APPLICATION GUIDELINES

OVERVOLTAGE PROTECTION

Dimensioning, testing and application of metal oxide surge arresters in railway facilities

ABB

Foreword

The overvoltage protection of the electrical energy supply installations of railway facilities holds increasing importance nowadays. This is not only the railways which are supplied with a. c. voltage but also increasingly by the d. c. voltage railways.
The standard-gauge railway is electrified with 3 kV d. c. voltage on over 70 000 km rails (that means about 38 % of the total length of the rails of the electrical railways) and with 1,5 kV d. c. voltage on more than 20 000 km (about 11%). That means that about half of the world-wide railway length of the long-distance traffic is operated with direct-current. The length of the electrified rails by the outer suburban service, including local trains, which operate with a d. c. voltage under 1000 V, is about 25 000 km. These figures show the extent of the d. c. voltage systems by railways and also the importance of an optimal overvoltage protection which is adjusted to the specific demands of the d. c. voltage railways.

The application and dimensioning of metal oxide surge arresters (MO-surge arresters) in alternating current networks with 50 Hz and 16 $^{2}/_{3}$ Hz of the railway supply is not very different from the one of the general energy supply. On the other hand the dimensioning and the load of the MO-surge arresters in direct-current railway facilities have not been extensively dealt with until now. Moreover the modern MO-surge arresters without spark-gaps and with silicon insulation make it possible to develop solutions for special applications.

Mr. Bernhard Richter, responsible for engineering and application of the overvoltage protective devices in the surge arrester division of ABB High Voltage Technologies Ltd, gladly presents in precise and clear form the technical bases of the MO-surge arresters and their application in railway facilities. Mr. Richter is an active member in different working groups of IEC SC 37 A and TC 81, and his activity field includes mainly the development, testing and the application of the surge arresters.

We hope, that you as a reader will find a lot of useful information in this booklet. We welcome amendments, suggestions and qualified hints, which may help us to cover all the demands of the customers.

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1 Introduction

Overvoltages in electrical supply networks result from the effects of lightning strokes and switching actions and therefore cannot be avoided. They endanger the electrical equipment, and due to economical reasons, their insulation capability cannot be designed for all possible cases. Therefore a more economical and safer on-line network calls for extensive protection of the electrical equipment against unacceptable overvoltage loads. On principle this applies to all networks of the energy supply.

We will not present here the different kinds of overvoltage and the possibilities of reducing them. For general information you may use the APPLICATION GUIDELINES: Dimensioning, testing and application of metal oxide surge arresters in medium voltage networks [1].

We want only to mention here that lightning strokes are the most dangerous threat for railway networks. That is why it is necessary to reduce the overvoltage to a safe value through appropriate protection. MO-surge arresters without spark-gaps give outstanding protection in this situation.

2 Surge arrester technology

The so-called "conventional" surge arresters were almost exclusively installed in networks of the electrical energy supply up to the middle of the eighth decade of the last century. They consisted of an active part (a series connection of SiC-resistors and plate spark-gaps) which was inserted in a porcelain housing.

In the last years there were two fundamental improvements in the surge arrester technology. First, the series connection of SiC-resistors and the plate spark-gaps were replaced by the metal oxid resistors (MO-resistors) [2] without plate spark-gaps, secondly the porcelain housing was replaced by others made of polymer material, in case of ABB surge arresters the material is silicon.

2.1 MO-surge arresters and spark-gap arresters

A fundamental advantage of the MO-arresters is that, due to their extremely non-linear characteristic of the MO-resistors, they do not need any spark-gaps [3]. The current starts to flow through the arrester when the voltage is considerable lower than with spark-gap arresters, and therefore it is possible to limit the voltage much earlier. This affords better protection and longer protection distance of the MO-arrester. Furthermore, an overvoltage by-pass cannot occur as with spark-gap arresters.

If the outside insulation of the arrester is very polluted, the potential distribution can shift along the active part, and this can cause unwanted spark-over in the spark-gap arresters, which in the end may destroy the arrester. MO-arresters without spark-gaps have a fundamentally higher pollution resistance. This fact is especially important for higher system voltages, because the longer an arrester is the more important is a uniform potential distribution along the active part.

If more spark-gap arresters are connected in parallel usually only one arrester switches on during an overvoltage, thus reducing the overvoltage to a value below that of the sparking voltage of the other parallel arresters. Therefore it is not possible to distribute the energy of the surge among more spark-gap arresters which are connected in parallel.

With MO-arresters without spark-gaps all the parallel MO-columns conduct current at the same time, distributing the energy so that the energy capacity as a limiting parameter disappears. The MO-arresters do not conduct any follow current like the spark-gap arresters, and therefore they can be used both with 50 Hz and with 16 $^2/_3$ Hz. In the spark-gap arresters the follow current flows three times longer with 16 $^2/_3$ Hz than with 50 Hz, which overloads the spark-gap arrester, (with constant voltage). In the past, spark-gap arresters, which were used in networks of 16 $^2/_3$ Hz, had an inconvenient higher voltage than the arresters of 50 Hz, and implicitly a worse protection level.

This is the reason why MO-arresters can be used without any problem even in direct current networks; because there is no necessity of extinguishing a d. c. arc.

2.2 Metal oxide resistors as arrester elements

The MO-resistors make up the active part of the MO-arrester. The MO-resistors are compressed and sintered in the form of round blocks out of different metal oxides in powder form. The diameters of the MO-resistors of ABB High Voltage Technologies Ltd., made for all the networks of the electrical energy supply and for special applications, lie between 38 mm and 108 mm. The height of the blocks is typically between 1 mm and 46 mm. The diameter of the MO-resistors decides the carrying capacity of the current, the height of the MO-resistors (or resistor stack) decides the voltage in continuous operation, and the volume of the blocks the energy capacity.

The diameter of the MO-resistors correlate with the line discharge classes corresponding to IEC 60099-4, as shown in Table 1 [4]. As the IEC specification 60099-4 is only for a. c. systems higher than 3 kV rated, the tests and demands which are mentioned here, are for lower system voltages and especially for d. c. voltage networks only partly applicable. The standard IEC 61643-1 deals with surge protective devices (spd) for the electrical energy supply of a. c. voltage networks rated up to 1000 V and d. c. voltage networks rated up to 1500 V [5]. Demands and testing for the overvoltage protection equipment for the d. c. voltage applications are still under consideration.

Line discharge class acc. to IEC 60099-4	**1**	**2**	**3**	**4**	**5**
Diameter of MO-blocks in mm	38 / 42	47	62	75	96 / 108
Rectangular wave, 2 ms, in A	250 / 350	550	1000	1350	2000
Energy absorbtion in kJ / kV_{Uc}	3,6 / 3,5	5,5	9,0	13,3	19,8

Table 1

Correlation of the typical MO-resistors with the line discharge classes acc. to IEC 60099-4.

The given energy relates to the operating duty test, and is the energy injected in the arrester before the prove of the thermal stability of the arrester under applied continuous operating voltage.

The contact areas of the MO-resistors are metallized up to the edge of the block with soft aluminium, the surface of the housing is with glass passivated, resulting in complete coverage of MO-material of ABB High Voltage Technologies MO-resistors. Figure 1 shows a selection of MO-resistors.

Figure 1
MO-resistors (selection) produced by ABB

Figure 2

Above: the transition from the MO-arrester type MDA with porcelain insulator to the modern type POLIM-H…ND with silicon housing, both of them for application in d. c. voltage networks.

Down: the transition from the MO-arrester MVR with PUR-moulding to the modern type POLIM-C with silicon housing, for application in d. c. and a. c. voltage networks, and for special applications.

3 Railway arresters of ABB

The wish to increase reliability and safety of the arresters, and correspondingly of the energy supply, brought about the development of the MO-arresters with silicon housing in the middle of the eighth decade of the last century. In the last 30 years silicon was well-known and tested as an excellent insulation material for the high voltage technologies, as for instance long-rod insulator and the bushing.

The first MO-arresters with silicon housing of typical ABB design (direct moulding) were introduced in 1986 in the networks. Today, in the year 2000, there are almost 800 000 arresters of this design in the networks all over the world, under the most different environmental conditions, and in all voltage levels. Due to flexibility of application in very difficult electrical and mechanical conditions, the ABB MO-arresters with silicon housing are increasingly recognized globally.

As stated above, in the past there was the transition from the porcelain insulators to the silicon insulators. This change brought about an improvement towards safety, pollution behaviour and mechanical resistance of the arrester.

Figure 2 shows the development of the arrester technology with two examples.

3.1 Construction of the arrester

The principle of construction of the ABB arresters with silicon direct-moulding consists of two electrodes which are connected to one another through two or more glass-fibre reinforced elements, resulting in a hard cage or frame, which guarantees the mechanical resistance. The MO-resistors are arranged inside this frame. Additional metal cylinders with the same diameter as the MO-resistors fill the inside completely, so forming a uniformly round active part. With a bolt in the centre of one of the electrodes the MO-blocks are pressed together, the bolt secured in the end position, providing each arrester the same contact pressure. This arrangement is placed into a form and, with high temperature, completely sealed with silicon. As a result the surge arrester, which is completely sealed and tight, has no void inside. This construction with its typical design features was patented by ABB Switzerland.

Figure 3 shows a MO-arrester of type POLIM-H, which was manufactured according to this technique. Figure 4 shows a selection of arresters built with the above described principle. They are especially used in railway facilities.
This flexible method of construction (modular concept), provides the possibility of changing the form of the arrester in order to fit each necessity.

Figure 3
MO-arrester of the type POLIM-H
Right: active part before it was moulded in silicon

Figure 4
MO-arresters for the application in railway facilities.

3.2. Insulation made of silicon rubber

Silicon rubber, or shortly called silicon, is an exceptionally good insulation material. Comparisons with other insulation materials such as porcelain, glass or other synthetic materials (for instance EPDM) show clearly the superiority of silicon.

As we already mentioned, during the manufacture of the surge arrester the silicon insulation is bonded to the arrester assembly through casting (or injection) of the liquid silicon in moulds at a high temperature. Through different forms it is possible to fit perfectly the insulator to the structure of the MO-arrester, resulting in an arrester without air gaps, which has the following properties:

– No hydrocarbon is in the chemical main chain. This helps the insulation to have an excellent resistance against pollution of the surface, and it prevents carbonised creepage paths from forming.

– Hydrophobicity. Water does not moisten the surface of the insulator, but forms only few, isolated drops that are removed by the effect of gravity or through normal exposure to wind, Figure 5.

– Layers of dirt on the surface of the insulator are also repelled because of the diffusion of short molecule chains from the silicon material into the surface layers. In this way even strong pollution does not influence the hydrophobicity of the surface of the insulation.

– In long-term tests, as for instance the 5000 hours weather-ageing test in conformity with IEC, the water-repellent property of the silicon was reduced at about 50 %, but it was restored after a couple hours of dryness. Under the same testing conditions with other materials, as for instance EPDM, the hydrophobicity is completely and permanently lost.

– The salt-fog tests show that, assuming the same salinity in each case, the creepage paths required for silicon insulation are, on average, 30 % shorter than the paths necessary with porcelain insulation.

3.3 Technical data of the arresters

The demands on the arresters depend on the operational conditions and the type of the electrical equipment. For the railway facilities, that have different voltage systems and special demands, both electrical and mechanical, ABB offers a selection of different types of MO-surge arresters. The safety and the ecological aspect are especially taken into consideration with all the arresters.

Table 2 presents main electrical data of the arresters applicable for railway facilities, essential mechanical data following in Table 3. Railway facilities are serviced with both d. c. and a. c. systems and the arrester types are operational for both d. c. and a. c. voltage networks. Therefore the definitions and data are slightly different and that requires a splitting of the table.

Arrester type a. c. systems	I_n kA	U_p / U_c	High current kA	E / U_c kJ / kV	Rectangular wave I in A (t=2000 µs)
MWK / MWD	10	3,07	100	5,5	550
POLIM-I	10	3,07	100	5,5	550
POLIM-S	10	3,0	100	9,0	1000
POLIM-H	20	3,19	100	13,3	1350
Arrester type d. c. systems and special applications	I_n kA	U_p / U_c, dc	High current kA	E / U_c, dc kJ / kV	Rectangular wave I in A (t=2000 µs)
POLIM-C	10	3,2	100	3,1	250
POLIM-H…ND	20	2,7	100	6,0	1350
POLIM-R…-1	10	2,4	100	6,0	1350
POLIM-R…-2	20	2,4	200	12,0	2400
POLIM-ID	40	3,0	300	21,0	2400
Arrester type a. c. and d. c systems, special applications	I_n kA	U_p / U_c	High current kA	E / U_c kJ / kV	Rectangular wave I in A (t=2000 µs)
MVR 0,44 bis 0,8 – 5	5	3,5	30	3,0	125
MVR 0,44 bis 0,8 – 10	10	3,64	65	4,5	250
MVR 1 – 6,6	5	3,3	30	3,0	125

Table 2
Electrical main data for the ABB arresters for the application in railway facilities.

The arrester types POLIM-C and POLIM-R may be also used in a. c. voltage networks. The corresponding technical data are to be found in the data sheets. The arrester types MVR have a PUR-moulding, and are used mainly for special applications and for protection of low voltage installations.

Arrester type	Breaking moment Nm	Torsion Nm	Vertical force N
MWK / MWD	350	68	1200
POLIM-C	350	50	1000
POLIM-I	2500	100	2000
POLIM-S	4000	100	3000
POLIM-H / -H…ND	6000	100	4000

Table 3
Mechanical data of the ABB arresters for application in railway facilities. The instructions are the approved short-time load (1 min). The continuous load is not allowed to exceed 40% of the given values. The arresters that are not mentioned in this table should not be stressed with mechanical loads at the high voltage connection, that is they have to be connected with flexible junctions. Other information concerning the mechanical loading capacity are to be required from the producer, if and when the need arises. All the arresters, which are applied on rolling material, are in addition tested with a special mechanical type test. See also the chapter: Special tests.

4 Operating conditions

The service life of the arresters are in the range of about 25 years if they are properly designed for the respective system voltage, and for the expected electrical and mechanical loads. In IEC 60099-4 are the normal operating conditions

- Ambient temperature -40° C up to +40° C
- Solar radiation (1,1 kW/m²)
- Altitude up to 1000 m above sea level
- Frequency of a. c. voltage between 48 Hz and 62 Hz
- Power frequency voltage at the arrester connections not higher than the continuous operating voltage U_c of the arrester.

All the arresters of ABB fulfil or even exceed these operating conditions.
ABB MO-arresters can be used without any restriction in voltage systems with a power frequency of 16 ²/₃ Hz. Higher frequencies than 62 Hz, and commutation overshots are no principle problem; but should be discussed with the manufacturer.

Some special cases are discussed in the following chapter.

4.1 Network short circuit power

Any arrester can be overloaded. The causes are extremely high lightning currents, a large number of multiple strokes or a so-called voltage-transition. This is understood to be a short circuit between two different voltage levels. In all the situations there is in principle an energy overloading. In such a case of overloading the MO-resistors either spark-over or break down. An arc results in the arrester and the current in this arc is defined by the short circuit power of the network. With porcelain housed arresters and in PUR moulded arresters it is possible that the housing explodes (or shatters violently) in case of higher short circuit currents. With the ABB arresters with silicon housing there is no danger of explosion or shattering in case of an overload. There is no air space between the active part of the arrester and its silicon insulation, thus there is no place for the pressure to build up. The occuring arc (or sparks) escapes the silicon insulation immediately as it occurs. Because of their special constructions the arresters are up to the highest short circuit currents insured against explosion and destruction.

4.2 Elevated ambient temperature

The ABB arresters (a. c. and d. c. voltage) function flawlessly up to 45° C ambient temperature. This includes also the maximum solar radiation of 1,1 kW/m² for outdoor arresters. If there are other heat sources in the vicinity of the arrester, the increase of the ambient temperature must be taken into account, and the value of U_c increased if necessary. If the ambient temperature exceeds 45° C, U_c must be increased by 2 % for every 5° C of temperature elevation. This correction is possible up to a maximum of 80° C ambient temperature.

4.3 Mechanical stability

The arresters of ABB are operationally reliable even in areas of high earthquake activity. The arresters may partially take on the support function or, as line arresters, they may have the function of suspension insulators. By such operational situations it is necessary to inform the manufacturer, with the following constrictions seen in the Table 3.

Figure 5
Repelling water on silicon surface (hydrophobicity-effect)

The arrester types, which are to be applied on rolling material, are delivered with a reinforced base plate and are tested under vibration and shock conditions, in conformity with IEC publication TC9.

4.4 Pollution and cleaning

Silicon is the best insulating material in case of pollution. This is mainly because the material is water-repellent (hydrophobic). Silicon arresters behave more favourably under conditions of heavy air pollution than porcelain housed arresters or other polymer insulation materials. In addition the self-cleaning feature of silicon itself is outstanding, because the dirt hardly adheres to the flexible surface and is washed away by rain and wind. In regions with strong pollution it is advisable generally to use arrester housings with a longer creepage distance.

Arresters which are applied on rolling material, and are regularly washed, are not affected in any way. Environmentally safe cleaning agents do not affect either the arrester function or the properties of the silicon housing.

4.5 Flying sparks

The silicon, which is used by the described ABB arresters, is a hardly inflammable and self-extinguishing material. Tests have shown that blazing hot particles, which emerge by the de-contacting of the pantograph or by braking, do not affect negatively the silicon housing of the arrester. There is no danger that the arrester can be ignited by the sparks, or that the insulation resistance of the housing may be decreased through humidity or rain because of the particles that adhere on the surface.

4.6 Altitude adjustment for the arrester housing

The ABB arresters can be used without any housing adjustment up to a height of 1800 m above sea level. At higher altitudes the air density is so low that the withstand voltage of the arrester housing may be no longer sufficient against external flashover. In this case the unaltered active part of the arresters (same protection level) must be placed in an elongated housing with a longer flashover distance.

As an orientation value one may consider that for every 1000 m over 1800 m above sea level the flashover distance of the housing must be enlarged by 12 %. For example, at an altitude of 3300 m above sea level the flashover distance of the housing must be 18 % longer than that of a standard arrester.

The flashover distances of arresters of lower voltage levels are relatively large initially, exceeding the minimum requirements of the withstand voltage. Thus, for each case should be tested whether the normal housings possess the sufficient withstanding voltage for the application in higher altitudes.

5 Tests

The requests and tests for MO-arresters in a. c. current railway facilities are not different from the ones for arresters in networks of the electric power supply (refer to the bibliography no. [1] and [4]). The additional tests, which are necessary for special application cases are shown in the following chapters.

The requests and tests for arresters in stationary d. c. current railway facilities are to be found in the standard EN 50123-5 [6]. This standard refers mainly to the IEC 60099-1 for arresters with spark-gaps, and to the IEC 60099-4 for the MO-arresters without spark-gaps. The partially different definitions and test procedures are shortly mentioned.

5.1 Definitions
(see also chapter 6)

Rated voltage (U_r)
The maximum d. c. voltage value between terminals at which the surge arrester is designated to operate correctly under temporary overvoltage conditions as established in the operating duty tests. This voltage U_r corresponds to the temporary voltage increase U_{max2} acc. EN 50 163 [7], which is allowed to appear for maximum 5 minutes.

Maximum continuous operating voltage of the arrester (U_c)
The highest voltage, which may be applied unlimited between the terminals of the arrester. It corresponds the voltage U_{max1} acc. EN 50 163.

Nominal discharge current of an arrester (I_n)
Peak value of the lightning current corresponding to IEC 60099-4.
The nominal discharge current I_n is used for classifying the arresters.

Protective voltage level of the arrester (U_p)
It is the highest residual voltage at the nominal discharge current I_n.
The relation U_p/U_c shows the protection level of the arrester. The smaller the relation U_p/U_c, the better is the protection characteristic of the arrester.

5.2 Type tests

The type tests are tests which are carried out only once to show that a special arrester type operates properly.
The type tests for MO-arresters without spark-gaps, which are used in a. c. voltage networks, are described in the standard IEC 60099-4. In EN 50 123-5 (surge arresters and low voltage limiters for special usage in d. c. systems) there is the description of the type tests for MO-arresters in stationary d. c. current systems.

The following type tests are to be carried out:
– testing of the insulation withstand voltage of the housing
– testing of the residual voltage
  with steep current impulse
  with lightning current impulse
  with switching current impulse
– testing with rectangular current waves
– operating duty test
– d. c. voltage versus time characteristic
– tightness test
– pressure relieve / overload test

The tests are similar to the ones for the MO-arresters, which are used in alternating current networks. Only the procedure of the operating duty test is different from the one of the MO-arresters in alternating current networks. This is why we describe here minutely only the operating duty test and the ageing test for the MO-resistors applied in d. c. voltage systems.

Operating duty test
– measuring of the residual voltage at I_n
– conditioning (4 groups of 5 applications of I_n, superimposed on 1,2 U_c)
– high current impulse 4/10 µs
– heating up to 60° C (in oven)
– high current impulse 4/10 µs
– rated voltage U_r for 300 s
– continuous voltage U_c for 1800 s
– measuring of the residual voltage at I_n
– visual inspection

In EN 50 123-5 is pointed out that in case there are not sufficient direct current sources for this test, it is possible to carry out the test with a. c. voltage, by arrangement between the manufacturer and the customer. The described procedure of the operating duty test is the one for high current impulse test. The operating duty test with switching surge current is still under consideration.

The experience shows that, corresponding to IEC 60099-4, the MO-arresters tested with a. c. voltage, which have the requested dimensioning, can be used without any problems in d. c. voltage networks, because the demands and the testing procedure are almost similar.

Accelerated ageing test
This test has to show that the power losses of the arrester in the network under applied continuous operating voltage does not increase with time. In order to demonstrate this, the power losses are measured in a time accelerated ageing test under increased load. It is decisively important that this test should be carried out with d. c. voltage. It is known that MO-material, which has a long-time stability with the alternating voltage load, is not necessarily long-time stable with direct voltage load. The ageing tests which are carried out with a. c. voltage are not transferable to the application in d. c. voltage networks.

All ABB MO-resistors, which are installed in arresters for d. c. voltage networks, fulfil the most strict demands towards the long-time stability under d. c. voltage load.

5.3 Routine- and acceptance tests

The routine tests are carried out corresponding to IEC 60099-4, and they are not different to the tests for arresters which are used in a. c. voltage networks of the general electrical energy supply.
Acceptance tests are in principle to be agreed upon by the manufacturer and the customer.

5.4 Special tests

The existing standards, which were mentioned earlier, are valid for the arresters with porcelain housing and are therefore only partially applicable for modern construction with polymer housing. Working group paper IEC TC 37/199/CDV discusses tests for MO-arresters with polymer housing. The demands and procedure for tightness, pollution and overload tests are still under consideration in the relevant working groups of IEC. Therefore special tests were carried out by ABB Switzerland in order to prove the behaviour of the MO-arrester with silicon housing under extreme conditions.

Weather-ageing test
Pollution and ageing tests under extreme weather conditions, which are carried out on complete arresters, with partially cyclical load and test duration between 1000 h and 5000 h, give realistic information about the behaviour of the arrester in the network. In the IEC working group paper TC 37/199/CDV [8] two procedures are recommended.
Procedure A is a test lasting 1000 h with constant salt fog from 1 to 10 kg/m³ salt content under applied continuous operating voltage U_c.
Procedure B is a test lasting 5000 h in all with changing stress of UV rays (solar radiation), rain, dry heat, steam and salt fog under applied continuous operating voltage U_c.

Figure 6 shows the cyclical stress during the test.
The ABB arresters with silicon housing have easily passed the very demanding test of procedure B.

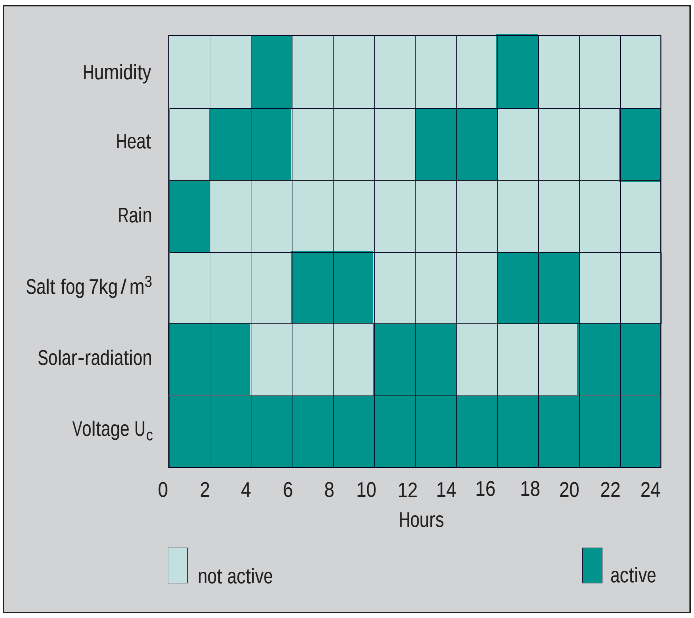

Figure 6
The cycle of the weather-ageing test after procedure B corresponding TC 37/199/CDV.

Test with high air humidity
This long-time test was carried out at the Technical University of Tampere in Finland as a research project. The test time was longer than two years. During all this time the tested arresters were in a climatic chamber under a temperature of 30° C up to 35° C, a relative air humidity of 95 % up to 100 %, and with a. c. voltage applied. Additional, each month the arresters were set under rain. During the whole time of the test no changes appeared in the electrical characteristics and no signs of possible penetration of humidity were detected. The MO-arresters with the described silicon direct moulding are tight even under such extreme environmental conditions. As a comparison, tests were done with other constructions and they showed that only the arresters with the silicon direct moulding were capable to withstand such stresses. Especially the arresters that, due to the construction, have inclusions of air could not withstand this extreme humidity stress. The results of the tests are published in [9] and [10].

Deep temperature test
In order to test the behaviour of the arresters at extreme deep temperatures a deep temperature test was carried out. The MO-arresters with silicon housing were cooled down to - 60° C under applied a. c. voltage in a climatic chamber. The cycle of the test in the climatic chamber is seen in Figure 7. The electrical characteristics of the arrester were measured before and after the temperature test in the chamber. No changes were noticed. The mechanical behaviour of the silicon, as well as the chemical bond of the different materials among one another were of special interest during this temperature test under extreme conditions. The silicon maintains its flexibility even in these deep temperatures, and no chemical or mechanical changes were observed.

In an additional experiment, MO-arresters with silicon housing were submerged in water and tested with a temperature cycle between + 60° C and - 40° C. Figure 8 shows the test cycle. Even repeated freezing and heating (up to 60° C in water) of the arrester did not influence either the electrical or the mechanical behaviour of the arrester.

On the basis of these very positive results it is possible to guarantee the employment of ABB direct moulding MO-arresters without any problems up to - 60° C.

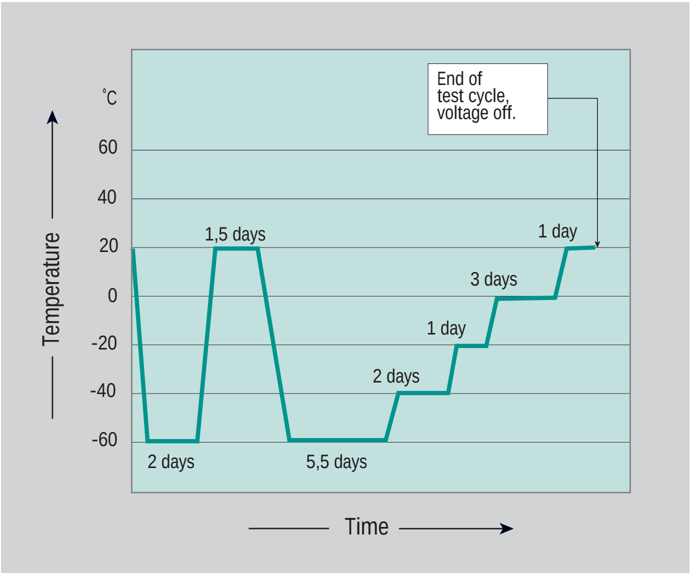

Figure 7
Deep temperature test. Duration of test was 16 days. During the test in the climatic chamber a voltage of 12,1 kV (phase – earth voltage in 20 kV network) was applied to the arrester.

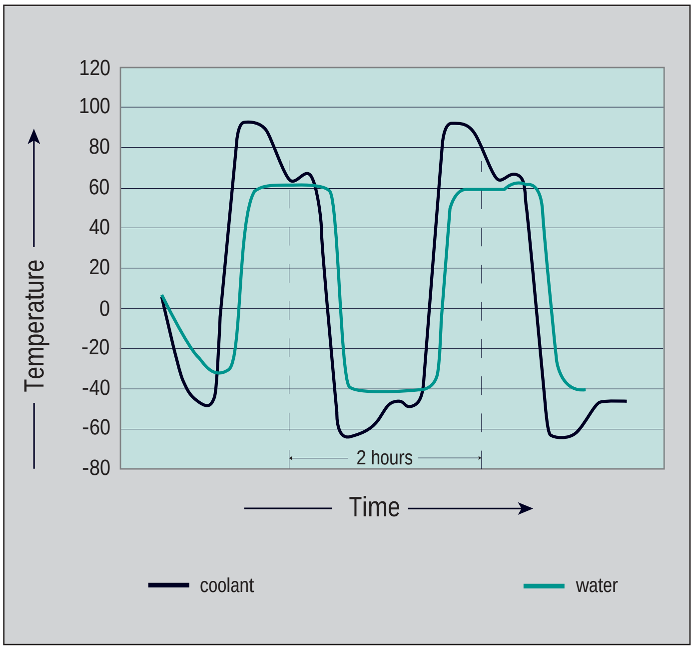

Figure 8
Freezing test. The tested arresters were completely submerged in water. The water was cooled within 10 min. from 60° C to - 40° C, a very quick and complete freezing took place. In all there were 300 cycles, each of them having a duration of two hours.

UV radiation test
In regions with a strong solar radiation it is important to know the behaviour of polymer materials under UV radiation stress. The energy of the radiation can crack the surface of the insulator made of a synthetic material, and as a result the insulator may erode and finally fail. The silicon behaves very positively under such conditions; this was tested during long-time tests in out-of-door test-fields, as for instance in Tunisia and South Africa. In addition, tests with UV radiation stress were carried out in the lab, for more than 1000 hours correspondingly to the relevant standards.

UV radiation represents no problem for the silicon, quite the opposite, the UV radiation has a supporting influence by the restoration of the hydrophobicity of the surface of the silicon following a long period of pollution.

Sparking
Through the jumping of the pantographs and during braking it is possible that hot rubbed-off particles may arise; they may be sprayed on the silicon insulation of the arrester which is close by (overhead line or the locomotive). In order to test whether such a sparking may have a negative influence on the silicon insulation, the arrester was exposed to an enforced sparking stress. The surface of the arrester was sprayed with sparks from different distances and for various periods of time, with the help of a grinding wheel and iron rails. After that the withstand voltage of the insulation was measured under rain. The test results showed no change in the insulating behaviour. There were no burning prints to be found on the surface of the silicon. Because silicon is a material which is very difficult to ignite and is also self-extinguishing, there is no danger that the arrester with silicon housing could be damaged through sparking.
The cold metal particles which were found on the surface of the silicon after the experiment could be removed without any problem.

Overload tests

In [8] there are described different methods of testing the pressure relief system of the MO-arrester or the overload behaviour of the MO-arresters without pressure relief system. Because of the direct moulding, ABB arresters do not have any pressure relief system in the conventional meaning. If an arc arises along the active part of the arrester because of an overload of the active part, the arc burns instantly through the silicon housing, and in this way no pressure can be build up inside the arrester. Explosion is out of question. All ABB arresters with direct moulding were tested with the overvoltage method without a fuse wire, and showed that they were safe in their failure behaviour. The arresters are safe from explosion and destruction. The arresters were tested with short circuit current of up to 65 kA, 200 ms, depending on their type. Figure 9 shows a POLIM-H 24 after an overload test with 25 kA short circuit current.

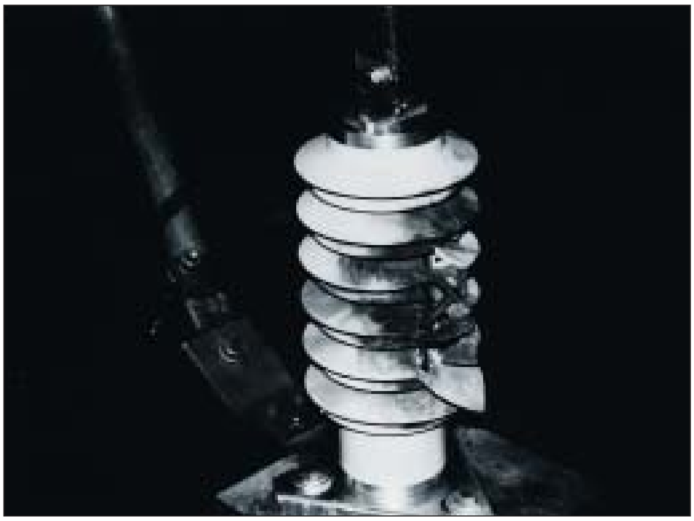

Figure 9

POLIM-H-arrester for 24 kV continuous operating voltage after an overload test with 25 kA, 200 ms.

Vibration and shock test

MO-arresters on rolling material are exposed to special mechanical stress. That is why the arresters POLIM-I, POLIM-S, POLIM-H and POLIM-H…ND are delivered with a reinforced base plate for the appliance on locomotives. The arresters with these base plates were vibration and shock tested according to IEC publication of TC 9 “random vibration and shock testing of equipment for use on railway vehicles”. No mechanical resonance step-up appear. Because of their very robust mechanical construction, the ABB arresters with direct moulding are especially suitable for the appliance under the most difficult mechanical conditions.

6 Supply voltages of railway networks

The supply voltages for the railway networks are given in the European Standard EN 50163 [7]. In the following chapter the definitions and voltage values, which are important for the surge arrester and the overvoltage protection, are given and shortly explained .

Voltage U

The potential at the trains current collector (pantograph), measured between the supply conductor and the return conductor.

Nominal voltage U_n

The designated value for a system.

Highest permanent voltage U_{max1}

The maximum value of the voltage likely to be present indefinitely.

Highest non-permanent voltage U_{max2}

The maximum value of the voltage likely to be present for maximum 5 min.

Overvoltage

A transient rise of voltage lasting less than 2 s.

Long-term overvoltage

A transient rise of voltage, lasting typically more than 20 ms, due to low impedance phenomena (e.g. a rise in substation primary voltage).

Medium-term overvoltage

A transient rise of voltage, lasting typically less than 20 ms, due to current transfer following switching (e.g. the opening of a circuit breaker).

Short-term overvoltage

A transient rise of voltage, lasting less than 20 µs (e.g. lightning strokes).

6.1 Parameters of the most important voltage systems

Electrification system	Nominal voltage U_n V	Highest permanent voltage U_{max1} V	Highest non-permanent voltage U_{max2} V	U_{max3} V
d. c (mean values)	600 750 1500 3000	720 900 1800 3600	770 950 1950 3900	 1269 2538 5075
a. c (r. m. s. values)	15 000 25 000	17 250 27 500	18 000 29 000	24 311 38 746

U_{max3} is a calculated overvoltage at t = 20 ms.

Table 4

The values for U_{max2} can become 800 V in the 600 V-system, and 1000 V in the 750 V-system, in case of regenerative braking.

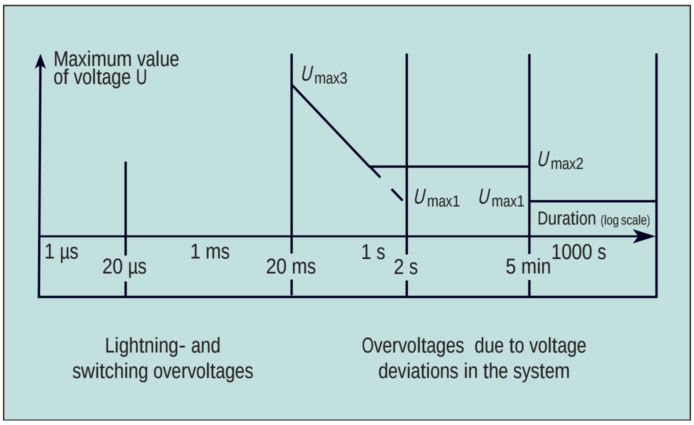

Figure 10

Figure 10 shows schematically the highest values of voltages which arise in the networks as a function of time.

6.2 Frequencies of the a. c. systems

The nominal value of the frequency in the 15 kV-network is $16\,^{2}/_{3}$ Hz. It lies in the range of $16\,^{1}/_{6}$ Hz up to 17 Hz.
The nominal value of the frequency in 25 kV-network is 50 Hz. It lies in the rage of 49 Hz up to 51 Hz.

6.3 Nominal voltages of d. c. railway systems

In addition to the preferential voltages 750 V, 1500 V and 3000 V, which are given (and standardised) in Table 4, there are some other voltages in the direct current systems which are in use. These voltages and their application areas are shown in Table 5.

Type of train	Nominal Voltage
Mine railway (underground)	220 V and 500 V
Mine railway	1,2 kV, 1,5 kV, 2,4 kV and 3 kV
Tramline, trolley-bus	600 V and 750 V
Underground railway	750 V, 1,2 kV and 1,5 kV
Suburban railway	750 V to 3 kV
Long distance railway	1,5 kV and 3 kV

Table 5

In the suburban service (street-car, trolley bus) the nominal voltage is below 1000 V, because of potential danger that may be caused by a too high voltage.

Figure 11 shows the example of the measured voltage U at the current collector of a modern suburban vehicle during the undisturbed operation. The voltage curve at the current collector is influenced not only from the power demands of the respective vehicle, but also from the demands of other vehicles which are in the network, and from their position to the supplying substation. The illustrated short-time voltage peaks appear for instance, when passing a neutral section of contact line, jumping of the current collector, switching, or at the beginning of the braking process, and they are provoked by the units of power control of the vehicle. Figure 12 shows in another example the voltage U at the current collector during a test ride.

The power switches which are used in direct current networks produce switching overvoltage. These depend on the type of breaker, and on the magnitude of the d. c. voltage. Table 6 shows typical breakers, and the switching overvoltage that appear, and also the total times of the disconnecting.

Type of breaker	Total disconnecting time ms	Switching-overvoltage U / U_n
Plunger type	>10	2…3
Magnetical blown	>8	1,5…2,1
Thyristor breaker with vacuum chamber	<1	<2

Table 6
Disconnecting times and switching overvoltage of the d. c. breakers in railway networks.

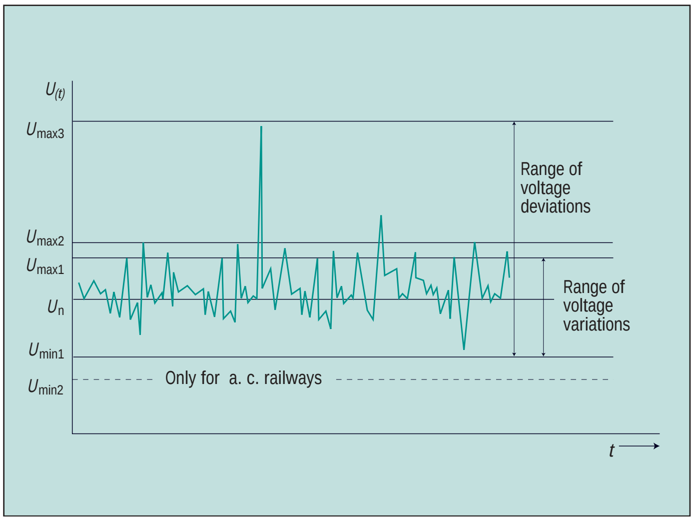

Figure 11
Voltage U at the current collector of a traction vehicle during 15 min.

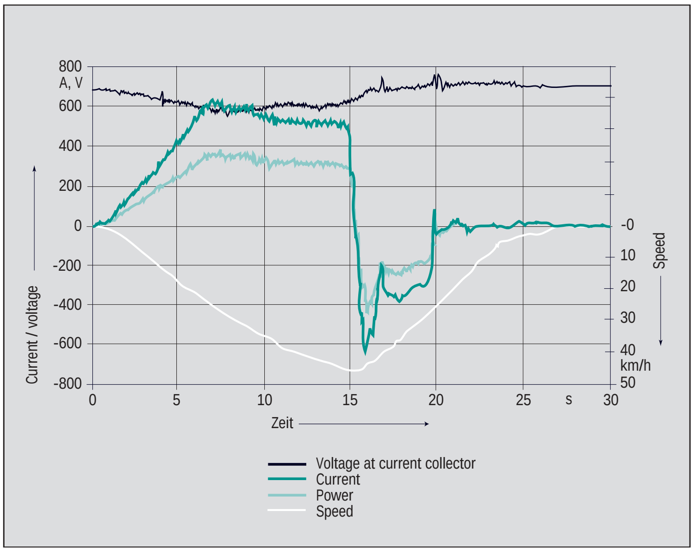

Figure 12
Characteristic curves of a trial ride, metropolitan railway vehicle, the acceleration from 0 to 45 km/h with maximal tractive power, afterwards braking with current regeneration.

Due to the relatively low voltages of the d. c. railways flow rather high currents if we take into consideration the high power which is necessary for these application fields (round about 100…500 kW). The acceleration current with the modern street-cars reaches values up to 1700 A.

A special problem with the operation of the d. c. railways is the electric drainage. With the d. c. railways the current which is necessary for transmitting the electrical power to the tractive vehicle flows back through the rails. Because of the relatively low transition resistance between the rail and the ground a part of the reverse current leaves the rail and goes into the ground, and afterwards it comes back from the ground to the substation. If there are metal installations in the ground close to the railway, as for instance pipes or cable coverings, the reverse current flows through these installations, too. At the point where the current flows out of the metal there appears an electrochemical corrosion: the ground has the function of an electrolyte. For example, in case of a permanent flowing current of only one ampere during a period of a year, 9.1 kg iron, 10.4 kg copper and 33.4 kg lead are leached out.

In order to diminish these negative influences, which become more powerful with the increase of transmission power of the d. c. railways, one tries to increase the insulation between the rail and the ground. This brings another problem, the contact voltage at the rail increases and can be life threatening. Especially when overvoltages go over the rails, an overvoltage protection with MO-arresters for diminishing these contact voltages should be taken into consideration.

7 Overvoltage protection of the a. c. railway networks

The European $16\,^2/_3$ Hz networks of the railway are differently constructed in comparison with the 50 Hz transmission networks of the railway facilities, which are rather similar to those of the public energy supply enterprises [11]. Figure 13 shows as an example the railway current supply of the Swiss National Railways (SBB) and the application points of the surge arresters. Both of the current conductors of the 132 kV networks have each a voltage of 66 kV versus earth. The middle point of some transformer is effectively grounded. In Germany and in Austria the transmission networks are grounded through coils. In case that in such a transmission network a single phase earth fault takes place, the other phase, which has no fault, can take a higher voltage versus earth. The MO-arresters without spark-gaps can bear even an increased $16\,^2/_3$ Hz voltage during an earth fault. The choice of the continuous operating voltage U_c takes place according to the TOV capability of the arrester. A MO-arrester with U_c = 84 kV is used, which has a very low residual voltage of $U_p = 268$ kV at $I_n = 20$ kA. It is installed the type POLIM-H 84 N. According to this, the arresters for the transformer neutral have an $U_c = 44$ kV.

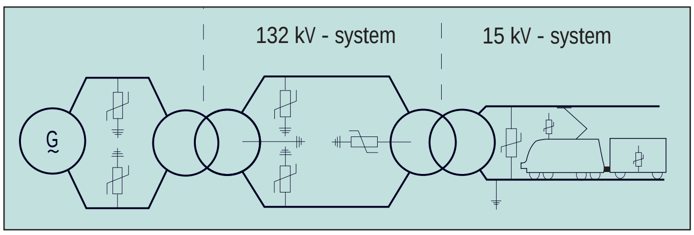

Figure 13
Schematic representation of a $16\,^2/_3$ Hz railway current supply and the application of surge arresters by the Swiss National Railways.

7.1 Overvoltage protection of overhead lines and locomotives

When designing the arresters for the different network voltages, three characteristics are to be taken into consideration: the highest continuous voltage that arises in the network, the protection level of the arresters, and the energy absorption capability of the arrester. The most important characteristic taken into consideration by the design is that the arrester in the network should be stable from the thermal point of view, no matter which stresses appear. The strong voltage fluctuations in the supply line due to the operating conditions makes it necessary to lay the arrester continuous voltage U_c over the highest continuous voltage of the network U_{max1}; see Table 4 and Figure 10. The highest non-permanent voltage U_{max2} can appear for maximum 5 min, but it is not known how often and in which time interval this voltage increasing may appear. As the modern ABB MO-arresters have a very favourable protection level by a high energy absorption capability, it is possible to lay the arrester continuous operating voltage U_c similar or higher U_{max2}, that is

$$U_c \geq U_{max2}.$$

Alternating current networks 25 kV, 50 Hz
With U_{max2} from Table 4 results an arrester continuous operating voltage of

$$U_c \geq 29 \text{ kV}.$$

The types POLIM-H 29 and POLIM-I 31 N are used on the locomotives of the German National Railways (DB). With modern E-locomotives the high voltage from the current collector is brought into the inner part of the locomotive through a cable, and this requires a co-ordination concept of the arrester for a good overvoltage protection.
On the roof of the locomotive there are two POLIM-H 29 N installed at the current collectors, and in the inner part of the locomotive there is a POLIM-I 31 N installed in front of the main power breaker.

Alternating current networks 15 kV, $16\,^2/_3$ Hz
With U_{max2} from Table 4 results a continuous operating voltage of

$$U_c \geq 18 \text{ kV}.$$

With the SBB and other Swiss Railways the arresters POLIM-H 18 N are installed on the locomotives and the types POLIM-S 18 N are used at the overhead lines.

The DB uses for instance a co-ordination concept with the locomotive BRE 101, which is set in the interregional trains, and installs on the roof an arrester of the type POLIM-H 18 N and in the inner part of the locomotive the type POLIM-I 20 N.

8 Overvoltage protection of d. c. railway networks

The protection of the electrical railways has the task, in case that faults appear, to

- prevent damages at the installation or try to reduce them as much as possible
- assure the availability of the railway energy supply as much as possible
- prevent or reduce the endangering of life through direct or indirect influence of the fault voltages.

Therefore all the stresses which are unacceptable, but however appear in the railway network, are to be removed quickly, totally and selectively. The unacceptable stresses in the network of electrical railways are all types of short circuits, and operational currents, which lead to an unacceptable warming of the conductor (overhead line or conductor rail).

Short circuits in the supply line installations of the direct current railways appear rather often when compared with the general energy supply of a country. With standard-gauge railways an average of three short circuits occur per year per kilometer track, with higher occurances for suburban service lines. The main causes for the short circuits are:

- the ride of the traction vehicle in section of the supply line which are grounded,
- insulation flash-over,
- violence (e.g. objects or animals on the supply line, storm, lightning stroke, vandalism),
- damages at the current collector, traction vehicle or in the supply line installation.

In addition to the usual protective measures in direct current railway energy supply for the MV-installations, transformers, power converter, and also for the overhead line and the traction vehicle of the railway, the overvoltage protection is increasingly important.

The reasons for this development are:

- the increased usage of electronic control and information systems,
- the increased degree of mashing in the system of the railway energy supply,
- the relative small resistance to jamming of the electronic installations.

The protection against step-voltages need to be considered more and more.

In [12] one can read:
"The experiences that we made with the application of surge arresters are mainly negative experiences when not using protection measures against overvoltages". The cited publication of Hamburger Hochbahn AG states that damages which appear through overvoltage during a thunder storm or breaker operations have an increased negative economic effect due to the breaking down of the electronic and data transmission installations.

8.1 Protection concept for direct current tractive units

From the very beginning it was standard and necessary to install surge arresters in d. c. traction vehicles. The first electrical traction vehicles had as an overvoltage protection inductance coils. Later horn arresters were additionally employed. Since the third decade arresters with non-linear resistors (SiC-resistors in series with spark gaps) were used.
Today, it is usual to employ surge arresters directly at the current collector of the d. c. traction vehicle roof, as seen in Figure 14. This protection concept, each current collector using a surge arrester, is employed with the main-line railway and suburban service. The two-system locomotives (50 Hz 25 kV; DC 3 kV) have at the in-connector surge arresters.

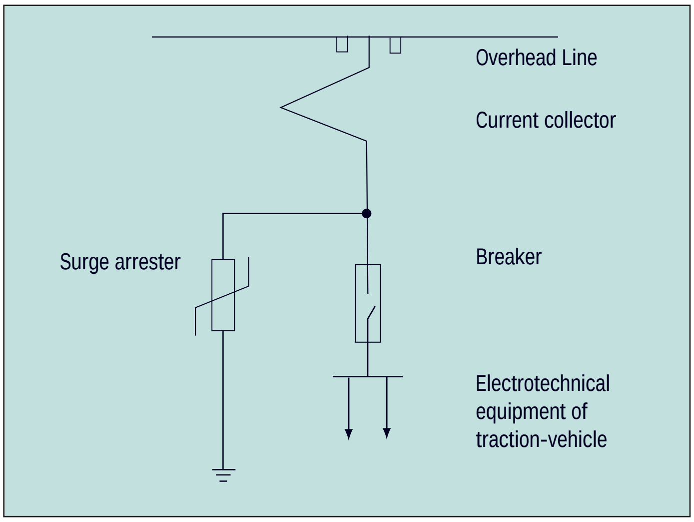

Figure 14
The arrangement of the surge arresters on the in-connector of the traction vehicle.

8.2 Dimensioning of the surge arresters

As with MO-arresters of the a. c. railway networks, it is correct to orient the arrester continuous voltage U_c to the highest non-permanent voltage U_{max2}, that is

$$U_c \geq U_{max2}$$

According to the Table 4 the following standard values result:
For networks with a nominal voltage from

$$U_n = 600\,V \text{ follows } U_c \geq 800\,V \text{ and}$$

$$U_n = 750\,V \text{ follows } U_c \geq 1000\,V$$

In both these situations, it is taken into account that in the case of regenerating braking, the values for U_{max2} can increase up to a maximum of 800 V (U_n = 600 V), and respectively up to a maximum of 1000 V (U_n = 750 V).

The VDV paper 525 [13] recommends for the overhead contact system to employ weather resisant surge arresters, at each service entrance, at the ends of feeding sections, and at the coupling point as well as at power demand points (e.g. for point heaters). For track sections with frequent lightning strokes, for instance on bridges or a free overland route, additional arresters are advisable. Feeding cables and the return wire in the transformer substation are also to be equiped with surge arresters. Figure 15 shows the protection concept.

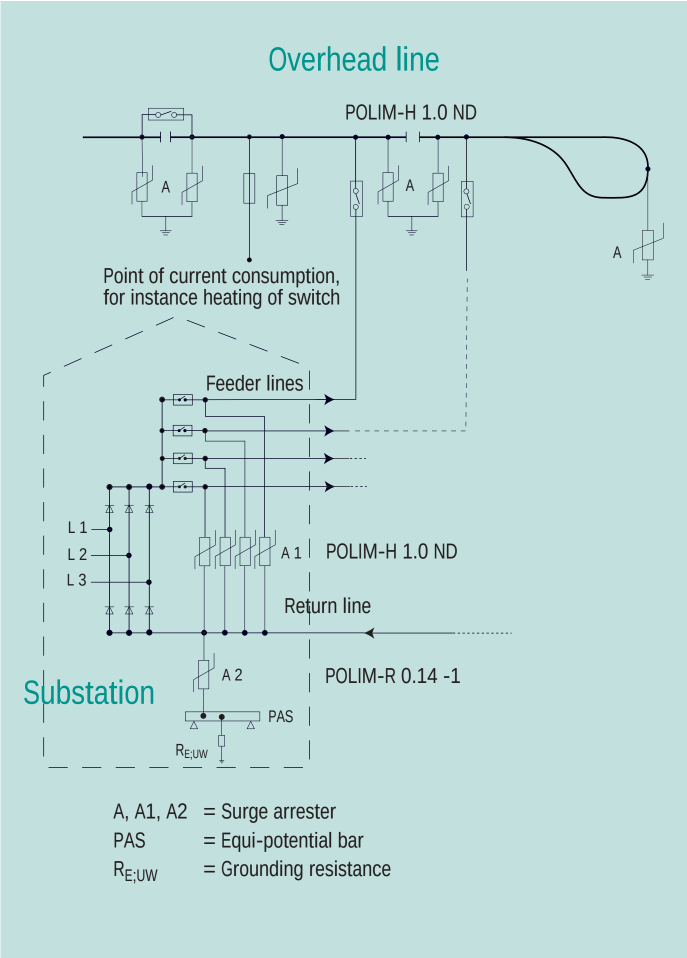

Figure 15

The protection of the traction current supply installation of a typical metropolitan railway ($U_n = 750$ V).

The arresters of the overhead line and the arresters A1 in the substation cause a reducing of the overvoltage to a harmless value in case of lightning strokes. The arrester A2 between return wire (rail) and the earth of the building should reduce the potential lifting of the rail. The arrester provides protection in the case of direct lightning hits in the railways, as for overhead tracks with current rails.

The ABB arresters POLIM-H…ND and POLIM-R prove to be suitable for all the above mentioned applications, due to their high energy absorption capability, the low protection level and a secure construction.

The type POLIM-H 1,0 ND with $U_c = 1{,}0$ kV and a $U_p = 2{,}7$ kV (at $I_n = 20$ kA) is employed in the overhead lines and in the transformer substation (arrester A1), as well as on the traction vehicles. This arrester fulfils and exceeds the required demands, and offers the best protection and security for traction current installations of direct current railways.

The type POLIM-R is recommended for the arrester A2, which has the same (POLIM-R…-1) or, depending on the product (POLIM-R…-2) even a higher energy absorption capability at the lowest protection level U_p as the POLIM-H…ND has. The arresters POLIM-H...ND and POLIM-R…-1 have active parts with the same diameter of the MO-resistors of 75 mm, and are suited to one another both in current-voltage characteristic and in energy absorption.

The arrester POLIM-R…-2 has as an active part two parallel switched MO-resistors of a diameter of 75 mm, and offers an even lower protection level by double energy absorption capability, which is very advantageous, especially by the protection against short-time contact voltages.

For networks with a nominal voltage of

$$U_n = 1500\,\text{V follows } U_c \geq 1950\,\text{V and}$$

$$U_n = 3000\,\text{V follows } U_c \geq 3900\,\text{V.}$$

If these values for U_c are not in the data sheets, the next higher arrester continuous voltage is to be chosen. In networks with $U_n = 3000$ V is employed as a rule the arrester POLIM-H 4,2 ND with $U_c = 4200$ V.

It is possible to work out special solutions for the most favourable application of the arrester upon request. For instance in Russia, a stagger conception should be employed for the main-line railway ($U_n = 3300$ V). In the substations, arresters of the type POLIM-H 4,0 ND are employed (partially two parallel switched), in order to receive the very high energies, which must be received by the switching off of the short circuits at the lowest protection level. It is also possible, if desired, to employ arresters of the type POLIM-H 4,5 ND in special points of the track.

Arresters of the types POLIM-C 4,7 and POLIM-C 5,6 are suited to overhead cables of the railways. With this staggering it is possible to guarantee the residual voltage and the energy absorption capabilities, so that the energies that appear at designated points can be branched off to the earth, and in this way a high protection and availability of the supply is guaranteed.

In the above case, the ABB MO-arresters were designed and tested, in close co-operation with the customer to fulfil particular high demands.

9 Conclusions

Lightning overvoltage and switching overvoltage are a risk for installations and equipment in the electrical railways. MO-arresters assure a reliable protection against unacceptable overvoltage stress. The ABB arresters with the direct moulding of the silicon housing on the active part are particularly suitable for the application in railways, especially on the traction vehicles, because of their high security in all operation cases.

During many discussions with the users of surge arresters it was noticed that a thorough information and co-operation is welcomed. Especially with the electrical railways is this very important because there are particular demands to be fulfilled, and with the modern MO-arresters with silicon housing without spark-gaps new application possibilities may appear. Many individual cases by different railway networks can be solved in this way.

An optimal protection concept, taking into consideration the most favourable solution from the economical and technical point of view, increases the security and the availability of the electrical facilities of the railway current supply.

We offer gladly information and calculations to the protection against overvoltage, which exceed the standard values given above.

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