APPLICATION NOTE 2.1

Transformers connected via a cable

Overvoltage protection
The APPLICATION NOTES (AN) are intended to be used in conjunction with the

APPLICATION GUIDELINES

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

Each APPLICATION NOTE gives in a concentrated form additional and more detailed information for the selection and application of MO surge arresters in general or for a specific equipment.

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Overvoltage protection of transformers connected via a cable.

Transformers, which are connected via a cable, require an optimized protection concept with coordinated MO surge arresters.

1 Introduction

In some cases it is necessary or advantageous to use two arresters in an installation separated from one another in space, but electrical parallel on the same line. Figure 1 illustrates a typical example in which the transformer in a substation is connected through a cable to the overhead line. An MO surge arrester A1 is installed on the pole at the junction of the overhead line to the cable. In some countries this arrester is described as a “riser pole” arrester. This is not a type description for an arrester, but specifies the installation place where the cable rises up to the pole and where it is connected with the overhead line. Another MO surge arrester A2 is installed in the substation at the other end of the cable, in front of the transformer.

The essential difference between the electrical data of overhead lines and cables is the surge impedance \( Z \). For overhead lines in medium-voltage distribution systems the surge impedance lies between \( Z_{OL} = 300 \, \Omega \) and \( 450 \, \Omega \), and for cables between \( Z_C = 30 \, \Omega \) to \( 60 \, \Omega \).

At first this difference causes a marked decrease of the lightning overvoltage as soon as the traveling wave reaches the cable entrance. The reduced voltage wave travels through the cable and is positively reflected at the cable end, so that the voltage increases there. Subsequently, the wave returns to the cable entrance and is again reflected, and so on.

In this way the overvoltage is build up gradually in the cable. The steepness of the overvoltage is in fact lower, but the maximum value reaches the same value as the incoming overvoltage on the overhead line. More about travelling waves, theory and examples, are given in Technical Note 2.1 “Travelling waves”.

One can distinguish between three different possibilities for the selection of the MO surge arresters:

- Protection with two MO surge arresters of the same type and rating
- Protection with two MO surge arresters of the same type but with different ratings
- Protection with two MO surge arresters of different types
2 Principle considerations with two arresters of the same type and rating

According to Figure 2 a cable is connected on one end to a lightning endangered overhead line. At the other end, a bus bar consisting of the sections a and b connects the cable end with the transformer. The A1-arrester takes over the overvoltage protection on the line side. Both the cable end and the transformer must be protected with an additional arrester A2. First we need to find the best location for the MO surge arrester A2.

The overvoltage reflection at the junction from the line to the cable causes a strong flattening of the voltage steepness in the cable. However, this has practically no influence on the admissible length of the connection b, because with increasing length of b the voltage $U_{CA}$ increases very quickly. Therefore, optimal overvoltage protection requires that the A2-arrester should be placed as close as possible to the cable end, in order to shorten the distance b.

With the bus bar section a it is different. In this section the voltage $U_T$ increases slower with increasing length of a. That is why the transformer is adequately protected even at a relatively far distance from the arrester. The maximum admissible values for a are indicated in Table 1.

For the performed calculations the capacity of the transformer is assumed to be 2 nF. Smaller capacitances result in longer distances of a. The connections c between the arrester and the cable should be at most 1 m in length, including the earth connection of the arrester.

The occurring overvoltages, and consequently the protective distances, are influenced by the capacitance of the transformer, the surge impedances Z of the cable and the overhead line, the cable length and damping factor of the cable, and the steepness of the incoming overvoltage. However, the figures in Table 1 are on the safe side and can be taken as rules of thumb. If the distance a between the cable and transformer is greater than indicated in Table 1 an additional MO surge arrester should be installed directly in front of the transformer.

<table>
<thead>
<tr>
<th>MO surge arrester with $U_{pU} = 4$ p.u. at $I_n = 10$ kA</th>
<th>Overhead line with wooden pole</th>
<th>Overhead line with earthed cross arms</th>
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<tr>
<td>$Z_C$ in Ω</td>
<td>a in m</td>
<td>a in m</td>
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<td>30</td>
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<td>17.5</td>
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</tr>
<tr>
<td>24</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

The cable is connected to a lightning endangered overhead line and protected on both ends with MO surge arresters. The values given are for systems with insulated star point.

The values given are for insulated star point. MO surge arrester with $U_{pU} = 4$ p.u. at $I_n = 10$ kA Overhead line with wooden pole Overhead line with earthed cross arms $Z_C$ in Ω 30 60 a in m 100 100 a in m 500 500 a in m 60 55 $U_S$ in kV 7.2 12 17.5 24 36 $a$ in m 45 12 9 13 7 $a$ in m 40 22 20 18 6 $a$ in m 60 15 13 11 11

Table 1: Maximum admissible distance $a$ between cable and transformer according to Figure 2 with distance $b = 0$. The cable is connected to a lightning endangered overhead line and protected on both ends with MO surge arresters. The values given are for systems with insulated star point.
The differences between overhead lines with wooden poles and overhead lines with earthed cross arms are due to the occurring different maximum steepness’s of the overvoltages in the two configurations. The surge impedance $Z_C$ of the cable has a remarkable influence on the protection distance, especially for higher system voltages. The influence of the surge impedance $Z_{OL}$ of the overhead line has lower influence on the protection distance.

3 Selection of the MO surge arresters (example for a system with $U_s = 12$ kV)

The MO surge arresters have to be selected as described in the Application Guidelines and the Application Notes 1.1.

The examples given below guide through the principle of the selection process step by step. Other system configurations are possible and have to be considered from case to case.

Depending on the expected stresses, electrical and environmental, and the importance of the equipment to be protected it is necessary to decide which characteristics of the MO surge arresters are most important to provide best protection. In this way the type of arrester (arrester class etc.) can be chosen from the beginning.

Supplied information
- Overvoltage protection of a substation in an overhead line system.
- Transformer connected via a cable.
- Medium pollution
- $U_s = 12$ kV
- Star point insulated

Without other specifications it is assumed
- Normal service conditions according IEC 60099-4 apply
- Maximum voltage for equipment $U_m = 12$ kV, $LIWV = 75$ kV
- Duration of earth fault > 30 min, i.e. continuous operation
- Nominal discharge current $I_n = 10$ kA
- Short circuit current of the system $I_s = 20$ kA
- Pollution class c $\Rightarrow 34.7$ mm/kV (minimum recommended specific creepage distance)

The transformer is connected via a cable to the lightning endangered overhead line. We decide to choose the type MWK, because of the very good (i.e. low) protection level. Especially for the protection of cables a low protection level is important.

3.1 Protection with two MO surge arresters of the same type and rating

Following the steps given in flow chart Application Note Annex 1.1 A1 it follows:

Step a) Continuous operating voltage $U_C$

According to Application Note 2.1 the continuous operating voltage is $U_C \geq U_s$

With a 10% safety margin for $U_C$ results

$$U_C = 1.1 \times U_s = 1.1 \times 12 \text{ kV} = 13.2 \text{ kV}$$

Thus it results an arrester with $U_C = 14$ kV

Step b) Rated voltage $U_r$

According data sheet the rated voltage is $U_r = 17.5$ kV

Step c) Nominal discharge current $I_n$

The chosen type MWK is of arrester class SL, with $I_n = 10$ kA

Step d) Charge $Q_{rs}$ and thermal rating $W_{th}$

According data sheet for the type MWK it follows

- Repetitive charge transfer rating $Q_{rs} = 1.6$ C, and
- Rated thermal energy $W_{th} = 6.25 \text{ kJ/kV}$

Step e) Check lightning impulse protection level $U_{pl}$ and withstand voltage $LIWV$

Required is:

$$U_{pl} \leq LIWV / K_s$$

With $LIWV = 75$ kV and $K_s = 1.15$, the maximum acceptable voltage for the equipment is 65.2 kV. The MWK 14 has an $U_{pl}$ of 43.0 kV and meets the demand with a good additional safety margin.

With the steps a) to e) the active part of the MO surge arrester is selected. It follows the selection of the arrester housing and confirmation of mechanical data.

Step f) Creepage distance

According the assumption of pollution class c (medium pollution) the minimum recommended specific creepage distance between phase and earth is 34.7 mm/kV.

Pollution effects on insulators or housings are long-term effects. In case of insulated systems a possible failure time in case of an earth fault of more than 30 min can be considered as continuous service. For this reason we calculate the needed creepage distance based on the continuous operating voltage $U_C$ of the MO surge arrester.
This results in a minimum recommended creep-age distance of \(14 \text{kV} \times 34.7 \text{mm/kV} = 486 \text{mm}\) for the MWK 14.

With a possible reduction of 20\% for silicone insulation (in case of medium pollution) we ultimately come to a creepage distance of 389 mm. The MWK 14 provides a creepage distance of 418 mm, which is sufficient in this application.

**Step g) Flashover distance**

The minimum necessary withstand values of the empty arrester housing are calculated according to IEC 60099-4, Ed. 3.0 and are listed in the data sheet for the type MWK.

The required value for the lightning voltage impulse \(1.2/50 \mu\text{s}\) is 56 kV peak, the guaranteed value according data sheet is 137 kV peak.

The required value for the a.c. voltage test is 26 kV rms, 1 min wet. The guaranteed value according data sheet is 58 kV rms, 1 min wet.

Therefore, the housing of the MWK 14 has much higher withstand values than required according to IEC 60099-4, Ed. 3.0.

**Step h) Short circuit current \(I_s\)**

The type MWK fulfills with a short circuit rating of \(I_s = 20 \text{kA}\) the requirement.

**Step i) Mechanical loads**

Special requirements for mechanical loads are not given. Therefore, no further considerations necessary.

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It follows: the MWK 14 is the right arrester from all points of view for this application and should be installed at both sides of the cable considering the above given guidelines.

In case of an incoming overvoltage both arresters A1 and A2 will discharge a part of the current towards the earth and will provide good overvoltage protection. However, due to slight variations in the voltage-current characteristics of the two arresters it is not to be assumed that the energy occurred will be uniformly shared.

**3.2 Protection with two MO surge arresters of the same type but different ratings**

MO surge arresters of the same type but with different characteristics that are matched to one another are used deliberately if an uneven sharing of the energy absorption is intended. This may be the case, for example, in stations in which the transformer is connected through a cable to the overhead line, as shown in Figure 1. An arrester is installed on the pole at the junction of the overhead line to the cable, and another arrester is installed in front of the transformer in the substation with a higher residual voltage characteristic.

The effect of such an arrester coordination is, that in case of a surge the largest part of the energy is absorbed by the arrester outside on the pole. The arrester in the substation has to discharge only a small part of the surge current and at the same time protects the transformer against overvoltages due to reflections in the substation. In practice, this principle can be used by choosing two MO surge arresters of the same type, such as MWK. The arrester in the substation should have a continuous operating voltage \(U_c\) of about 10\% higher than the arrester outside on the pole.

**3.2.1 Technical data of the MO surge arresters (example for a system with \(U_s = 12 \text{kV}\))**

The characteristics and the rating of the MO surge arrester A1 to be installed on the pole are the same as in the above example shown in section 3.1.

The MO surge arrester in the substation is of the same type, but with a 10\% higher continuous operating voltage. Thus, the continuous operating voltage should be \(U_c = 1.1 \times 14 \text{kV} = 15.4 \text{kV}\) and from the data sheet the type MWK 16 has to be taken.

Therefore, the data for the MO surge arrester in the substation are

**Step a)** \(U_c = 16 \text{kV}\)

**Step b)** \(U_r = 20 \text{kV}\)

All other data of the active part (steps c and d) are the same as for the MWK 14.

**Step e)** We have to check the lightning impulse protection level \(U_{pl}\) vs the withstand voltage (LIWV).

Required is:

\[ U_{pl} \leq \text{LIWV} / K_s \]
With $\text{LIWV} = 75 \text{ kV}$ and $K_s = 1.15$, the maximum acceptable voltage for the equipment is $65.2 \text{ kV}$. The MWK 16 has an $U_{pl} = 49.2 \text{ kV}$ and meets the demand with a good additional safety margin. It follows the verification of the arrester housing and confirmation of the mechanical data.

**Step f) Creepage distance**
The same assumptions as made for the MWK 14 apply.

The minimum recommended creepage distance is calculated to $16 \text{ kV} \times 34.7 \text{ mm/kV} = 556 \text{ mm}$. With a possible reduction of 20% for silicone insulation we ultimately come to a creepage distance of $445 \text{ mm}$. The MWK provides a creepage distance of $492 \text{ mm}$, which is above the recommended creepage distance and sufficient for this application.

**Step g) Flashover distance**
The minimum necessary withstand values of the empty arrester housing are calculated according to IEC 60099-4, Ed. 3.0 and are listed in the data sheet for the type MWK.

The required value for the lightning voltage impulse $1.2/50 \mu \text{s}$ is $64 \text{ kV peak}$, the guaranteed value according data sheet is $158 \text{ kV peak}$.

The required value for the a.c. voltage test is $30 \text{ kV rms}, 1 \text{ min wet}$. The guaranteed value according data sheet is $67 \text{ kV rms}, 1 \text{ min wet}$.

Therefore, the housing of the MWK 16 has much higher withstand values than required according to IEC 60099-4, Ed. 3.0.

For the short circuit current $I_s$ and the mechanical loads the same requirements as for the MWK 14 apply for the MWK 16. No further considerations are necessary.

It follows: the MWK 16 is the right arrester from all points of view for this application and should be installed in front of the transformer in the substation considering the above given general guidelines.

In case the substation is indoor an MO surge arrester A2 of type MWD 16 can be used alternatively for the installation in front of the transformer.

### 3.3 Protection with two MO surge arresters of different types

The same result as in 3.2 is reached if two MO surge arresters with the same continuous operating voltage $U_c$, but of different types are installed. The MO surge arrester on the pole is the same as in 3.1, a MWK 14, and the one in front of the transformer in the substation is, for example, a POLIM-D with $U_c = 14 \text{ kV}$.

Taking into consideration the smaller cross-section of the MO resistors of the POLIM-D compared to MWK, its residual voltage characteristic lies automatically higher than the one of the MWK.

#### 3.3.1 Technical data of the MO surge arresters (example for a system with $U_s = 12 \text{ kV}$)
The characteristics and the rating of the MO surge arrester A1 to be installed on the pole are the same as in the above examples shown in section 3.1 and 3.2, i.e. a MWK 14.

For installation in front of the transformer in the substation an MO surge arrester A2 of type POLIM-D 14 was selected.

With the same assumptions as under 3 the technical data for the POLIM-D are:

- **Step a) Continuous operating voltage $U_c = 14 \text{ kV}$**
- **Step b) Rated voltage $U_r = 17.5 \text{ kV}$**
- **Step c) Nominal discharge current $I_n$**
The chosen type POLIM-D is of arrester class DH (distribution high), with $I_n = 10 \text{ kA}$.
- **Step d) Charge transfer rating $Q_{rs}$ and thermal charge transfer rating $Q_{th}$**

According data sheet for the type POLIM-D it follows:
- Repetitive charge transfer rating $Q_{rs} = 0.5 \text{ C}$
- Repetitive thermal charge transfer rating $Q_{th} = 1.1 \text{ C}$

- **Step e) Check lightning impulse protection level $U_{pl}$ and withstand voltage LIWV**

Required is: $U_{pl} \leq \text{LIWV} / K_s$

With $\text{LIWV} = 75 \text{ kV}$ and $K_s = 1.15$, the maximum acceptable voltage for the equipment is $65.2 \text{ kV}$. The POLIM-D 14 has an $U_{pl}$ of $49 \text{ kV}$ and meets the demand with good additional safety margin.

With the steps a) to e) the technical data of the active part is given.

It follows the selection of the arrester housing and confirmation of mechanical data.
Step f) Creepage distance
The same assumptions as above apply. This results in a minimum recommended creep-age distance of \(14 \text{kV} \times 34.7 \text{mm/kV} = 486 \text{mm}\) for the POLIM-D 14. With a possible reduction of 20% for silicone insulation (in case of medium pollution) we ultimately come to a creepage distance of 389 mm. The POLIM-D 14-05 provides a creepage distance of 460 mm, which is sufficient in this application. This means that we have to choose a POLIM-D 14 (fulfilling the electrical data) with a housing size 05 according data sheet to meet the requirements for the housing.

Step g) Flashover distance
The minimum necessary withstand values of the empty arrester housing are calculated according to IEC 60099-4, Ed. 3.0 as:

Lightning voltage impulse 1.2/50 μs:
\[1.3 \times U_p = 1.3 \times 49.0 \text{kV} = 63.7 \text{kV}\]

a.c. voltage test 1 min., wet:
\[1.06 \times U_{ps} \text{(switching current impulse 500 A => } U_{ps} = 38.8 \text{kV) => } U_{test, pv} = 41.2 \text{kV, pv}\]

This results in a withstand value of \(41.2 \text{kV} / \sqrt{2} = 29 \text{kV, rms, 1 min. wet.}\)

The proved withstand values according to the data-sheet are: Lightning discharge voltage 1.2/50 μs: 140 kV, a.c. voltage test: 38 kV, rms, 1 min. wet.

Therefore, the housing of POLIM-D 14-05 has higher withstand values than are required according to IEC.

Step h) Short circuit current \(I_s\)
The type POLIM-D 14-05 fulfills with a short circuit rating of \(I_s = 20 \text{kA}\) the requirement.

Step i) Mechanical loads
Special requirements for mechanical loads are not given. Therefore, no further considerations necessary.

It follows: the POLIM-D 14-05 is the right arrester from all points of view for this application. The overvoltage protection concept in this case is to install an MO surge arrester type MWK 14 on the pole at the cable entrance, and an MO surge arrester type POLIM-D 14-05 in the substation in front of the transformer.

Table 2 summarizes the main electrical data of the selected MO surge arresters for the three protection concepts given above. It is worth noting that the protection levels \(U_p\) of the two MO surge arresters MWK 16 and POLIM-D 14-05 is almost the same. For this reason protection concept acc. chapter 3.3 offers the best technical/economical solution.

It ensures, that in case of a surge most of the charge will be directly conducted to earth by the A1-arrester outside the substation. Further, in case of an overload due to an unexpected high charge or impulse current the MO surge arrester outside the substation on the pole will be overloaded, protecting even then the cable and the transformer in the substation.

### Table 2: Main technical data of the selected MO surge arresters for the three protection concepts. The selection for the MO surge arresters at locations A1 and A2 is made for a system with \(U_s = 12 \text{kV}\) and insulated (open) star point.

<table>
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<tr>
<th>Arrester data In</th>
<th>Protection concept acc. 3.1</th>
<th>Protection concept acc. 3.2</th>
<th>Protection concept acc. 3.3</th>
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<td>14 kV</td>
<td>14 kV</td>
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<tr>
<td>(U_r)</td>
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<tr>
<td>(W_{th})</td>
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