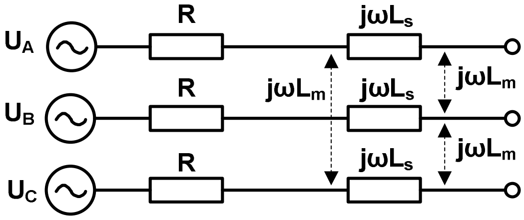

Figure 6. Modelling of network (substation 1 and 2) using Thevenin equivalent

Thevenin impedance is calculated by using the following expression:

$$[Z]_{TH} = [R]_{TH} + j\omega[L]_{TH} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} + j\omega \begin{bmatrix} L_S & L_m & L_m \\ L_m & L_S & L_m \\ L_m & L_m & L_S \end{bmatrix} \quad (12)$$

Thevenin impedance is coupled *RL*-branch with an impedance matrix given by the series connection of *R* and *L*. The matrices $[R]_{TH}$ and $[L]_{TH}$ can be entered directly or using sequence data. The power variant Fortescue transformation matrix $[A]$ is used in EMTP-RV to calculate the full matrices from sequence components.

$$[Z]_{TH} = [A] \cdot [Z_{012}] \cdot [A]^{-1} \qquad [A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad (13)$$

Sequence data (zero and positive resistance and reactance) are shown in Table 3.

Table 3 – Calculated sequence data for single-phase short circuit currents of 5 kA and 10 kA

I_{sc1rms} (kA)	R_0/X_1	X_0/X_1	Positive sequence data (Ω)		Zero sequence data (Ω)		I_{sc3rms} (kA)
			R_1	X_1	R_0	X_0	
10	5.5	3	0	9.79	53.83	29.36	24.78
5	5.5	3	0	19.57	107.65	58.72	12.39

6.3. Surge arrester

A metal-oxide surge arrester model suitable for temporary and switching-surge overvoltage studies would be a nonlinear resistance with characteristics which can be derived from a low frequency test wave consisting of a half sinusoid with a 1 ms time to crest [11]. This test wave is designated as the "1 ms wavefront". An example of a 1 ms wavefront characteristic for a metal-oxide disk is shown in Figure 7 and should be used in system simulations involving TOV and slow switching surges. The characteristics shown in Figure 7 are for example only. Data should be obtained from manufacturers for use in modelling. An additional consideration when evaluating the performance of metal-oxide arresters is to recognize that there are manufacturing tolerances associated with the actual construction of the arrester. In critical arrester applications, the effects of manufacturing tolerances should be addressed. The arrester characteristic with the maximum voltage for a given current should be used in the computation of protective ratios because such a model yields the most conservative assessment of the protective ratio. On the other hand, the lower voltage-current curve should be considered for situations where the discharge energy duty of the arrester needs to be maximized (Table 4).

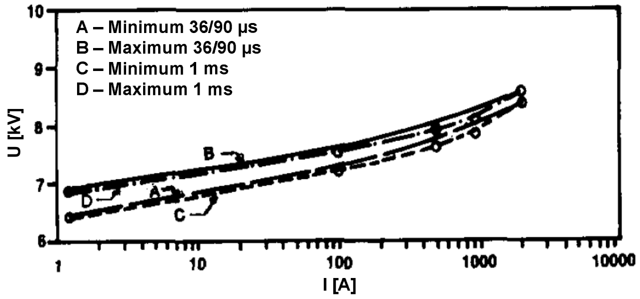

Figure 7. Examples of metal oxide disk characteristics including manufacturing tolerances [11]

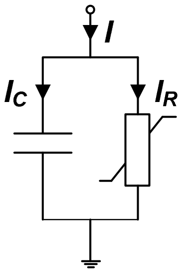

Figure 8. Surge arrester model for calculation of energy stress under TOV

MO disks are permanently exposed to power frequency voltage. In normal operating conditions, the current I through surge arrester consists primarily of capacitive current I_C and a small resistive component of non-sinusoidal current I_R (Figure 8). The resistive component creates energy losses and increases the temperature of surge arrester compared to surrounding temperature. Increasing the voltage increases the resistive component of current and energy losses. MO disks have capacitive character at nominal power frequency voltage. The capacitance C represents the terminal-to-terminal capacitance of the arrester and it can be calculated by using the following expression:

$$C = \frac{100}{d} \cdot n \qquad (14)$$

where:
d – length of arrester column in meters (dimensions from catalogue data d=3.216 m);
n – number of parallel columns of metal-oxide disks.

Table 4 – *I-U* characteristic

Current [A]	**U_r=330 kV**	**U_r=342 kV**
	Voltage [kV]	
1	491	508
10	542	561
100	593	619
200	608	631
300	616	639
400	623	647
500	627	650
600	631	654
700	635	658
800	638	662
900	642	666
1000	644	667
2000	667	691

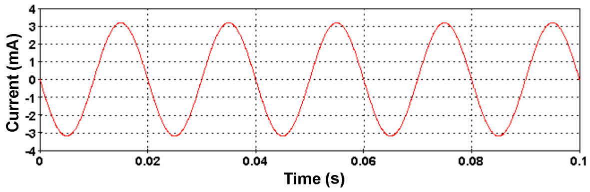

Figure 9. Capacitive component of the current at nominal voltage

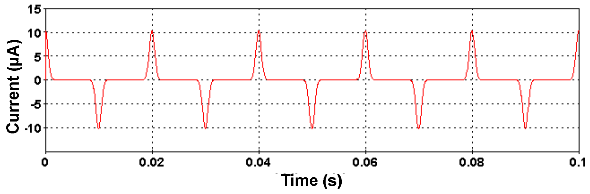

Figure 10. Resistive component of the current at nominal voltage

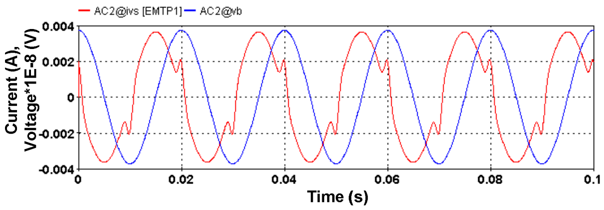

Figure 11. Surge arrester total current (red) at continuous operating voltage (blue) U_c=264 kV

Both capacitive and resistive components of the current for surge arrester with U_r=330 kV at nominal voltage (U_n=400/√ 3=230.94 kV) are shown in Figures 9 and 10. At continuous operating voltage U_c resistive component of current is still negligible compared to the capacitive component (Figure 11).

When the voltage exceeds the knee of *I-U* characteristic, the capacitive component becomes negligible compared to the resistive component. For the example mentioned above (Figure 5.), the surge arrester with U_r=342 kV and energy class 4 (energy capability 2394 kJ) was selected according to IEC 60099-5. Calculations of energy stress were carried out for the surge arrester with U_r=342 kV and for the surge arrester with a lower rated voltage U_r=330 kV (energy capability 2310 kJ). The surge arrester energy is calculated by using the following expression:

$$E = \int_0^t v(t) \cdot i(t) dt \qquad (15)$$

7. RESULTS

Three-phase load flow calculation results are shown in Table 5 in p.u., where 1 p.u.=420/√3·√2= 342.929 kV. Voltages at the beginning and at the end of line before the fault occurrence are determined.

Table 5 – Three-phase load flow results

Network configuration	**I_{sc1}=10 kA**		**I_{sc1}=5 kA**	
	U [p.u.]	**φ [°]**	**U [p.u.]**	**φ [°]**
Voltages at the beginning of the line (p.u.)	U_{1a}=1.0011 U_{1b}=0.9994 U_{1c}=0.9995	φ_{1a}=0.0410 φ_{1b}=-120.05 φ_{1c}=120.007	U_{1a}=1.0016 U_{1b}=0.9993 U_{1c}=0.9992	φ_{1a}=0.0547 φ_{1b}=-120.064 φ_{1c}=120.009
Voltages at the end of the line (p.u.)	U_{2a}=0.9742 U_{2b}=0.9756 U_{2c}=0.9752	φ_{2a}=-3.0609 φ_{2b}=-122.95 φ_{2c}=116.932	U_{2a}=0.9740 U_{2b}=0.9758 U_{2c}=0.9751	φ_{2a}=-3.0686 φ_{2b}=-122.919 φ_{2c}=116.893

The results of three-phase load flow calculations are used as input parameters for the calculation of TOV caused by single-phase and double-phase to ground fault. Calculated amplitudes of TOV in the transient (U_{max}) and steady state (U_{st}) are shown in Tables 6 and 7. Voltages are expressed as p.u. values for following cases: 1 – beginning of the line during the fault; 2 – beginning of the line after opening of circuit breaker 2; 3 – end of the line during the fault; 4 – end of the line after opening of circuit breaker 2. Analyses of maximum TOV values in phases B and C for different times of fault occurrence in phase A were conducted. For case c) I_{sc1}=5 kA, maximum voltages in phases C (U_{maxC} – Figure 12) and B (U_{maxB} – Figure 13) are computed in each simulation, in order to find the time of single-phase to ground fault occurrence at which the overvoltages are the highest. Results of TOV calculations are shown in Figures 14 - 17.

Table 6 – TOV for network with I_{k1}=5kA

	a)				**b)**		**c)**				**d)**	
	U_{maxC}	U_{stC}	U_{maxB}	U_{stB}	U_{maxA}	U_{stA}	U_{maxC}	U_{stC}	U_{maxB}	U_{stB}	U_{maxA}	U_{stA}
	Without surge arrestes											
1	1.61	1.51	1.13	1.03	1.40	1.29	1.93	1.63	1.42	1.28	1.66	1.41
2	1.54	1.45	1.15	1.02	1.36	1.29	1.91	1.73	1.52	1.38	1.57	1.47
3	1.88	1.59	1.38	1.25	1.62	1.38	1.58	1.49	1.17	1.07	1.40	1.28
4	1.68	1.52	1.40	1.18	1.49	1.37	2.06	1.74	1.66	1.39	1.83	1.48
	Surge arresters U_r=342 kV											
1	1.58	1.51	1.13	1.03	1.40	1.29	1.81	1.63	1.40	1.28	1.64	1.41
2	1.53	1.45	1.14	1.02	1.36	1.29	1.78	1.72	1.40	1.38	1.57	1.47
3	1.79	1.59	1.37	1.25	1.61	1.38	1.54	1.49	1.17	1.07	1.40	1.28
4	1.65	1.51	1.38	1.18	1.49	1.37	1.82	1.73	1.45	1.40	1.76	1.48
	Surge arresters U_r=330 kV											
1	1.56	1.51	1.13	1.03	1.42	1.29	1.76	1.63	1.39	1.28	1.62	1.41
2	1.52	1.45	1.13	1.02	1.36	1.29	1.73	1.71	1.42	1.41	1.56	1.47
3	1.74	1.59	1.36	1.25	1.59	1.38	1.52	1.49	1.17	1.07	1.39	1.28
4	1.63	1.51	1.37	1.18	1.49	1.37	1.75	1.71	1.48	1.45	1.72	1.48

Table 7 – TOV for network with I_{k1}=10 kA

	a)				**b)**		**c)**				**d)**	
	U_{maxC}	U_{stC}	U_{maxB}	U_{stB}	U_{maxA}	U_{stA}	U_{maxC}	U_{stC}	U_{maxB}	U_{stB}	U_{maxA}	U_{stA}
	Without surge arrestes											
1	1.44	1.39	1.12	0.94	1.40	1.20	1.89	1.62	1.38	1.29	1.67	1.41
2	1.40	1.30	1.04	0.95	1.24	1.19	1.75	1.71	1.44	1.37	1.53	1.46
3	1.84	1.58	1.34	1.25	1.64	1.37	1.41	1.37	1.12	0.96	1.40	1.19
4	1.59	1.40	1.29	1.14	1.48	1.31	1.99	1.72	1.60	1.38	1.57	1.47
	Surge arresters U_r=342 kV											
1	1.43	1.39	1.11	0.94	1.40	1.20	1.80	1.62	1.39	1.29	1.65	1.41
2	1.40	1.30	1.04	0.95	1.24	1.19	1.74	1.71	1.39	1.37	1.52	1.46
3	1.77	1.58	1.35	1.25	1.62	1.37	1.41	1.37	1.10	0.96	1.40	1.19
4	1.58	1.40	1.29	1.14	1.48	1.31	1.81	1.71	1.46	1.39	1.57	1.47
	Surge arresters U_r=330 kV											
1	1.43	1.39	1.10	0.94	1.39	1.20	1.75	1.62	1.40	1.29	1.62	1.41
2	1.40	1.30	1.04	0.95	1.24	1.19	1.71	1.70	1.38	1.37	1.52	1.46
3	1.73	1.58	1.35	1.25	1.59	1.37	1.41	1.37	1.10	0.96	1.38	1.19
4	1.59	1.40	1.28	1.14	1.48	1.31	1.74	1.70	1.46	1.40	1.56	1.46

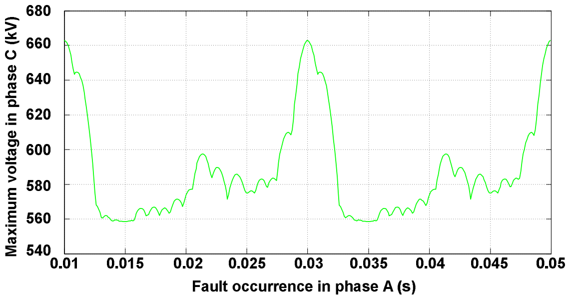

Figure 12. Maximum voltage at the beginning of the line in phase C U_{maxC}=662.9 kV, t_{faultA}=10 ms

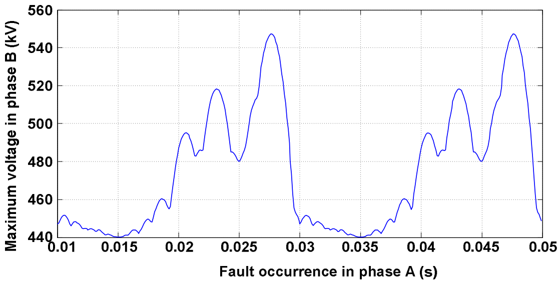

Figure 13. Maximum voltage at the beginning of the line in phase B U_{maxB}=547 kV, t_{faultA}=27.6 ms

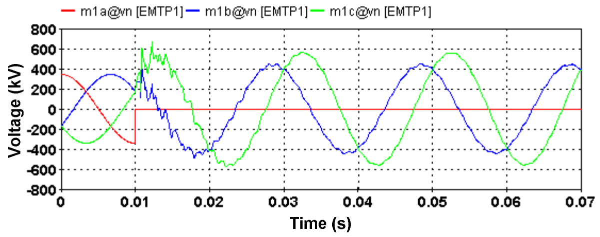

Figure 14. Voltages at the beginning of the line during single-phase short circuit

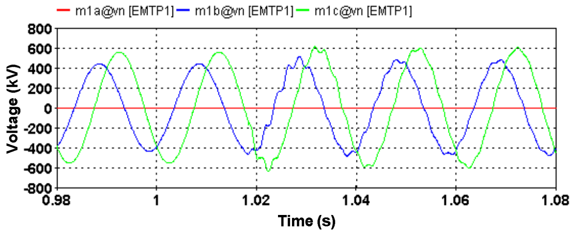

Figure 15. Voltages at the beginning of the line after opening of circuit breaker 2

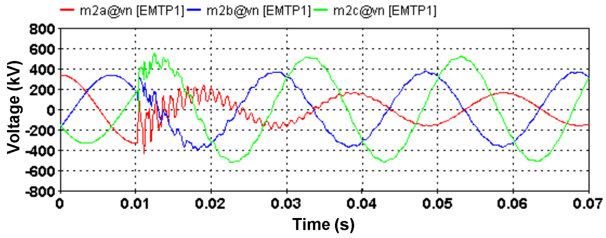

Figure 16. Voltages at the end of the line during single-phase short circuit

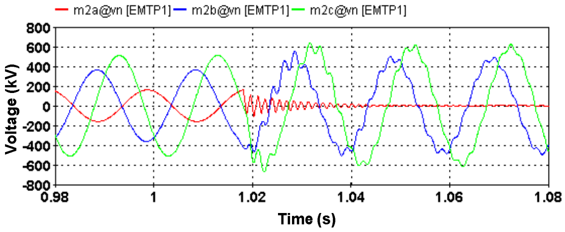

Figure 17. Voltages at the end of the line after opening of circuit breaker 2

Figures 18, 19 and 20 show the energy stress and the currents through the surge arresters with the rated voltage U_r=330 kV for case c) I_{sc1}=5 kA in substation 2. The energy stressing the arresters with the rated voltages 342 kV and 330 kV versus the duration of the fault and the time after the opening of the circuit breaker 2 is shown in Table 8 and 9.

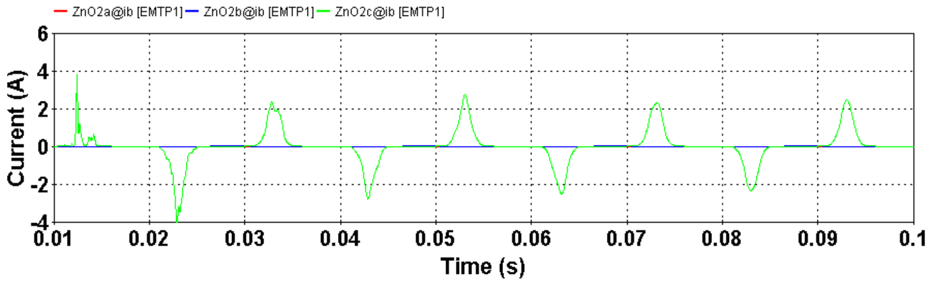

Figure 18. Currents through surge arresters at the end of the line during the fault

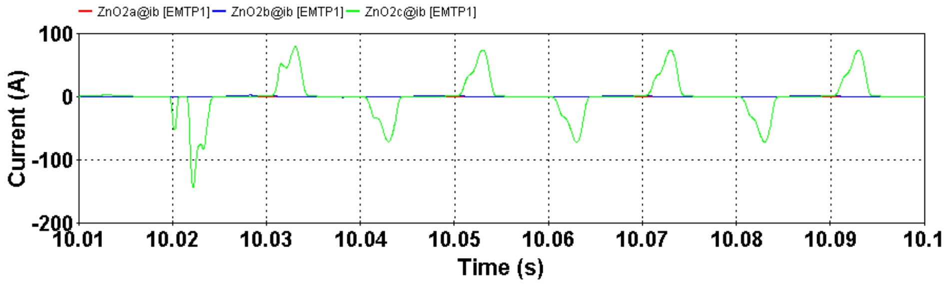

Figure 19. Currents through surge arresters at the end of the line during fault and after opening of circuit breaker in substation 2 (10.02 ms)

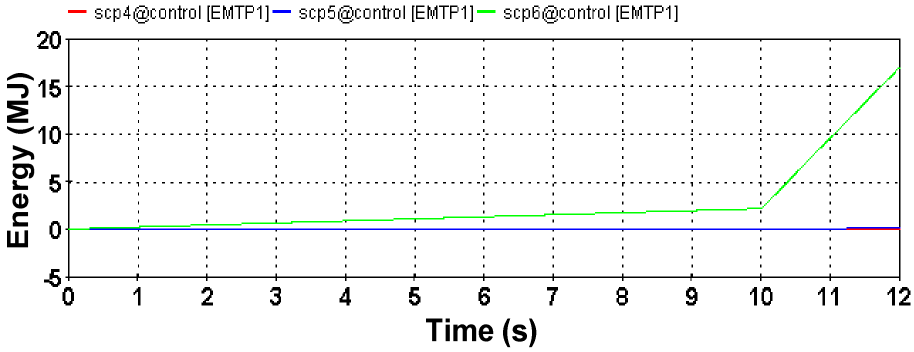

Figure 20. Energy stressing the arrester in phase C at the end of the line during the fault and after opening of circuit breaker in substation 2 (10.02 ms)

Energy stress (Figure 20) and currents (Figures 18 and 19) through surge arresters at the end of the line are higher in the period after opening of the circuit breaker in substation 2 than during the fault. Figures 21 and 22 present the combination of maximum allowed duration of fault versus maximum allowed time after opening of circuit breaker in substation 2, for which the arrester would stand the energy stress. If the duration of fault (relay protection settings) is known, from Figures 21 and 22 it is easy to determine whether the energy capability of the arrester is exceeded.

Table 8 Results of surge arrester energy stress [kJ/s] versus time for network with I_{sc1}=5 kA

U_r (kV)	Energy capability (kJ)	a)	b)	c)	d)
330	**2310**	Beginning of the line during the fault			
		285.03	8.636	1823.1	63.601
		Beginning of the line after opening CB2			
		112.75	9.316	**7561.8**	150.01
		End of the line during the fault			
		942.79	34.612	197.44	7.8565
		End of the line after opening of CB 2			
		309.75	33.73	**8298.8**	175.846
342	**2394**	Beginning of the line during the fault			
		126.185	2.3992	793.81	24.833
		Beginning of the line after opening CB2			
		47.48	2.6309	3277.5	64.714
		End of the line during the fault			
		424.51	12.2792	85.967	2.1352
		End of the line after opening of CB 2			
		138.39	11.924	3759.2	76.855

Table 9 Results of surge arrester energy stress [kJ/s] versus time for network with I_{sc1}=10 kA

U_r (kV)	Energy capability (kJ)	a)	b)	c)	d)
330	**2310**	Beginning of the line during the fault			
		42.032	2.0015	1560.8	60.755
		Beginning of the line after opening CB2			
		10.135	1.619	**6476.9**	119.93
		End of the line during the fault			
		817.25	33.643	30.185	1.7396
		End of the line after opening of CB 2			
		47.29	12.23	**7224.3**	140.85
342	**2394**	Beginning of the line during the fault			
		15.3723	0.39	684.39	23.549
		Beginning of the line after opening CB2			
		159.647	0.307	2643.7	50.724
		End of the line during the fault			
		366.95	11.881	10.459	0.331
		End of the line after opening of CB 2			
		17.63	3.641	3070	60.376

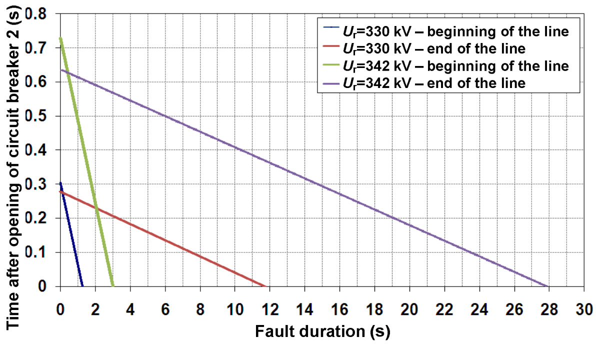

Figure 21. Fault duration versus time after opening of circuit breaker in substation 2, for which the energy capability of arrester is exceeded (network with I_{sc1}=5 kA)

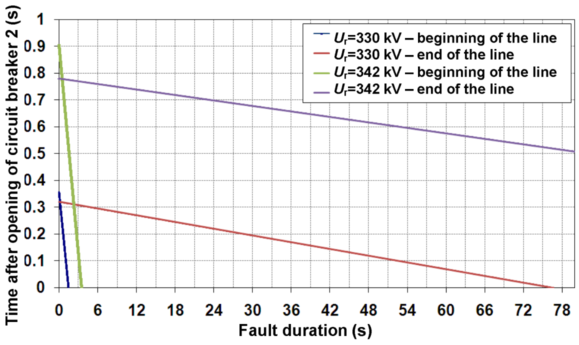

Figure 22. Fault duration versus time after opening of circuit breaker in substation 2, for which the energy capability of arrester is exceeded (network with I_{sc1}=10 kA)

In the case c) (I_{sc1}=5 kA) the energy capability of surge arresters with U_r=330 kV at the beginning of the line will be exceeded if the fault is not eliminated in both substations in less than 1.27 s (Figure 21). If the fault is eliminated in substation 1 (relaying problem) for example in 300 ms, the energy capability of surge arresters will be exceeded if time after opening of circuit breaker in substation 2 is greater than 233 ms. The energy capability of surge arresters will be exceeded for the combination of times that lie above the curves.

8. CONCLUSION

This paper describes the procedure for the calculation of the surge arrester energy stress during TOV. The energy stresses of station surge arresters were studied for different network configurations, short circuit currents, types of faults and rated voltages of surge arresters. The calculation was performed on compact 400 kV transmission line transmitting a power P=300 MW and Q=130 MVAr from substation 1 to substation 2. Networks with short circuit currents I_{sc1}=5 kA and I_{sc2}=10 kA were analyzed in calculations. Voltages at the beginning and end of the line before the occurrence of the fault are determined from three-phase load flow calculations. Combined TOV caused by occurrence of single-phase and double-phase to ground fault and Ferranti effect were analyzed. Modelling of surge arresters, compact transmission line and network equivalents were presented.

Method for selection of protective levels lower than that of the adopted arrester design was described. By using this method surge arrester with low protection level can be selected without being overstressed by TOV, and overvoltage protection of compact line can be improved. According to [6] surge arrester with rated voltage U_r=342 kV was selected. Calculation results show that the surge arrester with U_r=330 kV could also be selected without being overstressed by TOV, for certain durations of TOV. This surge arrester has a lower protection level and it reduces SFO and fast-front overvoltages more efficiently. Event c), in which a single phase to ground at the entrance of the line occurs and then three-phase opening of circuit breaker 2 - failure of the relaying, represents the most severe event regarding energy stressing of surge arresters. The level of TOV and energy stress is higher for the network with I_{sc1}=5 kA than for I_{sc1}=10 kA.

After the selection of the surge arrester according to the shown procedure, the study could be performed in order to check if the SFO are reduced to a level acceptable for the compact line. Another alternative for the limitation of SFO is the application of transmission line arresters that can be located along the line at selected points to obtain the required control of the overvoltage profile along the line [12], [13].

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