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Coordination of surge arresters in DC 3 kV railway traction system– field tests

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Abstract—**This paper presents field tests of surge protection devices used at railway lines in Poland. Two types of arresters have been investigated: a horn air spark gap and a varistor. The aim of the field tests was to verify the possibility of coordination of both types of arresters at railway line under normal operating conditions of the electric traction system 3 kV DC.**

Keywords - lightning and overvoltage protection, coordination of SPDs, air spark gap, varistor, railway electric traction system

I. INTRODUCTION

Actual overvoltage protection system of DC 3 kV railway electric traction system in Poland is based on traditional horn air spark gap arresters, which is a classic example of **inherent control**. Unfortunately, application of such system causes a high level of limited overvoltages in electromagnetic environment within overhead contact line zone. As a result, extensive damage of modern railway traffic control systems (including several dozen kilometer long sections along railway line) is caused by the influence of direct lightning strike currents with peak values of order of several dozen kA.

Therefore, to provide electromagnetic compatibility of sensitive to the influence of overvoltage, modern, interoperable railway traffic control systems, such as European Rail Traffic Management System (ERTMS) in Europe and Positive Train Control (PTC) in North America, which were intensively implemented over the last decade - it is necessary to mitigate electromagnetic environment of railway electric traction system through application of **protective control** based on additional arresters, which are able to limit overvoltages to lower levels than in the case of air spark gaps (e.g. varistor type arresters). The main goal of such advancement should be a significant reduction of overvoltages level within electromagnetic environment of railway traction system towards to existing levels corresponding to inherent control. It is essential that properly low overvoltage level of protective control provides the possibility of coordination of surge protection measures applied for low voltage track side equipment and surge arresters of DC 3 kV railway power supply system.

As mentioned above, overhead feeding wires of DC 3 kV railway system in Poland are protected against lightning effects with the use of old type horn air spark gaps, which are installed along railway line at distances of about 1200 m. Due to very high impulse spark over voltage and inconvenient maintenance, substitution of air spark gaps with varistors is under consideration. In contrast to air spark gaps - varistors provide lower protection level, but are not able to withstand surge current of a direct lightning strike. In view of the above and due to the high cost of disassembly of existing arresters, a proposition of supplementing air spark gaps with varistors was introduced. The aim of the field tests described in this paper was to verify the possibility of coordination of both types of arresters along an electrified DC 3 kV railway line.

II. THE TYPES OF POLISH RAILWAY ELECTRIC TRACTION POWER SUPPLY SYSTEMS

In Poland there are nearly 20 000 kilometers of railway tracks, most of which are electrified by overhead traction system with nominal voltage of DC 3 kV direct current power supply. There are two types of traction power supply systems in Poland which differ in the type of connection between metal construction of traction masts and the running rails, as well as in the method of connection of surge protection devices (SPD) to the DC 3 kV traction power supply:

A. Direct connection system

The old type of traction construction assumes direct connection of each individual metal construction of traction masts or portals to the running rails as presented in Fig. 1a). At present, this type of connection does not meet current standards due to the impact of the phenomenon of stray currents and is not used in new or renovated lines. However, there are a lot of old lines in such configuration which are still in use.

In the case of direct connection system, arresters of DC 3 kV traction power supply are connected between overhead feeding wire and running rails, therefore SPD limits voltage, directly affecting the trains. The lightning current is transferred to the running rails, what causes the threat to a sidetrack equipment.

B. Group open connection system

In modern railway tracks, a system with group connection to the rail system in open lay-out is currently used (Fig. 1b). The

Described field tests have been conducted within realization of research and development work „Implementation rules for protection against electric shock from electric traction system, lightning protection and overvoltage protection of railway technical equipment and related infrastructure in aspect of life threat and physical damage elimination” executed on request of PKP Polish Railway Lines, Inc. (agreement No 60/010/0010/14/Z/0 of Aug. 05, 2014)

railway line is divided into group open connection sections of 2,5 – 3,5 km length. In this type of system, metal constructions of traction masts are not directly connected to the running rails. All masts are interconnected with the use of overhead group connection wire and locally grounded at all masts or portals. The group connection wire of each section is connected indirectly to the rails at both ends with the use of a low voltage limiting device (VLD). According to a Polish railway standards required grounding resistance values are: 50 Ω individually for single mast and 2 Ω for each interconnected section. However, in practice grounding resistance of masts may be several times higher.

In this case the surge protection devices of the DC 3 kV traction supply are connected between overhead feeding wires and the group connection wire. This solution is safer due to the following reasons: the group connection wire is the highest part of the railway construction, therefore it intercepts the most of lightning strikes [1], and the lightning current is not transferred directly to the running rails but to the ground through grounded masts.

It should be noticed, that from the point of view of overvoltage protection concept, both types of power supply system differ in the conducting path of surge energy from the railway electric traction system due to the way of arrester connection (Fig. 1.):

a) in the case of direct connection system – between overhead contact line and running rails,

b) in the case of group open connection system – between overhead contact line and grounded group connection wire.

III. SPD USED IN FIELD TESTS

During the field tests for the verification of coordination of surge arresters for protection of DC 3 kV railway electric traction system, two types of SPDs - which are currently used at PKP Polish Railway Lines, Inc. traction system - were investigated: the horn air spark gap type 7310 and the varistor type arrester PROXAR IV 4.5, which is currently used only for protection of power supply feeders at traction substations. Basic properties and parameters of these arresters are described below.

A. Air spark gap type 7310

The air spark gap type 7310 arresters have been used at Polish railways since the 1950s. It is an old type construction presented in Fig. 2. A space between electrodes at the closest distance is 10 ± 1 mm and increases with height to enable extinguishing of arc arising during overvoltage due to DC power supply system of railway line.

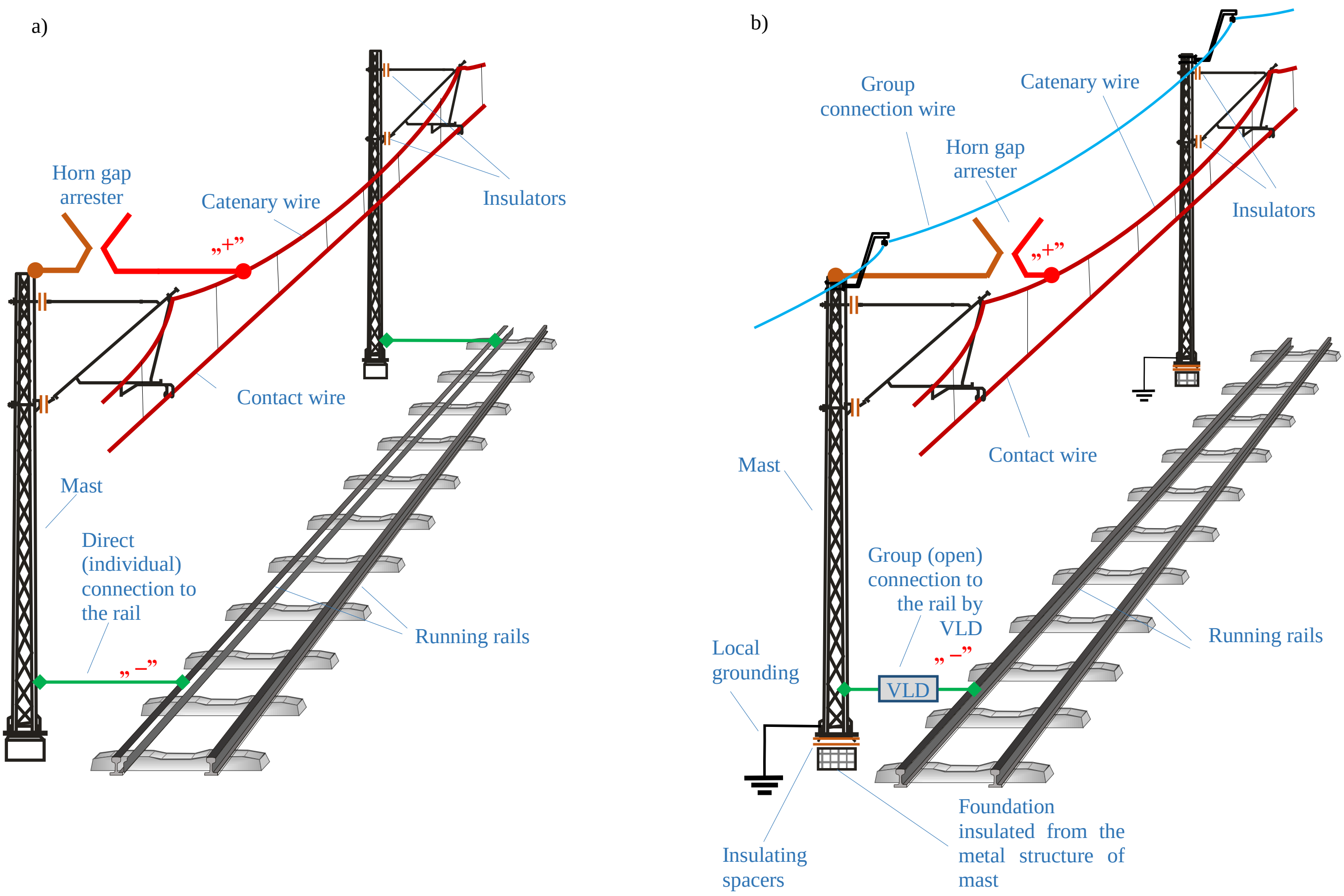


Figure 1. Two types of traction power supply systems DC 3 kV with different connection of conductive parts and SPD to the return circuit: a) the direct individual connection to the rail, b) the group open connection to the rail

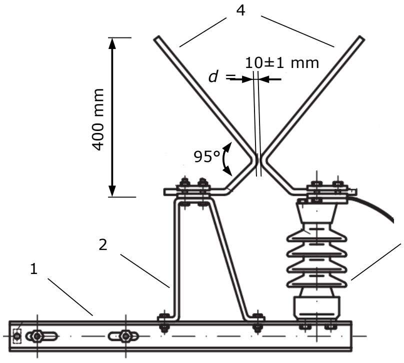


Figure 2. Construction of horn air spark gap type 7310

1) mounting metal base; 2) electrode support; 3) isolator; 4) electrodes

The main advantage of type 7310 arrester is the simplicity of its construction and very high withstand to surge currents. The main disadvantages are high spark overvoltage about 30 ÷ 40 kV and maintenance issues. Such voltage protection level is too high for protection of modern railway signaling equipment According to an information from the PKP Polish Railway Lines, Inc. there have been no cases that an air spark gap was damaged due to lightning current. However, there have been incidents where an arrester was damaged due to large birds (e.g. storks) sitting on electrodes causing long-lasting short circuit and melting of electrodes.

B. Varistor arresters

Varistor type arrester is a voltage limiting device, which impedance – very high in normal operating conditions – changes continuously during overvoltages occurrence. Consequently – contrary to the air spark gap – during its operation, varistor does not cause direct short circuit of electric traction system and therefore there is no following current phenomenon. Currently at traction system of the PKP Polish Railway Lines, Inc. varistor arresters type PROXAR IV 4.5 (Fig. 3) are mounted at feeders in traction substations. Basic parameters of PROXAR IV 4.5 varistor are as follows:

- nominal discharge current I_n: 20 kA 8/20 μs;
- high current impulse I_{hc}: 200 kA 4/10 μs;
- voltage protection level: 11,80 kV at 20 kA 8/20 μs.

There are several types of varistors dedicated for protection of DC 3 kV systems. Parameters of varistors from top manufacturers are very similar. Maximum continuous operating voltage typically equals about 4,5 kV and voltage protection level about 12 kV. Nominal discharge capability is usually 20 kA for the wave of 8/20 μs and 100 kA or 200 kA for 4/10 μs. Manufacturers do not provide information about withstand for 10/350 μs lightning surge current, because standards regarding DC surge arresters for railway applications do not require such tests as obligatory [2]. It is known, that it results from insufficient endurance to high energy surges.

The main advantages of varistors for railway applications are low voltage protection level and lack of following current typical for an air spark gap arrester. The disadvantages are: unknown withstand for lightning current and necessity of additional

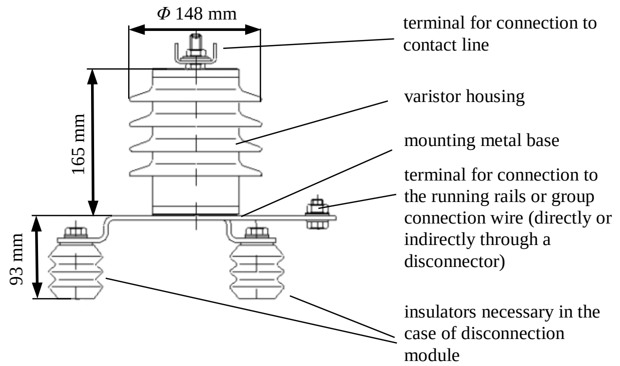


Figure 3. Varistor arrester type PROXAR IV 4.5

damage signalization. In the case of an air spark gap it is easy to identify the damaged arrester, because all parts of its structure are clearly visible. In the case of varistors, damage may not be visible, therefore varistors require additional disconnection modules for the case of the overload of the arrester.

IV. FIELD SITE CONFIGURATION

The field tests were conducted on the following types of railway lines:

- a single-track line with direct individual connection system,
- a double track line with group open connection system.

All tests were carried out in normal operating conditions of a railway line: in operation of DC 3 kV power supply system and train traffic in progress according to normal schedule. At both locations tests were carried out twice: the first tests in autumn 2014 and the second in spring 2015.

Scope of the tests included:

a) the analysis of coordination between a horn air spark gap and a varistor as a function of distance between arresters (60 m, 120 m, 180 m, 300 m and 600 m);

b) the coordination of arresters in configuration air spark gap – varistor – air spark gap, and varistor – air spark gap - varistor;

c) the measurements of voltage distribution along contact line at section protected in configuration air spark gap – varistor – air spark gap;

d) the influence of direct lightning strike to the contact line location for the two cases:

Case A – simulation of direct strike near air spark gap,
Case B – simulation of direct strike near varistor.

Due to the extensive scope of the tests, only selected results are presented and described in this paper.

A. Measurement equipment

During the field tests a mobile high voltage surge generator was used (Fig. 4.). The main part of the generator was located inside a delivery truck to facilitate transportation to the test site. Maximum voltage at open output of the generator was 40 kV

Figure 4. Surge generator post:

1) surge generator; 2) output of the generator's positive pole for connection to the overhead feeding wires + DC 3 kV; 3) output of the generator's negative pole for connection to the running rail or traction mast; 4) high voltage probe at generator output; 5) current probe at generator output; 6) kilovoltmeter for control measurements of voltage loading of capacitors; 7) pneumatic switch to key surge

Figure 5. Local measurement post - currents and voltages of SPDs:

1) special support construction for high voltage probe suspension for traction voltage measurements; 2) movable oscilloscopes; 3) high voltage probe

and short circuit current was up to 20 kA. During the tests, the generator was loaded up to maximum value of 40 kV to provide ignition of air spark gap arresters.

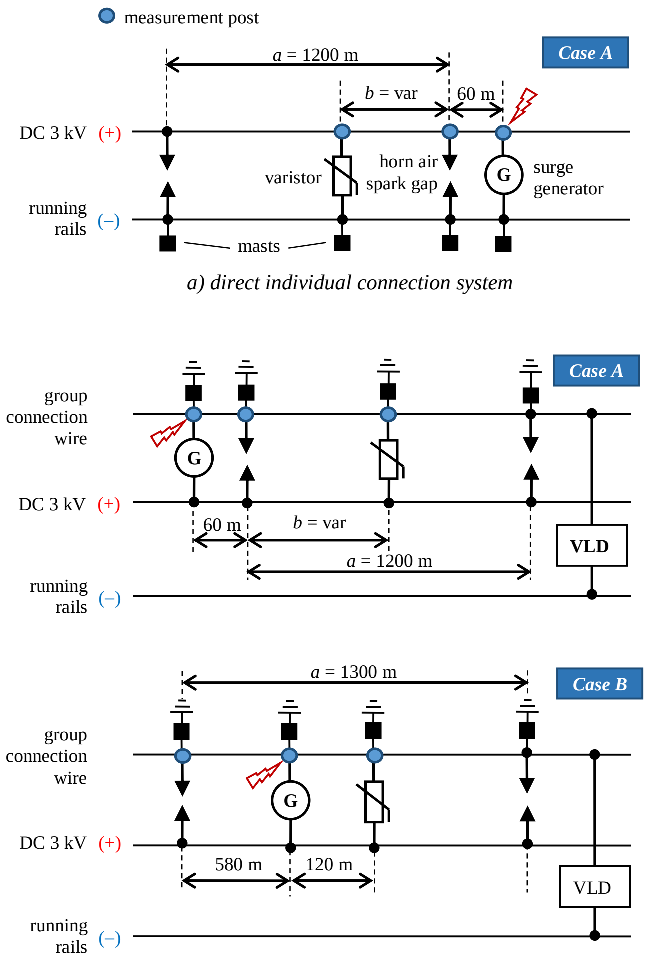
Such value was chosen as optimal to ensure operation of tested arresters and to minimize potential damage of railway infrastructure that may have happened due to the overvoltages occurring during the tests. To secure high certainty of results all measurements of generator's voltage and current were doubled.

The field measurements included voltages at contact line, currents flowing through arresters and additional measurements of different measurands such as touch voltages at different points and currents through masts grounding wire. A special support construction, made of high voltage insulating rods to suspend voltage probes, was used for measurements of voltage at contact line (Fig. 5). In the case of individual direct connection system, current through air spark gaps and varistors was measured on the wire connecting the SPD with the running rails. In the case of open group connection system, current probes were set up on the wire connecting the contact line with the SPD due to distribution of the surge current not only directly to the group connection wire but also to the ground through the mast structure.

All measurements were done with traction voltage DC 3 kV turned on, to simulate normal operating conditions. Any modifications of the measurement set up, especially connecting voltage and current probes, were made with traction voltage turned off and both ends of the railway line section grounded. All personnel operating measurement equipment on the field site were equipped with insulating footwear for the safety precautions.

B. Field site set up

At each location distances between the existing air spark gaps were adjusted to about a = 1200 m. Varistors were



a) direct individual connection system

b) group open connection system,

Figure 6. Configurations of field test:

a) direct individual connection system; b) group open connection system: *Case A* – simulation of lightning strike near a horn air spark gap; *Case B* – simulation of lightning strike near a varistor connected at different locations to investigate the effect of the distance b between both types of arresters (Fig. 6).

At both field tests *Case A* of direct strike near an air spark gap, simulation was investigated. The Generator was connected to the railway at about 60 m (distance between masts) from the mast with the nearest air spark gap installed. Varistors were connected (one varistor at a time) on the opposite side at different distances from the air spark gap b = 60 m, 120 m, 180 m, 300 m, 600 m (middle of section between air spark gaps).

Case B – simulation of direct lightning strike near a varistor – was investigated only at field site with open group connection system. The Generator was connected about 120 m from the varistor installed in the middle section between two air spark gaps (Fig. 6b). The Distance from the varistor to the air spark gaps at both sides was respectively 700 m and 600 m.

V. RESULTS

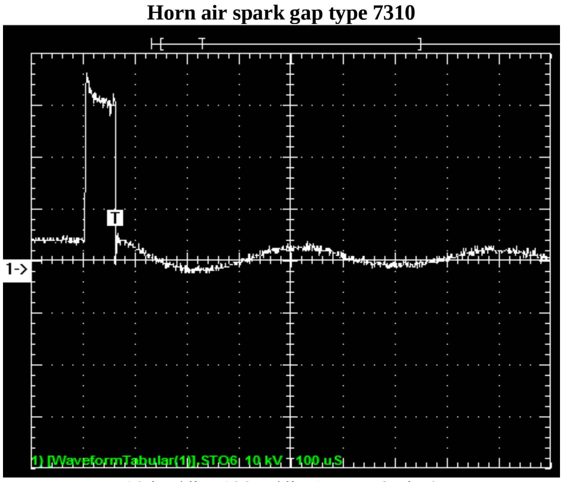
A. Air spark gap vs. varistor

During the field tests, each type of arrester was investigated separately to measure its basic parameters. The Horn air spark gap was tested at field site without any varistors connected. The Varistor was tested as installed 60 m from air spark gap, what caused that only the varistor was operating (no spark over at air spark gap). The exemplary measurement results of voltage between contact line and running rails at arresters location and surge currents through arresters are presented in Fig. 7.

The most important difference between the two types of tested arresters is a voltage protection level. In the case of the horn air spark gap, maximum voltage was about 35 kV in comparison to about 12 kV measured in the case of the varistor. Therefore, voltage protection level provided by a varistor is about three times lower than in the case of an air spark gap.

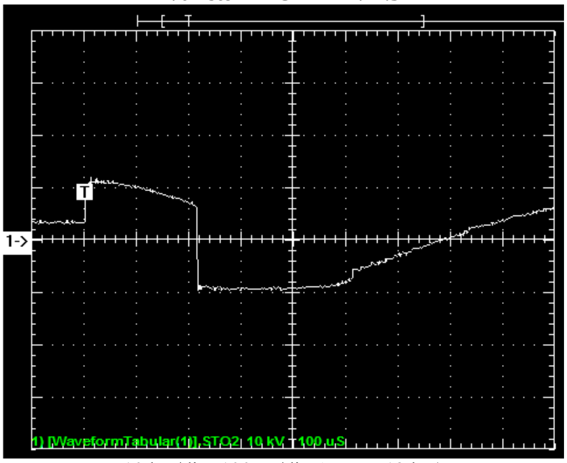
The second difference is current flowing through an arrester. In the case of an air spark gap, which causes short circuit during spark over, measured peak value of surge current was about 11 kA and its waveform shape was dumping oscillations. The current through a varistor was significantly lower (~4,5 kA), because of higher impedance of the arrester. The other thing is following current phenomenon, which occurs only in the case of an air spark gap due to the caused short circuit. The exemplary waveform of following current is presented in Fig. 8. The time of the following current extinguish is much longer than the surge duration time therefore Fig. 8. is presented in expanded timescale.

Horn air spark gap type 7310

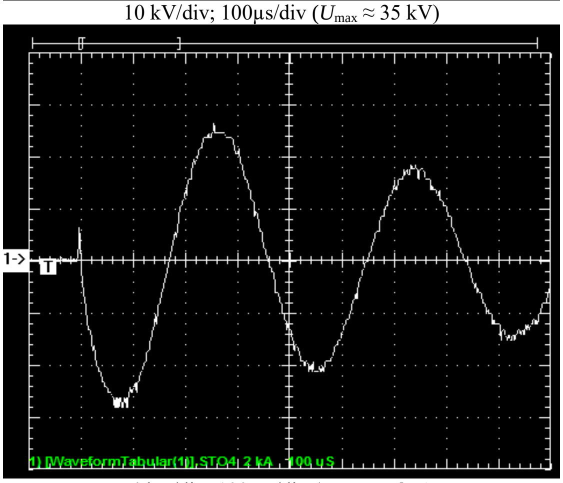


10 kV/div; 100µs/div ($U_{max} \approx 35$ kV)

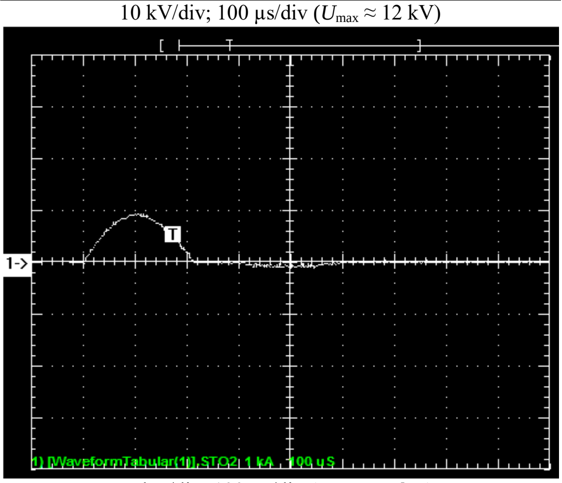
Varistor PROXAR IV 4.5



10 kV/div; 100 µs/div ($U_{max} \approx 12$ kV)

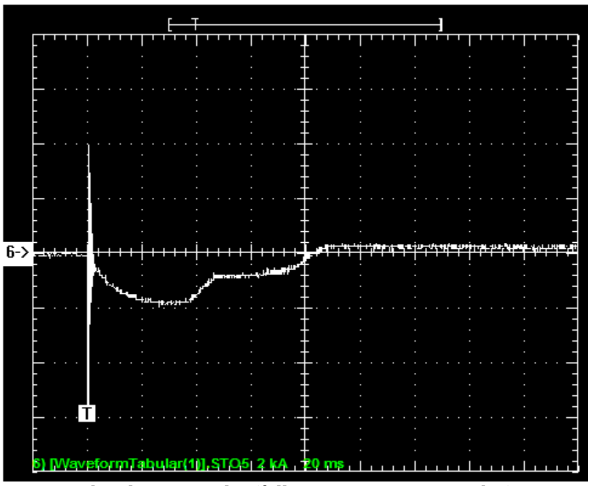


4 kA/div; 100 µs/div ($I_{max} \approx 11$ kA)



5 kA/div; 100 µs/div ($I_{max} \approx 4{,}5$ kA)

Figure 7. The examplary results of voltage (upper waveforms) mesured between contact wire and running rails and surge current (lower waveforms) through arrester in the case of the horn air spark gap type 7310 and the varistor type PROXAR IV 4.5



4 kA/div; 20 ms/div (following current $I_{max} \approx 4$ kA)

Figure 8. The examplary result of following current through an air spark gap

B. Coordination – Case A

From the point of view of surge protection, coordination of at least two SPD arrangement is a situation where a first stage device intercepts the main energy of a surge current and a second device provides lower protection level. In the case of the analyzed overvoltage protection system, as first and second stage devices are a horn air spark gap and a varistor respectively. Therefore, as a state of coordination, a situation when a horn air spark gap is operating was assumed.

Coordination of a horn air spark gap and a varistor arrangement along electric traction system was verified for *Case A* presented in Fig. 6 for different distances *b* between arresters. Because the maximum value of voltage at the generator output (40 kV) was close to the theoretical value of spark overvoltage of the air spark gap, a distance between electrodes was reduced from *d* = 10 mm to 6÷8 mm to ensure operation of the horn air spark gap.

To evaluate coordination of the arresters, a positive to negative results ratio was introduced –where a positive result is assumed in a situation when a horn air spark gap is operating (spark over between electrodes).

The table I presents results obtained at both field sites during all performed tests for simulation of direct strike near an air spark gap - *Case A*. Following columns present the time of the tests (month and year), the distance *b* between the arresters, the distance *d* between the electrodes of the air spark gap and the positive to negative results ratio.

In the case of the railway line with direct individual connection system, coordination was obtained successfully for the distance *b* = 600 m between arresters at both test periods and for the b = 300 m at the second test period. The gap between the electrodes of the horn arrester was *d* = 8 mm in both cases.

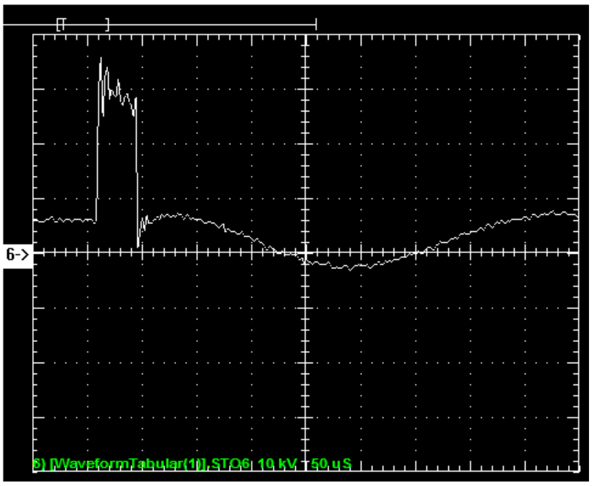
In the case of open group connection system, tests indicated worse coordination conditions. To obtain coordination, the distance between air spark gap electrodes had to be reduced more than in the case of direct individual connection system. Analyzing the results presented in Table I, it should be noticed that the tests in November 2014 were carried out in disadvantageous conditions: low temperature and low humidity, what influences conditions of spark over between electrodes of a horn air spark gap. The weather conditions were the reason of not operating an air spark gap in November 2014 in the case of 7 mm gap between electrodes while in May 2015 for the same gap distance and the same distance between the arresters a coordination was successfully obtained.

The exemplary results of coordination for *Case A* are presented in Fig. 9. Voltage and current waveforms measured at the horn air spark gap (Fig. 9a) and the varistor (Fig. 9b), and surge current at the generator output (Fig. 9c) are presented for the situation of the railway line with group open connection system and the distance between arresters *b* = 600 m. In the case of the presented results, the most of a surge current was intercepted by the horn air spark gap, therefore this situation is a precise coordination example of the arrangement of two SPD types. The other results, where air spark gap was also operating, show that the value of current flowing through a varistor increases with the reduction of distance *b* between arresters.

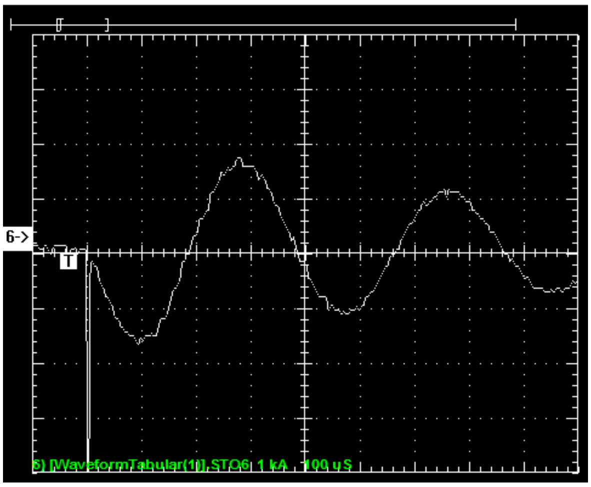
TABLE I. RESULTS OF COORDINATION TESTS (CASE A)

Period of tests	**Distance between an air spark gap and a varistor**	**Gap between air spark gap horns**	**Positive to negative results ratio**
Direct individual connection system			
10.2014	60 m	*d* = 8 mm	0/2
	600 m		2/0
04.2015	60 m	*d* = 8 mm	0/3
	120 m		1/2
	180 m		1/3
	300 m		2/0
	600 m		3/0 (12/1)*
Group open connection system			
11.2014	60 m	*d* = 7 mm	0/1
	120 m		0/2
	180 m		0/1
	300 m		0/3
	600 m		0/8
	60 m	*d* = 6 mm	1/2
	120 m		2/0
	600 m		2/0
05.2015	60 m	*d* = 7,5 mm	0/2
	120 m		0/2
	180 m		1/2
	300 m		3/2
	600 m		1/2
	600 m	*d* = 7 mm	2/0

* numbers in brackets corresponds to all surge tests for given field test configuration including other measurements



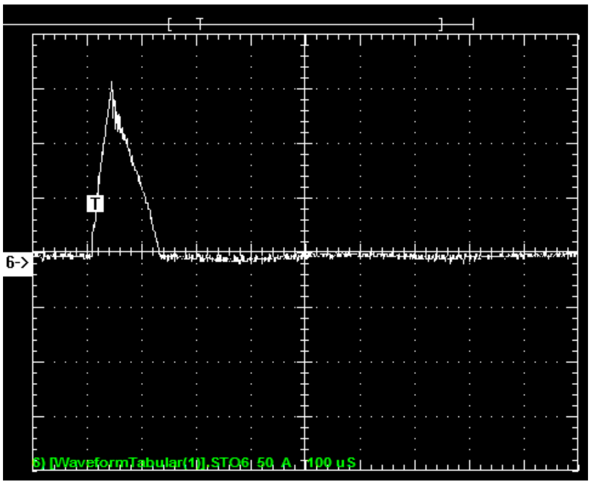
10 kV/div, 50 µs/div



5 kA/div, 100 µs/div (I_{max} = 8 kA)

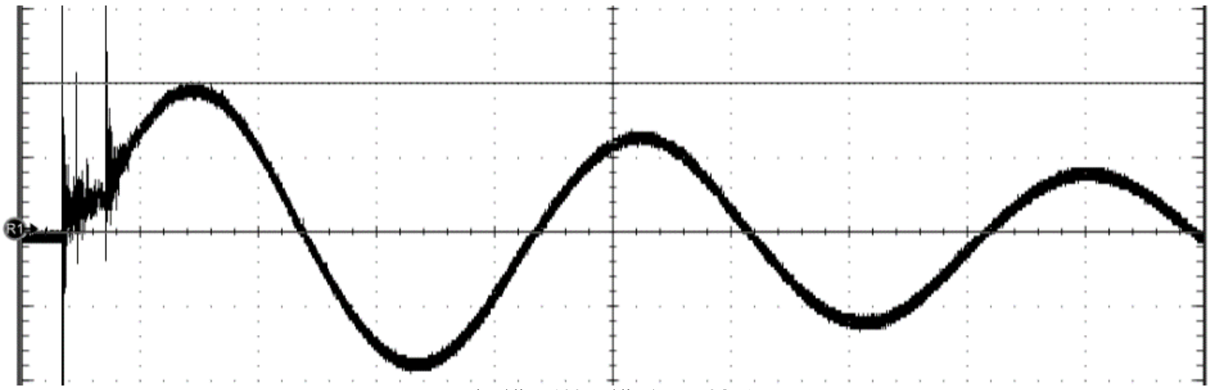
a) Voltage and current of a horn air spark gap

5 kV/div, 50 µs/div



250 A/div, 100 µs/div (I_{max} = 0,75 kA)

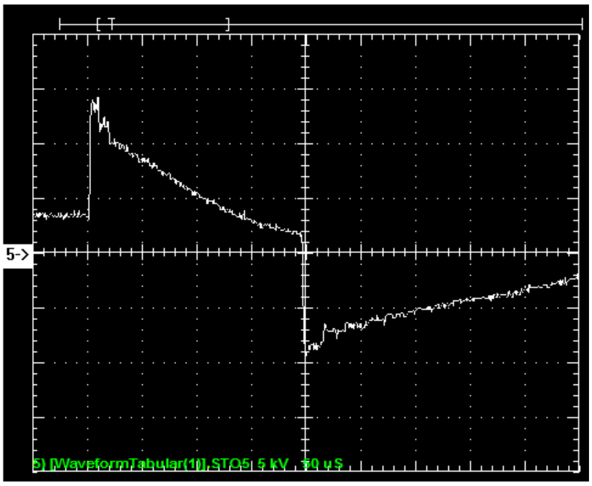
b) Voltage and current of a varistor

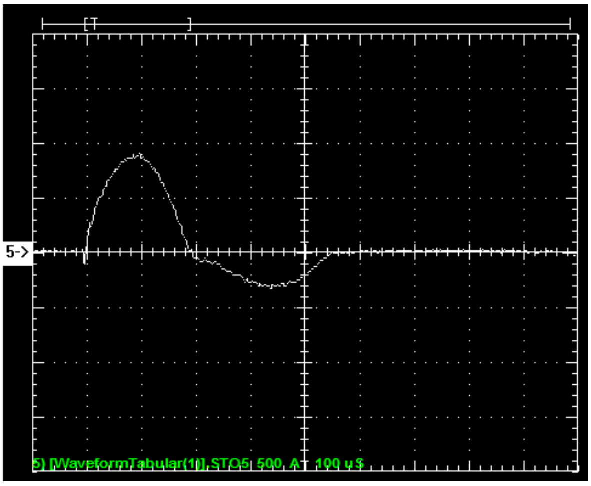


5 kA/div, 100 µs/div ($I_{max} \approx$ 9 kA)

c) Surge current at generator output

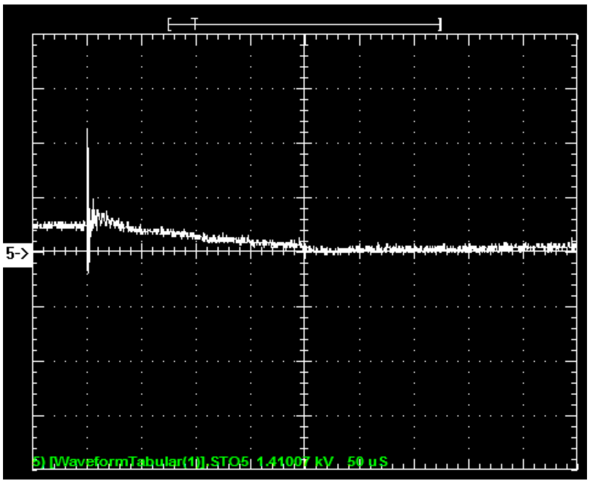
Figure 9. Voltage and current waveforms of a horn air spark gap and a varistor at railway line with open group connection system in the case of simulation of direct lightning strike near an air spark gap (configuration according to Fig. 6b - *Case A*, distance between arresters b = 600 m)

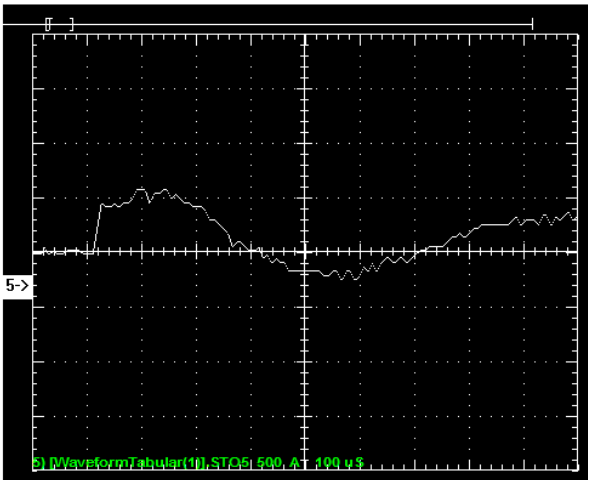




5 kV/div, 50 µs/div — 2,5 kA/div, 100 µs/div ($I_{max} \approx 4{,}5$ kA)

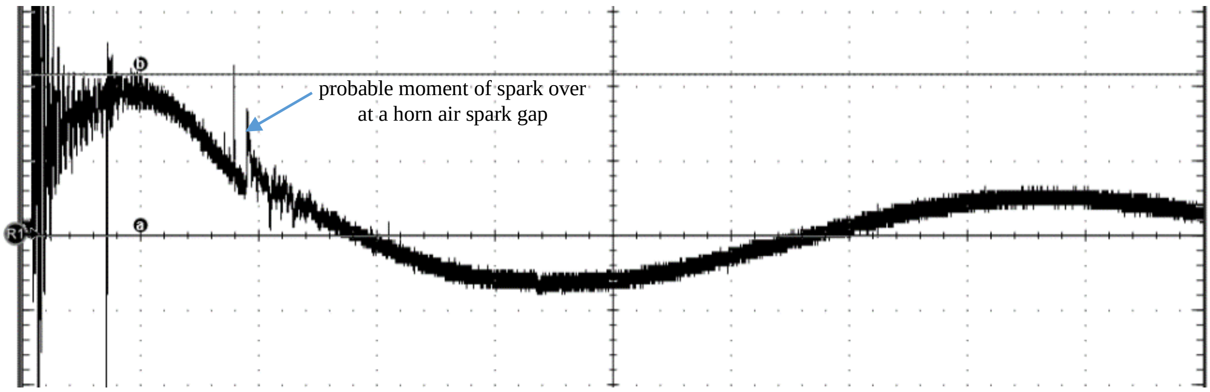
a) Voltage and current of a varistor





10 kV/div, 50 µs/div — 2,5 kA/div, 100 µs/div ($I_{max} \approx 2{,}5$ kA)

b) Voltage and current of a horn air spark gap



2,5 kA/div, 100 µs/div ($I_{max} \approx 5$ kA)

c) Surge current at generator output

Figure 10. Voltage and current waveforms of a varistor and a horn air spark gap at railway line with open group connection system in the case of simulation of direct lightning strike near a varistor (configuration according to Fig. 6b) *Case B*, distance between arresters $b = 700$ m)

For both field sites coordination was obtained at the distance between the horn air spark gap and the varistor $b = 600$ m, which is a situation when a varistor is placed in the middle of a typical section between horn air spark gap arresters.

C. Coordination – Case B

It should be noticed that *Case A* is a simulation of an idealized situation when a lightning strikes close to a more durable device which is a horn air spark gap. In practice, due to insufficient withstand of varistors to carrying partial lightning currents (10/350 µs) the worst case should be assumed when a lightning strikes near a varistor, therefore *Case B* was also investigated.

Simulation of direct lightning strike near a varistor – *Case B* – was investigated only during the last period of the tests at field site with open group connection system. The Exemplary results for *Case B* are presented in Fig. 10 in analogic way to the results presented for *Case A* (Fig. 9). The waveforms correspond to configuration presented in Fig. 6b) *Case B*.

As expected in such configuration, the most of surge current is intercepted by the varistor, however, the air spark gap is also operating. Therefore, it can be assumed that even in the worst case – which is direct lightning strike near a varistor – an air spark gap will intercept part of the lightning current energy reducing the exposure of a varistor.

D. Results analysis

To coordinate arrangement consisting of a horn air spark gap and a varistor installed along railway line it was necessary to reduce the distance between electrodes of the air spark gap arrester. It was necessary due to the restrictions related with voltage limited up to 40 kV at generator output and steepness of applied surge current ($\mathrm{d}i/\mathrm{d}t \approx 0{,}1$ kA/µs). Obtaining coordination in such conditions allows to assume that in actual conditions of direct lightning strike, where overvoltage reaches at least hundreds of kV and steepness of lightning current is much higher ($\mathrm{d}i/\mathrm{d}t \approx 10 \div 20$ kA/µs), coordination of such overvoltage protection system will be even more assured.

Although, according to the obtained results, coordination of the tested arresters is possible in the case of closer distances than 600 m, it would not have practical justification. Currently, a typical distance between horn air spark gaps along railway line is about 1200 m. Such distance was defined in the 1950s as sufficient for the protection of electric traction isolators. Therefore, the most sensible solution is to supplement railway line with varistors connected in the middle of sections between horn air spark gaps.

The overvoltage protection system consisting of coordinated horn air spark gaps and varistors installed alternately at distances of 600 m from each other along railway line provides lower voltage protection level for electromagnetic environment of railway electric traction system. In such configuration damage of varistors cannot be excluded in situation of direct lightning strike close to the varistor, however, complete surge withstand of such system will be definitely higher than in the case of system consisting only of varistor type arresters.

A disadvantage of such system is a phenomenon of following currents occurrence associated with operation of horn air spark gaps, what affects operation of traction substations. However, it should be noticed that parameters of modern high speed DC circuit breakers used at traction substations allow to secure extinguishing of following current without interruption of train traffic at railway lines.

Additional measurements including VLD did not indicate its contribution in distribution of surge currents but it can be stated that application of coordinated overvoltage protection system improves electromagnetic environment for operation of VLD. However, further researches are necessary in this area.

VI. Summary

The main conclusion from the conducted tests is the confirmed validity of the varistor type arresters for protection of DC 3 kV railway electric traction system in coordinated arrangement with existing horn air spark gaps. Conducted tests proved that coordination of existing horn air spark gaps with varistor type arresters is possible in order to reduce overvoltages within DC 3 kV traction system. Horn air spark gaps in such configuration conducts significant part of lightning current from the traction system and varistors provide several times lower voltage protection level than horn air spark gaps up to 12 kV at the point of their installation. Such protection system would improve electromagnetic environment of a railway electric traction system and provide better conditions for modern trackside equipment of train traffic control systems especially in cases when lightning strikes near a horn gap arrester location. Therefore, expensive disassembly of horn air spark gaps at modernized railway lines is not necessary. However, situation of lightning strike near varistor cannot be excluded as the worst case, where the semiconductor arrester is exposed to surge currents exceeding its critical parameters.

Taking into consideration threats caused by surge currents, transferred from traction system to the group connection wire or to a running rails, location of electronic sidetrack equipment should always be properly chosen at design stage. Furthermore, modern sidetrack equipment - based on microchip technology - requires additional protection measures such as dedicated surge protection devices which can provide properly low voltage protection levels.

Due to current modernization of railway system and implementation of open group connection system – the application of coordinated overvoltage protection system consisting of horn spark gaps and varistors in conjunction with lightning protection zones provided by overhead group connection wire seems to be simple and very effective protection measure providing improvement of train traffic safety even in the case of direct lightning strikes to the railway traction system.

The field tests provide the essential conclusions, cannot always be obtained from theoretical analysis or computer simulations. Therefore, it is important to continue field tests to develop further recommendations regarding varistor type arrester location with reference to optimal protection of modern trackside equipment of train traffic control systems.

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