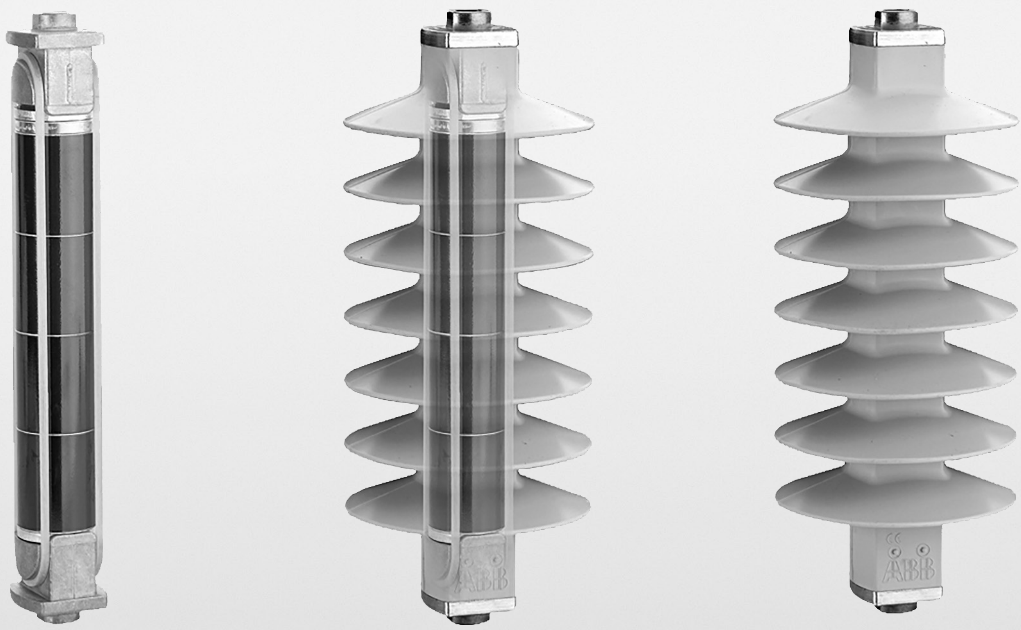
APPLICATION NOTE 1.3

Arresters between phases

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 between phases

Arresters are typically installed phase to earth. In some specific cases it may be necessary to install additional MO surge arresters between the phases as well.

1 Introduction

The MO surge arresters are typically installed phase to earth at each terminal. As can be seen in **Figure 1** the windings of e.g. a transformer are protected by two arresters in series via their earth connection. However, the sum of the continuous operating voltage U_C of two phase to earth arresters will be all the time higher than the system voltage U_S (phase-to-phase voltage). Further, due to the length of the connections and the impedance Z_E between two earthing points, additional voltage drops U_i may occur. Overvoltages between the phases are therefore not limited sufficiently by the phase-to-earth arresters. This is especially true for transformer windings in delta-connection. Consequently additional MO surge arresters between the phases are required.

Overvoltages between phases can result from switching surges, lightning surges, or from backflashover caused by a lightning to a pole.

Switching surges (slow-front overvoltages):
High phase-to-phase overvoltages may occur due to capacitor bank switching or misoperation of capacitor switching devices. Considerable overvoltages between phases may also occur when a reactor or reactive loaded transformer is switched off.

Lightning surges (fast-front overvoltages):
High overvoltages can occur due to lightning strikes in a phase conductor of transmission lines. Induced voltages in neighbor phases and reflection phenomena on the lines may lead to unacceptable high overvoltages between phases.

Surge transfer through transformer windings (resonances):
Lightning surges entering a transformer terminal can excite the natural frequency of transformer windings resulting in high overvoltages between the phases.
For transformers with a delta-connected low-voltage winding, arresters between phases may be also necessary on the low-voltage side to limit inductively transferred overvoltages. These arresters can also protect the medium-voltage side of the transformer by absorbing the magnetic energy when switching off transformers.

Two different arrangements can be used when overvoltage protection between phase-to-earth and phase-to-phase is required, the “six-arrester arrangement” and the “four-arrester arrangement”.

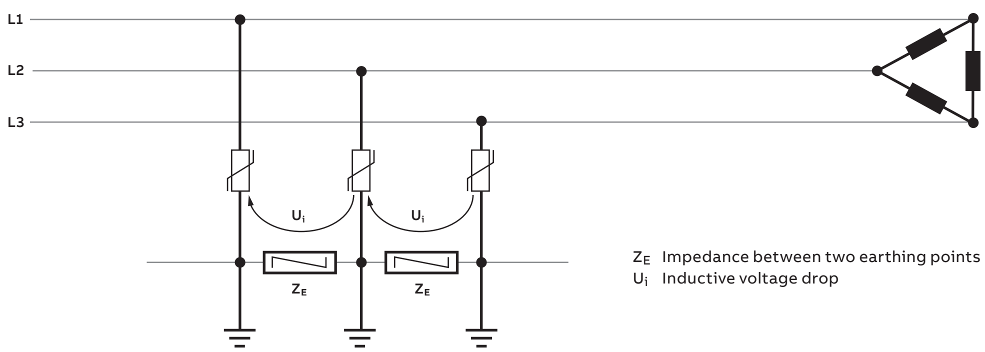


Figure 1: Principle arrangement of MO surge arresters

Z_E Impedance between two earthing points
U_i Inductive voltage drop

2 Six-arrester arrangement

The continuous operating voltage U_C of the phase-to-earth MO surge arresters depends on the earthing of the transformer neutral.

2.1 System with insulated star point or delta-connection of the transformer windings

A typical arrangement for systems with insulated transformer neutral or a transformer with delta-connection of the windings is given in **Figure 2**. In this case all six arresters should be of the same type and rating and have the same continuous operating voltage of

$U_C \geq 1.05 \times U_S$

The factor 1.05 takes account of possible harmonics in the system voltage U_S.

The same equation is valid for transformers in delta connection.

2.2 Directly earthed system

In case of a system with low-ohmic star point earthing (directly earthed, see **Figure 3**) of the transformer the continuous operating voltage can be chosen to

$U_C \geq 1.05 \times U_S$

for the arresters **between phases**

$U_C \geq (1.05 \times U_S) / \sqrt{3}$

for the arresters **between phase to earth**

Note: All MO surge arresters should be of the same type and arrester class.

Figure 2: Six-arrester arrangement. All six arresters have the same continuous operating voltage U_C.

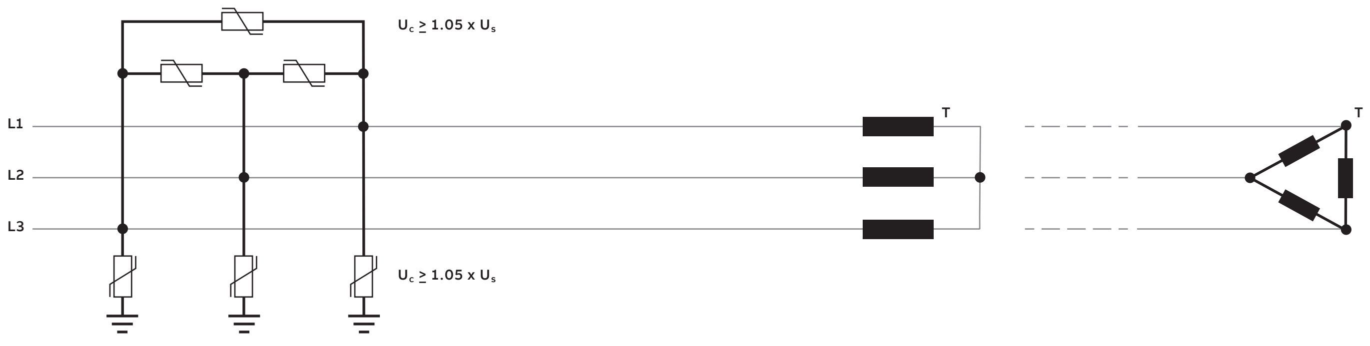
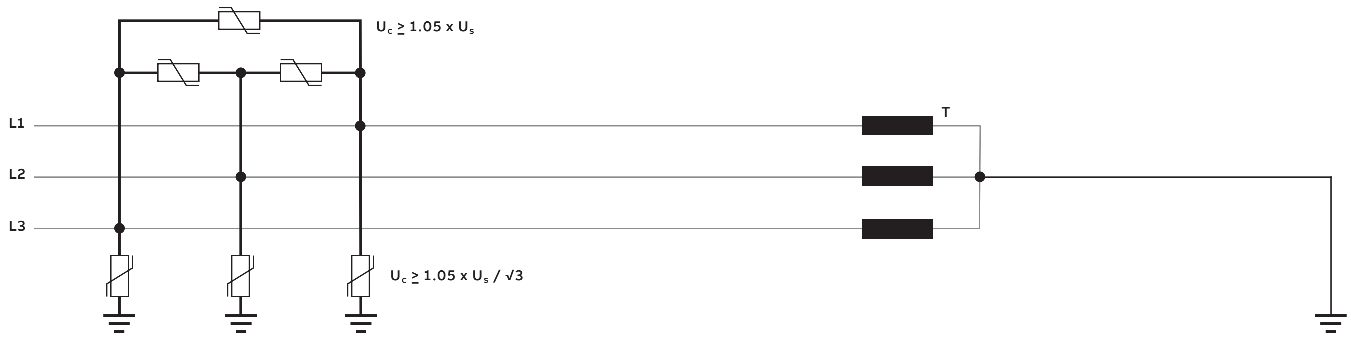


Figure 3: Six-arrester arrangement for overvoltage protection between phases and phase to earth. The star-point is directly earthed.



3 Four-arrester arrangements

A variation of the six-arrester arrangement is the “Neptune” (or “candle”) design, because of its arrangement of the arresters. This arrangement with four arresters is also called “four-legged surge arrester arrangement”. In any case all arresters should be of the same type and arrester class.

3.1 Arrangement with four identical MO surge arresters

It consists of four similar arresters. Two arresters in series are fitted between the phases and the earth and also between the phases, as shown in **Figure 4**.

This arrangement permits overvoltage protection both between the phases and phase-to-earth. This kind of arrangement however, has a fundamental disadvantage in comparison to the six-arrester arrangement. The arresters behave in a capacitive manner at continuous operating voltage. In case of an earth fault in the system, all four arresters form an unsymmetrical system. In the case where each arrester has identical capacitance (meaning that the arresters are all of the same type with identical ratings), arresters A1 to A3 would be stressed with

$0.661 \times U_S$ and A4 with $0.433 \times U_S$.

It follows for the arrangement with four identical MO surge arresters a continuous operating voltage

$U_C \geq 0.661 \times U_S$
for all four arresters

The protection level of this arrangement, which has all the time two arrester in series, is therefore similar to one offered by an arresters with $U_C \geq 1.322\ U_S$. The residual voltage of this arrester is therefore 26 % higher than that of the six-arrester arrangement. In case the continuous operating voltage in case of the six-arrester arrangement is calculated to $U_C \geq U_S$, the residual voltage U_{pl} would be even 32 % higher for the four-arrester arrangement.

3.2 Arrangement with three identical MO arresters and one with lower U_C

If a lower protection level is required between phase and earth, a lower continuous operating voltage for arrester A4 may be chosen compared to the arresters A1 to A3. In this case another capacitive ratio has to be considered, and a detailed calculation may be necessary. Since the arrester capacitance is inversely proportional to the arrester U_C, the final steady-state voltages need to be calculated iteratively for each specific case. In case of detailed calculations not only the influence of the capacitances of the MO surge arresters has to be considered, but also the phase shift between the phase to neutral voltages and the neutral to earth voltage.

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Figure 4: Neptune design with four similar arresters (A1 to A4), each with $U_C \geq 0.661 \times U_S$.

A simplified selection procedure for the continuous operating voltages of the phase to neutral and neutral to earth MO surge arresters is as follows, see **Figure 5**. During normal symmetrical system conditions, the voltage on the neutral surge arrester A4 is zero, and the phase to neutral arresters (A1 to A3) are stressed with the phase to earth voltage, which is $U_S/\sqrt{3}$. The voltage of the neutral arrester A4 should be selected such that the sum of the phase to neutral (e.g. A3) and neutral to earth arrester (A4) voltages meet the same requirements as a standard MO surge arrester phase to earth. The following shows the principle of selection for an isolated (open) system. For transformers with delta-connected windings the same applies.

The phase to neutral (or earth) voltage is $U_{L\text{-}N} = U_S / \sqrt{3}$ in an undisturbed system.

The voltage neutral to earth is $U_{N\text{-}E} = U_S - U_{L\text{-}N}$

For the continuous operating voltages follows:

$$U_C \geq U_{L\text{-}N} = \frac{1.05 \times U_S}{\sqrt{3}}$$

for the MO surge arresters A1 to A3 **between phase and neutral, and**

$$U_C \geq U_{N\text{-}E} = 1.05 \times U_S - \frac{1.05 \times U_S}{\sqrt{3}} = 0.444 \times U_S$$

for the MO surge arrester A4 **between neutral and earth.**

The factor 1.05 takes account of possible harmonics in the system voltage U_S.

These simplified formulas are based only on the system voltage, disregarding the capacitance ratios of the MO surge arresters and the phase angle between the voltages. However, for practical reasons they can be used as rules of thumb and give reliable results.

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Note: As always, the arresters must also withstand the TOV conditions that unfaulted phases will see during a phase-to-earth fault.

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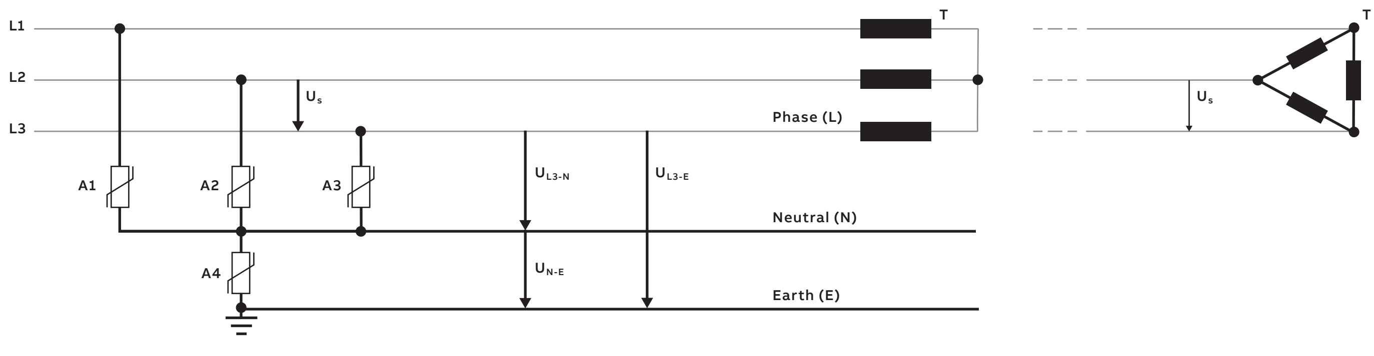
Figure 5: Neptune design with three similar arresters and one with lower U_C



4 Summary

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Table 1: Continuous operating voltage U_c for the three different possibilities of arrester application between phases.

Arrester arrangement	six-arrester arrangement	four-arrester arrangement	four-arrester arrangement
	All six arresters have identical ratings.	All four arresters have identical ratings.	Three arresters with identical ratings, one with lower U_c.
Equation for U_c	$U_c \geq 1.05 \times U_s$	$U_c \geq 0.661 \times U_s$ (total $U_c \geq 1.322 \times U_s$)	$U_c \geq 1.05 \times U_s / \sqrt{3}$, L-N $U_c \geq 0.444 \times U_s$, N-E

Comparing the three arrangements discussed above for transformers with insulated star point or delta-connected windings, the following conclusions can be drawn.

Six-arrester arrangement
The continuous operating voltage for all six arresters is the same:

$U_c \geq 1.05 \times U_s$
for the arresters **phase-to-phase**

$U_c \geq 1.05 \times U_s$
for the arresters **phase-to-earth**

Four-arrester arrangement
Three identical arresters and one with lower U_c
The continuous operating voltage between the phases is

$U_c \geq 1.23 \times U_s$
for the arresters **phase-to-phase**

The residual voltage U_{pl} between the phases of this arrester arrangement is 16 % higher than that of the six-arrester arrangement.

$U_c \geq 1.05 \times U_s$
for the arresters **phase-to-earth**

Four identical arresters
$U_c \geq 1.32 \times U_s$
for the arresters **phase-to-phase**

$U_c \geq 1.32 \times U_s$
for the arresters **phase-to-earth**

The residual voltage U_{pl} between the phases and phase-to-earth of this arrester arrangement is 26% higher than that of the six-arrester arrangement.

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