TECHNICAL NOTE 2.3

Inductive voltage drops
Overvoltage protection
The TECHNICAL NOTES (TN) are intended to be used in conjunction with the

APPLICATION GUIDELINES
Overvoltage protection
Metal-oxide surge arresters in medium-voltage systems.

Each TECHNICAL NOTE gives in a concentrated form additional and more detailed information about various topics of MO surge arrester and their application under normal and special service conditions.

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Inductive voltages at connection leads

Besides the location of the MO surge arrester the connecting leads relative to the protected equipment are very important.

1 Introduction

The inherent resistive and inductive impedance in the leads will increase the effective residual voltage seen by the equipment being protected. This issue is particularly sensitive for protection from fast-front overvoltages. Therefore, it is important to keep these connecting leads as short as possible and free of inductive loops. The induced voltage should be considered from case to case in special applications. See for more information IEC 60099-5, Ed. 3.0, 2018-01 Surge arresters – Part 5: Selection and application recommendations.

2 Earthing considerations

The earthing system is different executed for distribution systems and transmission systems. The high-voltage side of the arrester is in both cases directly connected to the overhead line, whereas the ground leads are connected in different ways. Figure 1 and Figure 2 illustrate the difference between transmission and distribution installations.

Arrangements according Figure 1 are typical for pole mounted transformers and small distribution substations. The ground lead should be connected directly to the transformer grounding point.

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Figure 1: Installation without earth-mat (distribution systems), adapted and modified from IEC

Figure 2: Installation with earth-mat (high-voltage substations), adapted and modified from IEC

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Length of conductor between transformer bushing and point of connection of arrester line lead</td>
</tr>
<tr>
<td>b₁</td>
<td>Length of arrester line lead</td>
</tr>
<tr>
<td>b₂</td>
<td>Length of arrester ground lead</td>
</tr>
<tr>
<td>U_res</td>
<td>Residual voltage of arrester</td>
</tr>
<tr>
<td>A</td>
<td>Arrester</td>
</tr>
<tr>
<td>Z_e</td>
<td>Grounding impedance</td>
</tr>
<tr>
<td>T</td>
<td>Transformer</td>
</tr>
</tbody>
</table>
Installations according Figure 2 are typical for substations in high-voltage transmission systems, where the arresters are installed on pedestals in a significant distance to the equipment to be protected. This is the case, in particular, in systems with $U_s > 245$ kV. The arrester ground lead is connected to the earth mat of the substation.

In general, low earth resistance is essential and should be as small as possible to limit the earth potential rise at the earth terminal, and hence mitigate safety hazards and flashovers on the low-voltage side of the transformer. A value of earth resistance $\leq 10$ Ω is generally considered to be sufficient. In some special cases in substations an earth resistance in the range of 2 Ω or even lower may be required. Earth resistances are measured mainly with d.c. current or 50/60 Hz a.c. current; however, in case of high frequency (or current impulse with high frequency content) the value may be much higher. That is why specially executed earthing installations are used to discharge current impulses.

The earth resistance is influenced by the condition of the soil, e.g. rocky regions, desert regions, dry or humid soil etc. In unfavorable situations the value of the earth resistance can be far above 100 Ω.

3 Induced voltage drop

These induced voltages are considerable during high rate of changes $\frac{di}{dt}$, such as when lightning currents occur. The MO material itself reacts almost instantaneously even with very steep voltage and current impulses. In view of the dimensions of the connections, there are always inductive voltages and it is necessary to take them into account especially with steep current impulses. The specified residual voltages, which are to be found in the datasheets, are always the voltages between the arrester terminals only; for explanations see also Figure 3.

The induced voltage is calculated as:

$$U_i = L \times \frac{di}{dt} .$$

$U_i$  Induced voltage  
$L$  Inductivity  
$\frac{di}{dt}$  Steepness of current impulse

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**Figure 3:** Typical arrangement of a transformer with a connected arrester.

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1 Poor. The connection leads are too long and the transformer and the MO surge arrester do not have the same earthing point.

2 Good. Common earth of MO surge arrester and transformer. The connection leads are much shorter.

3 Very good. The MO surge arrester is earthed directly at the transformer tank. The loop is very short. In this way the inductance is kept to a minimum.
The following two examples give a rough overview about the magnitude of the expected induced voltage \( U_i \) which can superimpose the arrester residual voltage.

An approximate inductive voltage of \( U_i = 1.2 \text{ kV per meter connection line} \) results from an inductivity of \( L = 1 \mu \text{H} \) for a straight wire of 1 m length and a lightning current of 10 kA peak value of the wave shape 8/20 \( \mu \text{s} \) (assumed steepness 10 kA / 8 \( \mu \text{s} \)).

A voltage of \( U_i = 10 \text{ kV per meter connection line} \) results from a steep current impulse with a rise time of 1 \( \mu \text{s} \) and 10 kA peak value.

The peak value of the induced voltage \( U_i(b) \) does not appear simultaneously at the peak value of the arrester residual voltage. The reason is that an inductive voltage has another phase angle to the current than a resistive voltage. This means that the two voltages \( U_{res} \) and \( U_i \) cannot be added algebraically but must be geometrically added. In case of high current impulses, we can consider the MO arrester being in the ohmic region. The self-inductance of the MO resistor or MO arrester (depending on the length of the resistor or arrester) is covered by the measured residual voltage of the MO resistor or the MO arrester.

However, especially for steep current impulses and long lead lines the possible inductive voltage drops, which can superimpose the arrester residual voltage, should be considered if necessary.

At distribution voltage levels \( (U_s \leq 52 \text{ kV}) \), often arresters can be located very close to the equipment to be protected, e.g. transformers. In this case, and where possible, the earth terminal of the arrester and equipment should be bonded with a very short conductor. For an optimized solution see Figure 4.

### 4 MO surge arrester with fixed cable connection

As mentioned, the residual voltages given in the data sheets are valid for the terminals of the arresters. This is correct, because it is not known how and where the arresters are installed in the system. It is up to the customer to ensure that the protective distance is considered, and the connections are done correctly as recommended.
We can give only guidance if requested, but we are not providing engineering for the station layout.

The situation is different when we deliver MO surge arresters with fixed cable connection, as shown for example in Figure 5. In this case the top terminal is not at the top of the arrester but at the end of the fixed cable. For being correct the inductive voltage drop $U_i$ along the cable should be considered and added to the residual voltage of the arrester.

The following example gives information about the magnitude of the induced voltage.

Given is an MO surge arrester type MWD 36 with lightning protection level $U_{pl} = 110.6 \text{kV}$ and a residual voltage of $U_{res} = 120.6 \text{kV}$ at a steep current impulse of 10 kA with a rise time of the current of 1 µs, and a fixed cable of 0.75 m length.

With the equation given above the induced voltages result with an assumed steepness of 10 kA/8 µs to

$$U_i = L \times \frac{di}{dt} = \frac{0.75}{\mu H} \times 10 \text{kA/8 µs} = 0.94 \text{kV}$$

for a wave shape of 8/20 µs

and with an assumed steepness of 10 kA/µs

$$U_i = L \times \frac{di}{dt} = \frac{0.75}{\mu H} \times 10 \text{kA/1 µs} = 7.5 \text{kV}$$

for the steep current impulse.

The results show that in case of a standard lightning impulse $I_n$, an induced voltage of $U_i = 0.94 \text{kV}$ should be added. This is 0.84 % of the residual voltage and can be neglected, especially considering that the voltage $U_i$ must be added geometrically.

In case of the steep current impulse we should add geometrically an induced voltage $U_i = 7.5 \text{kV}$. This results in approximately 122 kV as absolute value, which is 1.16 % above the residual voltage of the MO surge arrester at a steep current impulse with 10 kA peak value. In practical applications this very slight increase can be neglected.

A lead length of 0.75 m is relatively long and a steep current impulse with 10 kA peak value will rarely occur in an indoor medium voltage system. Therefore, the induced voltage at steep current impulses needs to be considered case by case in special applications only.

5 Summary

As a rule, surge arresters should be located as close as possible to the equipment to be protected to ensure effective overvoltage protection. The length of high-voltage and earth connection leads should be short and straight as practical to minimize the loop inductance and ensure minimum voltage drops across the leads.

The residual voltages of MO surge arresters as given in the data sheets apply to the terminals of the arresters only.

Induced voltages across connecting leads have to be considered only if arresters are delivered with fixed cable connections. The inductive voltage drops $U_i$ do not occur simultaneously with the peak value of the residual voltage $U_{res}$ of the MO arrester. Therefore, they have to be geometrically added.

Inductive voltage drops $U_i$ of MO surge arresters with fixed cable connection are to be considered in special cases only, and can be neglected in standard applications in medium voltage systems.
Additional information

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