NEW CONCEPT FOR THE PROTECTION AGAINST LIGHTNING OVERVOLTAGES AND TOUCH VOLTAGES

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INTRODUCTION

Overvoltages in electrical supply networks of AC and DC railway networks result from the effects of lightning strokes and switching actions and cannot be avoided. Furthermore, the power supply of electrical railways is endangered by direct or nearby lightning. Considering additional the safety aspects for people (touch voltages) in railway systems, one has to deal with three aspects: direct or nearby lightning, induced voltages, and unacceptable voltages due to failures in the system (e.g. breaking of overhead line). Depending on the insulation of the rails against earth, different aspects have to be considered for a general protection concept. A new device, combining protection against overvoltages and touch voltages is introduced.

VOLTAGES IN RAILWAY SYSTEMS

System voltages

The supply voltages for railway networks are given in the European Standard EN 50 163: Railway applications – Supply voltages of traction systems. In the following some definitions and values are given, which are necessary for the dimensioning of the MO-surge arresters and the protection concept in general.

Nominal voltage $U_n$: the designated value for a system.

Highest permanent voltage $U_{\text{max}1}$: the maximum value of the voltage likely to be present indefinitely.

Highest non-permanent voltage $U_{\text{max}2}$: the maximum value of the voltage likely to be present for maximum of 5 min.

Table 1 gives the voltage values for the relevant DC and AC systems.

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\begin{array}{|c|c|c|}
\hline
U_n \text{ in V, DC} & U_{\text{max}1} \text{ in V, DC} & U_{\text{max}2} \text{ in V, DC} \\
\hline
600 & 720 & 770 \\
750 & 900 & 950 \\
1500 & 1800 & 1950 \\
3000 & 3600 & 3900 \\
U_n \text{ in V, AC} & U_{\text{max}1} \text{ in V, AC} & U_{\text{max}2} \text{ in V, AC} \\
15000 & 17250 & 18000 \\
25000 & 27500 & 29000 \\
\hline
\end{array}
\]

Table 1: Voltages in railway electrification systems. The values for $U_{\text{max}2}$ can become 800 V in the 600 V system, and 1000 V in the 750 V system in case of regenerative breaking.

The AC values are given in rms values. The system with $U_n=15$ kV has a power frequency of $f=16.7$ Hz, the system with $U_n=25$ kV a power frequency of $f=50$ Hz.

Overvoltages

Typical peak values of lightning currents are in the range of 10 kA to 100 kA with a rise time of 1 µs to 10 µs. The charge on an overhead line due to direct lightning travels along the line in the form of two equal current waves in both directions. Considering a typical surge impedance of $Z=400 \, \Omega$ for overhead lines, an overvoltage of 10 MV will occur, if a current peak of 50 kA for the lightning current is considered. The overvoltage wave will lead to flashovers on one or more insulators and reduce the voltage to the withstand value of the insulators. Depending on the type of insulator and the earthing conditions of the pole this voltage can still reach values up to the MV range.

Lightning strokes in the vicinity of the lines can induce overvoltages. The induced voltages can be calculated with the approximation according to Rusk to $U=Z_0 \times I \times H/D$.

With $I=50$ kA, $Z_0=30 \, \Omega$ being the surge impedance between the point of stroke and the line, the distance $D=100$ m and the height $H=5$ m a voltage peak of 75 kV results.

No electrical equipment in railway systems can be insulated against such overvoltages in an economical way. The voltages have to be reduced to a non-dangerous value for the insulation.

The most effective protection against overvoltages is the use of gapless MO-surge arresters in the vicinity of the electrical equipment.

Touch voltages

In DC railway systems stray currents are flowing in the ground from the rails to other metallic structures (e.g. drainpipes, bridges, metallic fences, etc.). This stray currents lead to corrosion and a remarkable excavation of the metal. To avoid this problem the rails are normally insulated against the surrounding earth. But this may lead to unacceptable potential rises and too high touch voltages of the rails due to normal train service, and especially in case of failures like broken overhead lines or derailed pantographs. This leads to endangering of persons and has to be avoided by the use of low voltage limiters.

PROTECTION CONCEPT

A protection concept for railway systems, especially for DC systems, has to consider the protection of equipment (against overvoltages) and the protection of persons (against touch voltages) in the same time. Of great importance is the safety
aspect in public places, as for instances train stations, rail crossings, etc.. Based on the VDV publication 525 [1] a protection concept for DC railway systems is discussed which considers the overvoltage protection of the supply lines against the return line (generally the rail) and the protection of the return line against the station earth. The protection against touch voltages is included in this concept.

**MO surge arresters and low voltage limiters**

**MO surge arresters.** When designing arresters for different network voltages, three main characteristics are to be considered: the highest continuous voltage that arises in the network, the protection level, and the energy absorption capability of the arrester. The strong voltage fluctuations in the railway systems make it necessary to lay the maximum continuous operating voltage $U_n$ of the MO-arrester above the highest continuous voltage $U_{max}$ of the system. The highest non-permanent voltage $U_{max}$ of the system can appear for 5 min, but it is not known how often and in which time intervals this can happen. As long as the modern MO-surge arresters have very favourable protection levels combined with a high energy absorption capability, it is possible to lay the MO-arresters continuous operating voltage $U_n$ equal or higher to $U_{max}$, so that follows $U_n \geq U_{max}$.

It follows for the system voltages acc. to Table 1:

- $U_n = 600 \, \text{V} \Rightarrow U_p \geq 800 \, \text{V}$
- $U_n = 750 \, \text{V} \Rightarrow U_p \geq 1000 \, \text{V}$
- $U_n = 1500 \, \text{V} \Rightarrow U_p \geq 1950 \, \text{V}$
- $U_n = 3000 \, \text{V} \Rightarrow U_p \geq 3900 \, \text{V}$
- $U_n = 15 \, \text{kV} \Rightarrow U_p \geq 18 \, \text{kV}$
- $U_n = 25 \, \text{kV} \Rightarrow U_p \geq 29 \, \text{kV}$

**AC networks with 15 kV, 16.7 Hz.** With the SBB and other Swiss Railways MO surge arresters with $U_n=18 \, \text{kV}$ are used on electrical locomotives and in overhead lines. Due to safety aspects completely in silicon moulded MO surge arresters with line discharge class 3 are used for the overhead lines, and line discharge class 4 for the use on locomotives. The German DB adopted a coordination concept with the locomotive BRE 101, which is used in the interregional trains, and installs on the roof of the locomotive a MO surge arrester with $U_n=18 \, \text{kV}$ and in the locomotive one with $U_n=20 \, \text{kV}$. Again, the arrester on the roof of the locomotive is of line discharge class 4, the one in the locomotive has a lower line discharge class.

**AC networks with 25 kV, 50 Hz.** MO surge arresters with $U_n=29 \, \text{kV}$ to $U_n=31 \, \text{kV}$ are used in the High Speed Railways Systems. With modern E-locomotives the high voltage from the collector is brought into the inner part of the locomotive through a cable, and this requires again a coordination of the MO arresters on the locomotive and in the locomotive. On the roof of the locomotive are two arresters with $U_n=29 \, \text{kV}$ and line discharge class 4 are installed, at each pantograph one, and in the locomotive an arrester with $U_n=31 \, \text{kV}$ and a lower line discharge class in front of the main power breaker.

**DC networks of 600 V and 750 V.** In [1] a protection concept for DC railway systems with a nominal voltage $U_n=600 \, \text{V}$ and $U_n=750 \, \text{V}$, and the requirements for MO-surge arresters to be used, are proposed. The protection concept defines two arresters according to their place of installation and their application, a type A1, between the overhead line, or the feeder-line, and the return line (may be the rail), and type A2 between the return line (rail) and the so called station earth (equipotential bar). The details of this concept are given in the following chapters.

**Requirements on A1-arresters:**
- Maximum continuous operating voltage $U_n \geq 1.0 \, \text{kV}$
- Protection level $U_p \leq 3.0 \, \text{kV}$
- Nominal current $I_n(8/20 \, \mu \text{s}) \geq 10 \, \text{kA}$
- Rectangular current, 2 ms $I_{1n} \geq 1200 \, \text{A}$
- Short circuit current $\geq 20 \, \text{kA}$

**Requirements on A2-arresters:**
- Maximum continuous operating voltage $120 \, \text{V} \leq U_n \leq 300 \, \text{V}$
- Protection level $360 \, \text{V} \leq U_p \leq 900 \, \text{V}$
- Nominal current $I_n(8/20 \, \mu \text{s}) \geq 10 \, \text{kA}$
- Rectangular current, 2 ms $I_{1n} \geq 1200 \, \text{A}$
- Short circuit current $\geq 20 \, \text{kA}$

The ratio $U_p/U_n$ can be chosen $\leq 3$, as long as the thermal stability of the MO-arrester in the system is not endangered. A ratio $U_p/U_n > 3$ is not acceptable.

Most of the modern MO-surge arresters on the market to be used as A1-arresters have a lower protection level than the here proposed 3,0 kV, for instance $U_p=2,4 \, \text{kV}$. It should be taken advantage of the better protection level when choosing an A1-arrester. Figure 1 shows examples of A1- and A2-arresters.
overhead line (falling down of the conductor) an unacceptable high touch voltage may occur. Normal train service may also produce a voltage rise of unacceptable height. In such cases personal protection is given by the use of low voltage limiters (LVL). As long as low voltage limiters, installed along the rails, may be stressed by lightning and overvoltages due to lightning, they have to withstand and protect against both, unacceptable touch voltages and overvoltages.

For this reason a new device was developed, the hybrid voltage limiter HVL. The HVL combines the required personal protection against touch voltages with the protection of electrical equipment against lightning overvoltages. The HVL contains a metal oxide (MO)-resistor in parallel to two anti-parallel connected thyristors. The MO-resistor has the function of a surge arrester and limits lightning and switching overvoltages, the thyristors short circuit potential rises of the rail and provide the protection against dangerous touch voltages.

The MO-resistor in the HVL has the same diameter and the same electrical characteristics as the MO-resistor in the A1-arrester. Therefore, by combining an A1-arrester with a HVL an optimised protection can be realised. This protection concept can be used in overhead lines and in substations as well, just by replacing the A2-arrester by a HVL. Figure 2 shows a HVL with accessories.

Protection measures

In [1] a protection concept for DC railway systems with \( U_n = 600 \) V and 750 V is proposed, as already mentioned. This concept considers the protection of overhead lines and substations.

Protection measures on the overhead lines. It is recommended to install gapless MO-surge arresters for outdoor use at each service entrance, at the end of feeding sections, and at the coupling point as well as at points of power demand (e.g. for point heaters). For track sections with frequent lightning strokes, for instance at bridges or free overland routes additional arresters are advisable. This arresters are called A1-arresters and should fulfil the electrical requirements as given above. Figure 3 shows the principle arrangement.

The arresters should be installed at the level of the overhead line and connected in the shortest possible way with insulated conductors. In case the rails are isolated against earth in open ballast (to avoid stray currents) it is recommended to connect the A1-arrester to a separate earth connection with a resistance less or equal than 10 \( \Omega \).

In case the rails are in closed ballast not isolated against the earth, the A1-arrester is to be connected via an insulated connector directly to the rail. Figure 4 shows the two possibilities.

In the very rare cases of an overload of the A1-arrester a current of some 10 A would flow against earth, which would be not detected as a failure current by the protection relays in case of isolated rails (open ballast). The remaining potential on the pole may lead to touch voltages of unacceptable height. The remaining of the failure voltage can be avoided with the installation of a second MO-surge arrester. It is proposed to install a second MO-surge arrester, a type A2-arrester as used in the substations, between the earthing terminal and the rail. A low voltage limiter could be used alternatively to the A2-arrester, as it is shown in Figure 5.

It has to be pointed out, that the installation of a hybrid voltage limiter HVL is the better solution in all respects.
Due to the limited protection distance of surge arresters an arrester is protecting only a distance of some meters. This means that the arresters generally have to be as close as possible to the equipment they have to protect. The connections should be as straight and short as possible.

Figure 5: Connection of an A2-arrester, or alternatively a hybrid voltage limiter, between the earth terminal and the rail in case of isolated rails.

b: insulated cable.

Protection measures for substations. Arresters installed along the track can protect only the equipment in the vicinity, and not electronic or other equipment in the substations. For the protection of the DC-substations it is proposed to install A1-arresters directly at the breakers in the substation between the feeder line and the return line (rail). Additional an A2-arrester should be installed between the return line (rail) and the equipotential bonding bar. The A2-arrester reduces overvoltages travelling along the rail, originated by lightning, and protects against potential rise of the rail against the earth of the building. The use of A1- and A2-arresters in the substations is nowadays essential, because electronics are more and more used. Nowadays A1- and A2-arresters are on the market, which are adapted to the special requirements of DC railway systems. Figure 6 shows the principle of the substation protection.

Alternative to the A2-arresters hybrid voltage limiters can be installed as well. This should be done in general, if, besides the overvoltage protection, personal protection against touch voltages is required.

Protection of traction vehicles. It is state of the art to protect the cable bushings and the equipment downstream with MO-surge arresters of type A1. The arresters are installed on the roof of the traction vehicles and directly connected to the pantograph. The arresters have to fulfil the same requirements as the A1-arresters on the poles of the overhead lines. Special mechanical requirements as shock and vibration resistance have to be fulfilled in addition. Safety aspects, as explosion resistant design and the use of inflammable materials have to be considered.

TESTS AND FIELD EXPERIENCE

Three categories of tests have to be considered. First the electrical tests. Besides the type tests, specified in the arrester standard IEC 60099-4 and the standard for surge arresters and low-voltage limiters in DC railway applications EN 50123-5.

special tests proving the energy withstand capability had to be performed. As long as the arresters as well as the hybrid voltage limiter may be subject to direct or nearby lightning tests with the lightning current impulse with a wave shape of 10/350 µs were performed.

In the second category are the mechanical and material tests. Very high safety requirements have to be considered. Third and finally the long term performance under severe pollution has to be proved.

The protection concept with coordinated MO-surge arresters and the combination with hybrid voltage limiters is introduced successfully in DC railway systems with Un=750 V. Test installations are running in the 1500 V system of the SNCF in France, and MO-arresters as well as hybrid voltage limiters for special applications in the 3000 V systems will be installed soon.

OUTLOOK

Modern MO-surge arresters with silicon housing have been adapted to the special requirements in AC and DC railway systems. The installation of AC and DC MO-surge arresters in substations, overhead lines and on locomotives is state of the art and worldwide practise. Coordination concepts and newly developed hybrid voltage limiters allow new protection concepts, covering the protection of equipment and of
persons in the same time. It is necessary to introduce new test procedures to cover the special demands for railway systems.

REFERENCES