Overvoltages in DC Urban Light Railway Systems: Statistical Analysis and Possible Causes

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***Abstract*—In DC light railway systems the equipment in the power substations and certain devices along the lines are protected against lightning overvoltages thanks to surge arresters. This paper analyses the overvoltages occurring on the tram network of Torino, Italy to discover the causes that brought to the explosion of several surge arresters in the past years. The cause is found to be the regenerative breaking of a particular type of vehicles, in conditions of low load in the system. The benefits of regenerative breaking are discussed in the light of the possible problems introduced. Finally, possible solutions are proposed.**

I. Introduction

DC light railway systems are used for public transportation in many cities worldwide. For these systems the DC power supply, at different voltage levels, is commonly used [1].

For these DC tram networks, the Traction Electrification System (TES) is normally fed by power substations, which contain the power transformers, AC/DC converters, protective relays and circuit breakers; from these substations several DC feeders (positive cables) are used to energize the Overhead Contact System (OCS). The return current is collected by the rails and by the negative cables [2]. The OCS is divided in electric zones, each fed by a single substation at a time, with the possibility of a reserve feeding substation.

In previous works the authors have studied ground faults inside the substation and along the lines, describing therefore accurately the structure of the network and developing appropriate steady state models for the different elements which constitute the TES [2], [3]. Also normal operation and fault currents have been studied, in order to properly set the digital protection relays for correct short circuit discrimination [4]. In this work, instead, the focus is on overvoltage protection of TES components.

The contact lines of electric railways are in fact exposed to direct and to indirect lightning overvoltages. These overvoltages may cause flashover of the line insulation and, travelling along the lines, may enter the supply substations and stress or even damage the insulation of the equipment inside. Overvoltages may also appear on the track and, travelling along it, stress the insulation of the electronic equipment connected to it [5]. For these reasons, the components installed in the power substations (measurement devices, AC/DC converter, etc.) and certain devices installed along the lines and fed by the DC voltage of the OCS (e.g. switches, signals, etc.) are normally protected against lightning overvoltages by Surge Protective Devices (SPDs). SPDs are installed in the network near the components that must be protected and in the substation between the positive conductors and ground.

In DC urban light railway systems, however, different types of overvoltages, called internal overvoltages, can occur. Internal overvoltages are generated during normal operation of the system and can be caused by switching operations [6] or regenerative breaking [7].

This paper deals with the problem of internal overvoltages in the tram network of Torino, Italy. In recent years, in fact, due to the change in the operation practice of the network and to the change of the number and type of circulating vehicles, several SPDs exploded, creating big damages in the switchboards inside the substations. This caused unacceptable service interruption and economic losses for the network operator. A picture of a damaged SPD is showed in Fig. 1 as an example.

In order to find out the origin of the overvoltages that caused damages to the SPDs a measurement campaign was performed in a power substation. The measured overvoltages have then been analysed.

As different clues were indicating that probably the responsible for the overvoltages was a specific type of vehicle circulating in the network, a second measurement campaign was then organized on board of a vehicle. The idea was to correlate the behavior of the vehicle to the overvoltages measured in the substation.

In the rest of the paper the correct choice of surge arresters is discussed, the two measurement campaigns are presented, the results are analyzed, the probable causes of the overvoltages are described and a discussion on the possible solutions is presented, also discussing the types of SPDs that are currently installed in the network. Finally, the benefits of regenerative breaking are discussed in the light of the possible problems introduced.

Fig. 1. Exploded SPD.

II. Surge Arresters and Overvoltages

As previously mentioned, surge arresters are installed in the tram network near the components that must be protected, and in the substation between the positive conductors and ground. A correct choice of the surge arresters, however, is not easy [6].

The main rules for the choice and installation of SPDs are provided, in Europe, by the Standard EN 50526-1 [8] and by the Application Guide EN 50526-3 [5]. In order to protect the equipment, it is necessary to properly coordinate the characteristics of the SPDs with those of the protected insulation.

The protection is effective if the protection level provided by the SPD U_{pl} (the maximum residual voltage for the nominal discharge current) is lower than the lightning impulse withstanding level of the equipment to be protected, with enough margin. Indications on the insulation coordination are provided by standard EN 50124-1 [9].

The maximum internal overvoltages generated in the system must also be evaluated, as it is necessary to verify that the charge transfer capability Q_T (maximum charge per impulse that can be transferred during the charge transfer test and during the operating duty test) of the SPD is not exceeded.

TABLE I
Arrester Classification

Class	Charge transfer capability Q_t [As]	Nominal discharge current I_n [kA]
DC-A	1.0	10
DC-B	2.5	10
DC-C	7.5	20

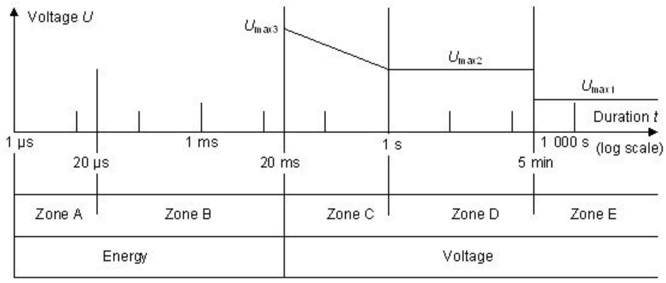

Fig. 2. Overvoltages classification.

For this purpose, surge arresters are classified by Standard EN 50526-1 [8] in three categories, as reported in Table I.

For equipment connected to the OCS, information on internal overvoltages can be found in Annex A of EN 50163 [10] and in section 5.7 of EN 50123-2 [11] for switching overvoltages. The highest switching overvoltage may be assumed to be 3 - 4 times the nominal voltage as the arc voltage in the circuit breaker is limited to four times the nominal voltage.

In general, overvoltages similar to switching overvoltages can occur every time a current is interrupted in the DC system [6], for example in case of:

- DC Circuit Breaker Operation (including rapid breakers on vehicles);
- pantograph arcing, due to an uneven pantograph contact with the OCS wire at crossings or at the commutation between two zones;
- voltage transient due to dv/dt across diodes;

These switching overvoltages should be of short duration (in the meaning intended by EN 50124-2 [12] shorter than 20 ms) but should not be neglected in the design phase as they can impact vehicles and surge arresters [13].

A different type of overvoltages can instead take place because of regenerative breaking of vehicles, when the network is non-receptive [7]. This can be due to incorrect design of the vehicle control system, to malfunctioning, or to modifications of the electric circuits on board of the vehicle, made by the maintenance technicians to solve other problems.

A classification of the overvoltages and of their duration is provided by Standard EN 50163 [10] and then detailed by Standard EN 50124-2 [12] and is reported here in Fig. 2.

Where:

- Zone A includes lightning overvoltages;
- Zone B includes switching overvoltages, due to high impedance phenomena (currents switched off in inductive circuits);

TABLE II
OVERVOLTAGES

Nominal voltage U_n [V]	750	1500	3000	15000	25000
Coefficient k	0,0611	0,0676	0,0673	0,0767	0,0741
U_{max1} [V]	900	1800	3600	17250	27500
U_{max2} [V]	1000	1950	3900	18000	29000
U_{max3} [V]	1270	2540	5075	24300	38750

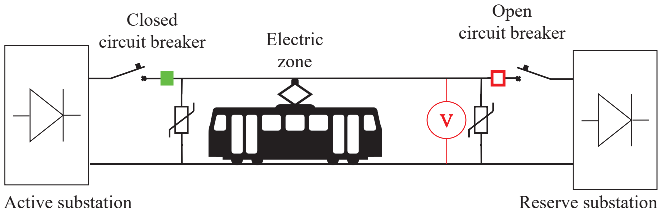

Fig. 3. Measurement scheme.

- Zone C includes temporary overvoltages, due to low impedance phenomena (voltage variations on primary network). NOTE: The Term temporary overvoltage is identical to the term long-term overvoltage in EN 50163; the variation of the ratio U/U_{max2} versus duration is identified by $U = U_{max2}t^{-k}$ where:
  - t is the time in seconds (0,02 s $\leq$ t $\leq$ 1 s);
  - k is the coefficient given in Table A.1 of standard EN 50124-2;
- Zone D includes non-permanent voltages, that must be lower than U_{max2};
- Zone E represents permanent voltages, that must be lower than U_{max1}.

The maximum voltages and coefficient k values defined in Table A.1 of standard EN 50124-2 are reported in Table for the reader's convenience.

The overvoltages caused by regenerative breaking of vehicles can exceed the limits described in Fig. 2 and can strongly stress the equipment that must be protected and surge arresters.

III. OVERVOLTAGES MEASUREMENT CAMPAIGN IN THE SUBSTATION

To find out the origin of the overvoltages that caused damages to the SPDs, a high speed digital recorder has been installed inside a power substation, measuring the voltage between positive and negative conductors feeding an electric zone of the network.

The recorder was installed in the reserve feeding substation, where the circuit breaker was open, as shown in Fig. 3.

In Torino the nominal voltage of the TES is 600 V and a trigger was set at 800 V in order to record the phenomena leading to overvoltages in the system. The recorder was left in the substation, measuring all the overvoltages, from October 30th 2017 to November 14th 2017. In the 16 monitored days, a total number of 207 overvoltage transients have been recorded. Two main types of overvoltages have been measured: short spikes and long overvoltages. Two examples are presented in Fig. 4 and Fig. 5 respectively.

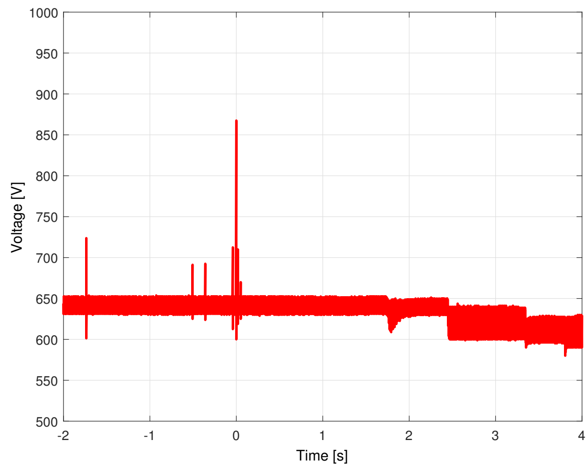

Fig. 4. Short spike overvoltage.

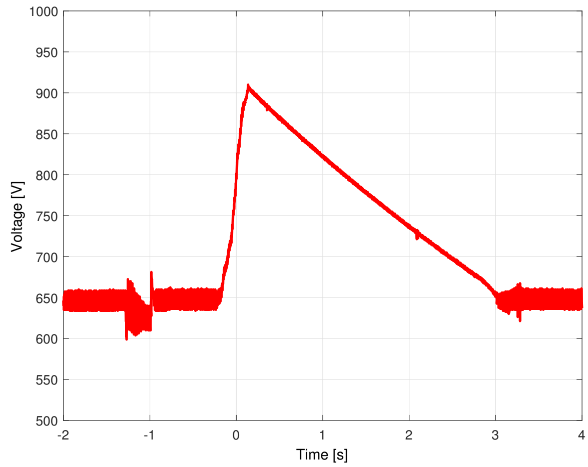

Fig. 5. Long overvoltage.

In order to understand the causes of the two types of overvoltages, a statistical analysis was then performed. The main parameters taken into account in the analysis were the day and time of occurrence, the peak value and the duration of the overvoltages.

The analysis showed that there is no difference between working days and holidays. The distribution in the different times of the day instead is not homogeneous. The bubble chart in Fig. 6 presents all the measured overvoltages. From the position of the bubble in the chart is possible to understand the time of the day of occurrence and the peak value of the overvoltage. The radius of the bubble indicates the overvoltage duration. It can be observed that the short overvoltages occur homogeneusly at all times of the day, while the big bubbles, that are the long overvoltages, are concentrated in the night hours.

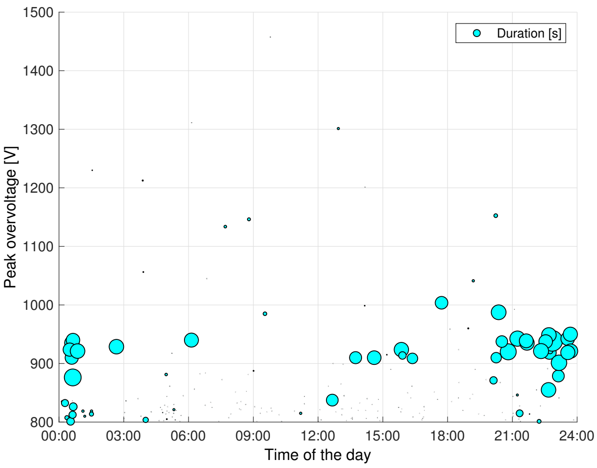

Fig. 6. Overvoltages characteristics.

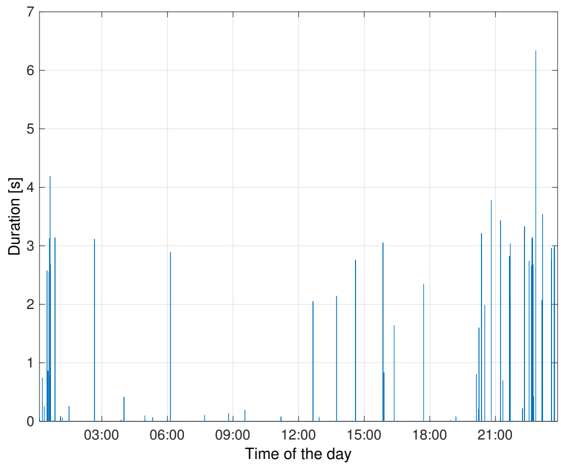

Fig. 7. Overvoltages duration.

The maximum peak during the monitoring was approximately 1460 V even if most of the overvoltages were below 1000 V. Many overvoltages had a duration longer than 1 s, as is clearly visible in Fig. 7.

It must be highlighted that several overvoltages exceeded the limits of duration and peak value presented in Fig. 2. This can be clearly seen in the comparison between the measured overvoltages and the limits defined by Standard EN 50124-2 [12] presented in Fig. 8.

As most of the long overvoltages take place at night, when the number of vehicles in the network is reduced, it is possible to guess that the cause may be the regenerative breaking of vehicles when the network is not receptive due to the reduced load.

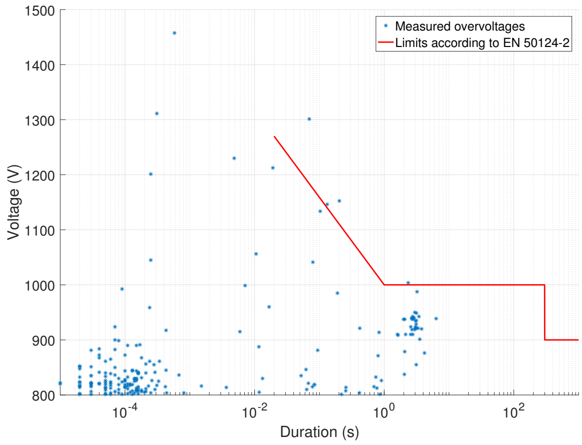

Fig. 8. Comparison between the measured overvoltages and the limits defined in Standard EN 50124-2.

IV. Overvoltages Measurement Campaign on the Vehicle

To correlate the overvoltages measured in the substation with the behavior of the vehicle suspected to be the cause, a second measurement campaign was organized on board. In this case two digital high speed recorders were used: one was set to record the line voltage and the current absorbed/injected by the vehicle during the different phases of acceleration, coasting and braking; the second was set, as in the substation, to measure overvoltages with a trigger at 700 V.

It was discovered that in zones with no other vehicles absorbing power, the tentative regenerative breaking was leading to overvoltages similar to the long ones measured in the substation. An example of breaking overvoltage measured on the vehicle is showed in Fig. 9. In this figure it is in fact clearly visible that after a short acceleration phase, when the driver is starting the braking phase, as the line voltage is already above 650 V the vehicle does not manage to inject a significant current in the network and makes the voltage rise up to 950 V.

When instead the line voltage is low due to high load in the zone (below 600 V) the regenerative breaking is working properly, as shown in Fig. 10. In this figure, after a long acceleration phase, the driver is breaking. The regenerative breaking injects up to 140 A back into the TES.

V. Discussion

The torque and speed control during acceleration and electric braking in the studied vehicle is done by a chopper. When the driver decides to brake, the logic of the vehicle tries to inject the generated current into the TES. If the network is not receptive, the injected current charges the capacitances (in particular the vehicle filter capacitor). If the voltage rises above a certain threshold, the on-board logic activates the rheostatic braking by closing a specific gate turn-off thyristor (GTO), draining a portion of the generated current on a rheostat placed on the vehicle imperial. A small delay in the activation

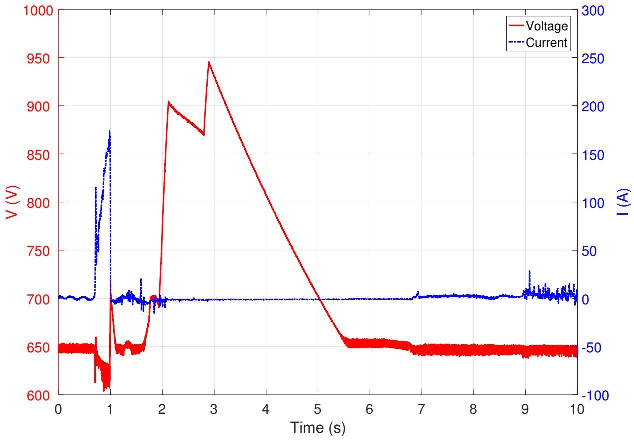

Fig. 9. Overvoltage measured on the vehicle.

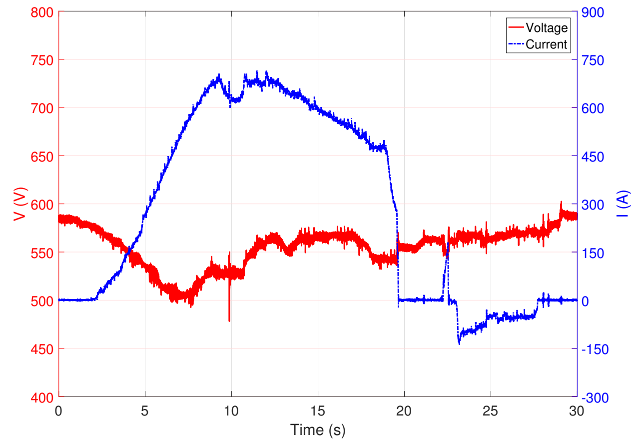

Fig. 10. Overvoltage measured on the vehicle.

of the rheostatic braking GTO is sufficient to produce high overvoltages in the network.

The energy produced and re-injected into the TES during regenerative breaking was measured during normal vehicle operation. To cover the distance of 17.7 km the absorbed energy was 59 kWh, the energy re-injected in the TES thanks to regenerative breaking was 0.82 kWh, thus leading to a net consumption of 58.2 kWh. It is clear that the recovered energy during regenerative breaking is very small (less than 1.4% of the absorbed energy) and does not justify the overvoltage problems created.

The overvoltages, in fact, can create important economic damages to the system operator, in terms of service interruption and of damage to the components. One of the exploded surge arresters, for example, triggered an electric arc inside the switchboard in a substation, requiring the complete substitution of the switchboard cubicle. Before the operator was able to complete the cubicle substitution, an electric zone of the TES was left without possibility of reserve power supply, with a strong impact on system reliability.

Furthermore, the explosion of surge arresters can involve serius risks for the people. For the arresters installed in the substations the risk is only for the employees, while for the arresters installed to protect equipment along the tramway lines, the risk is for the general public.

Two are the possible ways to solve the problem presented in this work: changing the surge arresters to reduce the risk of explosion (Section V-A) or reducing the generated overvoltages (Section V-B).

A. Arresters Substitution

The easiest way to reduce the probability of arrester explosion is the substitution of SPDs with new ones with higher continuous operating voltage U_c. Standard EN 50526-3 [5] requires that for the arresters to be connected to the contact line voltage, the minimum value of U_c shall be equal to or higher than the highest non-permanent voltage U_{max2} reported in table II. This is already verified in Torino, as the system nominal voltage is 600 V and the arresters have a continuous operating voltage $U_c = 1kV$. It is still possible to increase the continuous operating voltage, choosing for example an arrester with $U_c = 2kV$. This would certainly solve the explosion problem, but will also increase the protection level U_{pl} provided, exposing the protected devices to higher overvoltages. A higher U_{pl} would not be a problem for the recently installed cables, that have nominal voltages higher than 2 kV. On the contrary, all the equipment installed in the past would suffer and would need to be substituted with extremely high costs.

A second and more interesting possibility is to substitute the arresters with higher class ones. The arresters installed in Torino are class A or class B arresters. Installing class C arresters would increase the charge transfer capability Q_t to 7.5 As, without negatively impacting the protection level and reducing the risk of explosion.

B. Overvoltages Reduction

A better but more difficult way would be to solve the problem at its source, eliminating the regenerative breaking overvoltages. This could be done modifying the operation of the vehicles, modifying the network operation, or installing additional devices.

A modification of the vehicle involves modifications on the on-board logic, that on old vehicles is not an easy task. Moreover, a modification in the braking system would require new costly tests and certification.

An interesting possibility could be a different operation of the network. Now the electric zones are fed by a single substation, with an open circuit breaker in the reserve substation. The power generated by a braking vehicle in one zone has therefore to be absorbed by an accelerating vehicle in the same zone or in the other few zones fed by the same power substation. By feeding all the zones in parallel by two substations, the TES would become a unique big meshed system, greatly increasing the probability of having an accelerating vehicle capable to consume the power generated during braking. This solution, however, would require an accurate analysis of the current flows in the meshed TES and a modification of the overcurrent protection system.

A third possibility would be the installation of additional devices to harvest the energy generated during breaking when the network is not receptive [14], [15]. These devices could be super-capacitors installed on the vehicles or in power substations [16] or flywheels installed on the DC bus-bars in power substations [17]. Particular care should be put in the design of such systems in order to properly reduce the overvoltages.

VI. Conclusion

This paper analyses the overvoltages occurring in the tram network of Torino, Italy, to find out the causes that brought to the explosion of several surge arresters in the past years. Two types of internal overvoltage are detected: spikes and long overvoltages. Thanks to an analysis of the date and time of occurrence, of the peak and of the duration of the overvoltages, it was possible to understand that the first type is due to switching, while the second type is due to regenerative braking of a particular type of vehicles, in conditions of low load in the system.

It is interesting to highlight that some of the measured overvoltages exceed the duration and peak limits provided by Standard EN 50124-2, which are normally used as a guideline to choose the surge arresters.

A substitution of the surge arresters is recommended, with the installation of class C devices, having a higher charge transfer capability. The installation of arresters with higher continuous operating voltage would reduce the risk of explosion, but is not recommended as it would expose the protected devices to higher overvoltages.

An interesting possibility to solve the problem at its source would be the installations of super-capacitors to harvest the energy generated during vehicle braking. These devices could be installed on the vehicles or inside the power substations.

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