Earthing and bonding in urban electrified rail transport systems return networks

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Abstract -**Return networks of electrified power supply systems create a vital part of their electric circuits during operating and fault conditions but msy cause problems due to stray current emission. In order to fulfil all these functions specific, in some case contradicted criteria and requirements must be fulfilled. Their main characteristic parameters are: longitudinal resistance and resistance to earth, electric potential during operating and short-circuit conditions, longitudinal and short--circuit voltage drop and currents. Calculations of all these parameters allow to assess: if the return network properly fulfils its main function – power supply to electric vehicles; if the operation of the certain return network does not cause danger for the people in the zone of the electric traction network, and the last but not the least, if there is no negative influence on the surrounding environment.**

1. Introduction

The running rails of the electrified rail urban transport systems make a part of the electric traction power system: a return circuit (when are connected to the negative –'minus' busbar of the rectifier traction substation) or a supply circuit (when are connected to the positive 'plus' busbar of the rectifier traction substation). The first one solution is the most common in the systems applied in Poland.

The return electric circuit comprises, quite apart from the running rails, track and inter-track electric connections, bonding circuits, impedance bonds (in a case signalling track circuits are used), return cables and the negative busbar. There exists different technical and safety aspects (priority), which must be taken into account, when the return traction circuit is analysed:

a.) accessible and touch voltage,
b.) metallic and to-ground short-circuit currents clearing,
c.) stray currents,
d.) track circuits operation.

In any case the resistance of rails should be as low as possible. The requirements towards the rail-earth conductivity, according to the specific problem may be contradictory. For the first two aspects, connected with the electric safety, the higher rail-earth conductivity (lower resistance) creates better functional conditions, while in the farther two cases lower conductivity (higher resistance) is preferred.

Generally in tram systems rails are not used as a circuit for signalling and protection of the traffic. So the requirements towards the maximum permitted value of the rail-earth conductivity are resulted mainly due to stray current mitigation [15].

Although the traction system voltages in the urbanised areas are generally lower (600, 750 or 1500V) than in railway systems (3000 or 1500V), an anti-electric shock protection, due to easy access to the power supply and return circuit installations should be more restrictive than for the outside town railways. Even the electric shock does not cause immediately deadly events; the further results may be very dangerous.

The running rails, a part of the traction power circuit, are as well used as a protective circuit, to which there are connected (bonded) conductive parts of structures (usually having low resistance to the earth) placed in the overhead contact line and pantograph zone. This bonding to the rails of conductive parts of external conductive elements (normally not being a part of the electric traction power circuits) has a significant influence on:

- effectiveness of switching-off of short-circuit currents in a case of isolation disruption,
- stray currents flow,
- safety of the passengers, staff and by-passers.

There are applied the following types of bonding:

- direct connections (closed) and indirect (open), using voltage limiting devices (spark-gaps, voltage valves – a semiconductor or a conductor type),
- individual (each of the protected structures is individually bonded to the rails) or group bonding (when special additional wires connecting a group of structures is applied which is bonded to the rails in some points).

A more complicated indirect bonding (applied for instance in a system of a group open bonding) fulfils all the requirements a.)÷d.), as during operational conditions (when voltage: rail-bonded construction is low) the construction is separated from the rails. As soon as the voltage exceeds the defined level (for instance when the isolator is broken), the voltage limiting device closes the connection and the structure is temporarily (as long as the voltage is high enough) bonded to the rails. In that way the short-circuit to the structure is changed into a metallic short-circuit.

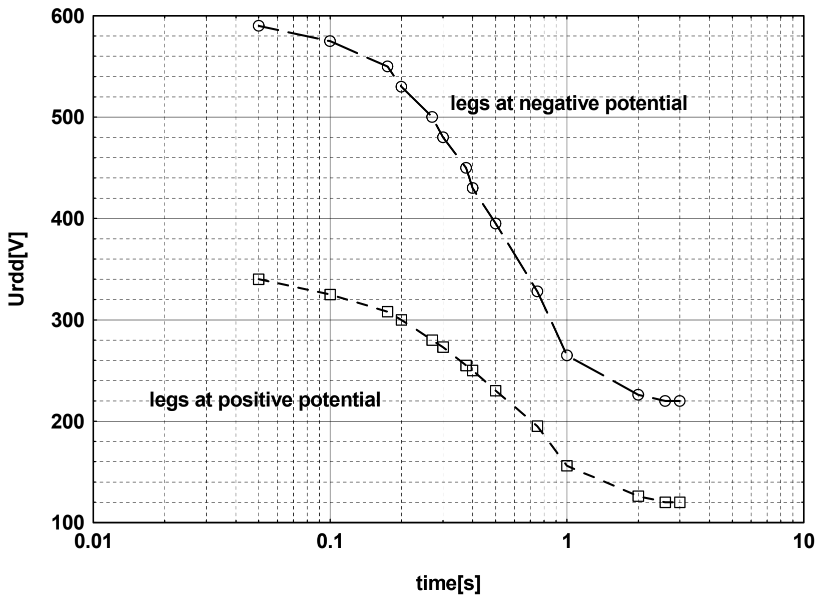

Fig. 1 Curves of maximum permitted touch voltages Urdd versus time of their occurrence (time of a short-circuit), during which the accessible part is under voltage.

The necessary condition, which assures safety of passenger is an effective and quick clearing of each of the short-circuits, in order to maintain touch voltage (hand-legs) below the permitted level. There are presented in Fig. 1 curves of maximum permitted touch voltages U_{rdd} versus time of their occurrence (time of a short-circuit), during which the accessible part is under voltage [EN50179-1994).

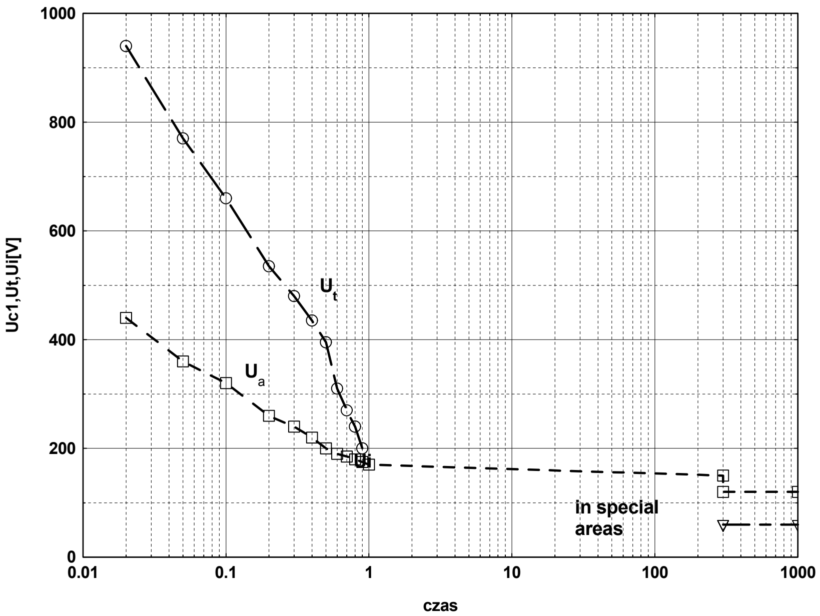

Fig. 2: Permitted values of accessible Ua and touch Ut voltages: hand-legs (for time below 0.5s it is assumed additional resistance of 1kΩ -'wet shoes').

For a permanent state maximum permitted accessible voltage is 120V, but in special areas (as depots or workshops) only 60V. In a case these values are exceeded, special means having in aim reduction of the accessible or touch voltages should be imposed:

- decreasing of resistance of the return circuit (as: increasing the cross-section of rails or its conductivity, connecting additional return wire),
- applying of voltage limiting devices,
- isolating of the standing surfaces,
- improving of earthing (or bonding to the rails) of the conducting structures, to reduce its potential,
- decreasing time of clearing of short-circuits.

It has to be point out a possibility of appearing of a dangerous voltage when the electric vehicle's body is touched. In that case the touch voltage may be higher than the appropriate voltage rails-earth due to a vehicle's body-rails resistance.

The problems, which must be defined already at an early stage of the technical feasibility study of the rail transport system, are following:

- application of anti-electric shock protection,
- assuring effective metallic short-circuits clearing,
- short-circuit to earth protection,
- introducing of stray currents mitigation,
- assuring low voltage drops in rails.

2. Methods of calculations of electric traction return network

Criteria and technical parameters concerned the electric traction return networks includes:

- allowed voltage drop in rails ΔU_R[V/km],
- unitary resistance of rails r_R [Ω/km],
- unitary resistance rails-earth r_{R-G} [Ωkm] (or conductance $g_{R-G}=1/r_{R-G}$ [S/km]),
- voltage rails-earth U_{R-G} [V],
- normal operation traction current I [A],
- current flowing in the rails I_R [A],
- stray current (flowing outside the return network) I_S [A],
- short-circuit current I_{zw} [kA],
- short-circuit to ground current I_{zwe} [kA],
- time of switching-off (clearing) of a short-circuit current t_z [ms],
- accessible/touch voltages U_a /U_t [V]

and general requirements towards safety and designing of power supply networks including:

- safety measures against direct contact,
- safety measures against indirect contact,
- rules and guidelines concerned structures of power supply networks (types and locations of traction substations, configurations and parameters of feeder and return cables, rail network).

There are presented in Fig. 3 a÷e: a simplified scheme of a rail return network (a), an equivalent scheme of a system rails-earth (b), simplified curves of a rail current I_R, current in the earth I_B (c,d) and potential of rails to the ground U_R as well as a transverse distribution of potentials (e).

The basic dependencies for the circuit presented in Fig.3, assuming constant value of a traction current I and homogenous resistivity of soil and constant resistance in the circuit modelling system: rails-earth (ladder circuit) are as follow:

$$U_R(x) = \frac{mI}{ch(k\frac{l}{2})} sh(kx) \tag{1}$$

$$I_R(x) = \frac{I}{ch(k\frac{l}{2})} ch(kx) \tag{2}$$

where

$$m = \sqrt{r_R r_{R-G}} \tag{3}$$

$$k = \sqrt{\frac{r_R}{r_{R-G}}} \tag{4}$$

The calculations of electrical parameters of the supply network (catenary and feeder cables), due to the defined configuration and supply sections are easier than the calculations of the return network (multilateral supply by many return cables). Although the currently being in law standard [15] does not require (as it was the obliged by the previous standard [13]) keeping the average voltage drops in rails to the point of a return cable connection below the defined level, it is reasonable to design the return cables network in the way that they are loaded uniformly and the voltage drops in the rails are not too high. It is justified not only by the stray currents but as well by the safety reasons.

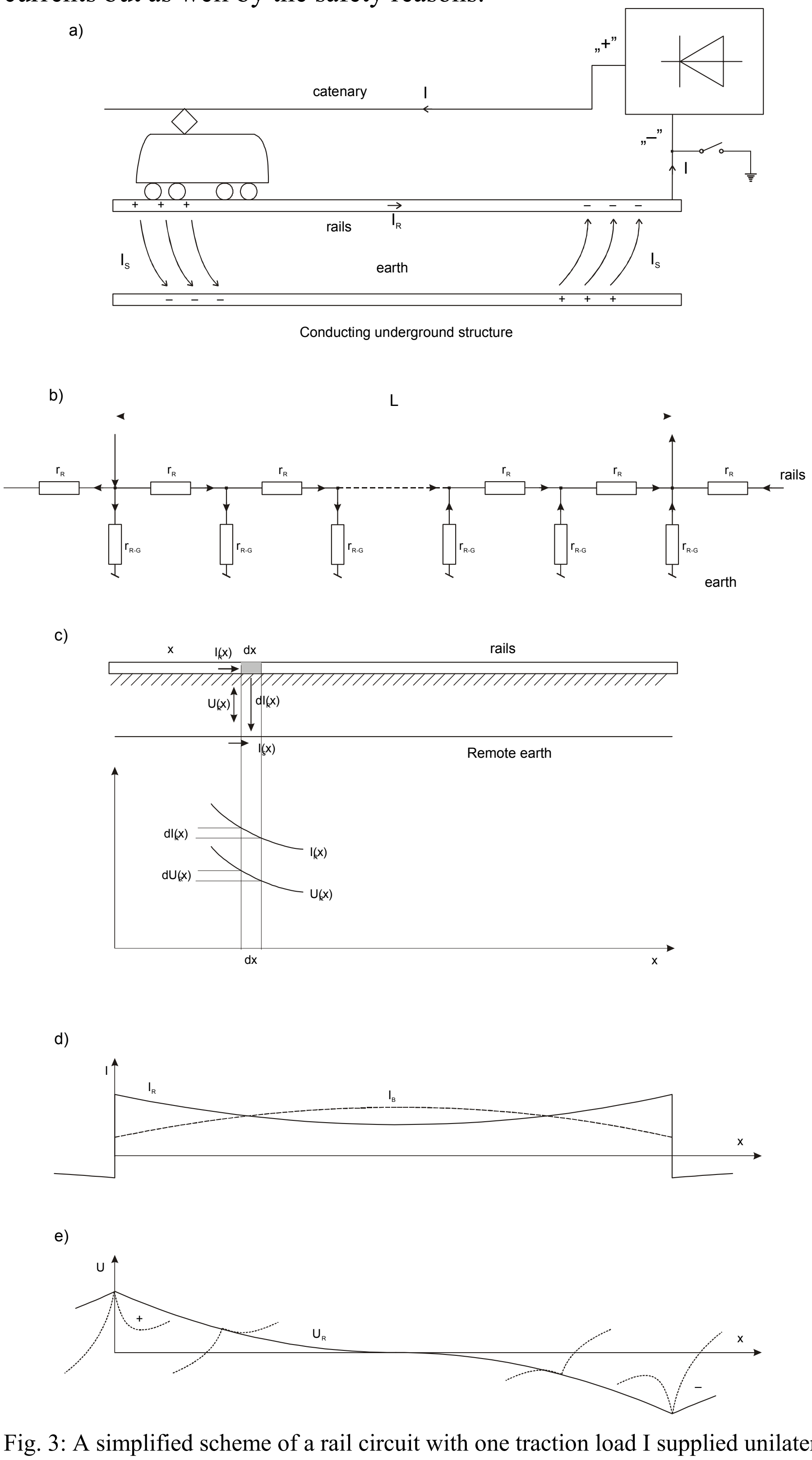

Fig. 3: A simplified scheme of a rail circuit with one traction load I supplied unilaterally from one traction substation (a), an equivalent scheme (b), rail current I_R (c), current in the earth I_S (d) and voltage of rails U_R to the remote and local earth (e).

The scope of the return circuit calculations is a proper configuration of the network via fulfilling the following criteria:

- permitted accessible and touch voltages (Fig. 1 and 2),
- metallic short-circuit protection (setting tripping levels of high-speed breakers),
- short-circuit to ground protection (current and voltage protection),
- maintaining required level of resistance: rails-earth (dependent of the type of track and ballast, soil, underground technical infrastructure, weather conditions).

All of the above mentioned aims may be defined with the level of details dependent on the assumed methodology of calculations. The methods require a preliminary placement of the return cables network and checking of the technical criteria. In practice, for the real rail transport system there exist usually several configurations fulfilling the technical criteria. The choice of the final configuration should take into account technical limitations and superior criteria as area restrictions (routes of cables), amount of investment costs, energy losses and assessment of stray currents negative influence for each of the variant.

Implementation of proper stray current mitigation means gives results which are difficult to be assessed, but they are observed after a longer period, as the experience shows much higher (2-3 times) damages of underground technical infrastructures in cities with rail electrified transport.

Simulation methods allowing to model widely spread transport networks are currently in common use for these purposes. Deterministic and statistic approach allows analysing operational conditions of the system for different power supply schemes, type of rolling stock and traffic. It is of a special importance when new electric vehicles with regenerative braking are to be put into service into the functioning system [5].

3. Earthing and bonding in return traction networks

The simplest solution, not requiring spending additional costs and make exploitation supervision, is application of an isolated system, when there are neither used, quite apart from the natural ones, additional connections between the negative busbar of the traction substation and earth nor between the rails and the support structures (Fig.4). This system assures relatively high safety provided dry weather conditions, very reliable main isolation of catenary (with its monitoring) and possibly low voltage system. In a European climate zone it is not recognised as a safe one. A more reliable and safe system is shown in Fig. 5, where a direct bonding of the support structures to the rails is applied. An earthing of the negative busbar of the traction substation via ZN in a case of a short-circuit to the ground is made (ZN- a voltage limiting device). This system may cause stray currents flow and dangerous of electrochemical corrosion of the basement of the support structures and underground constructions.

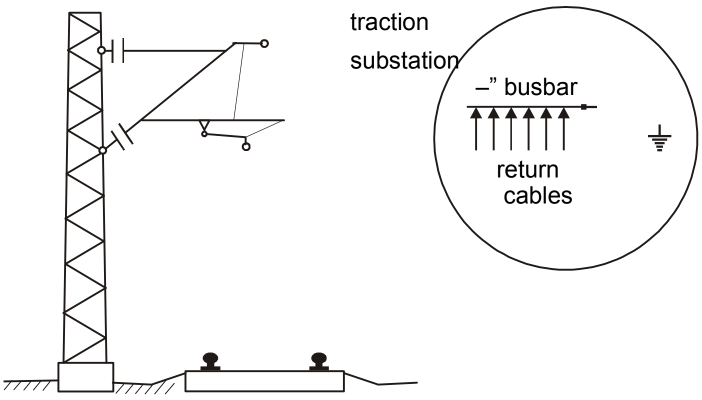

Fig. 4 A scheme of the system without bonding of support structures to the rails.

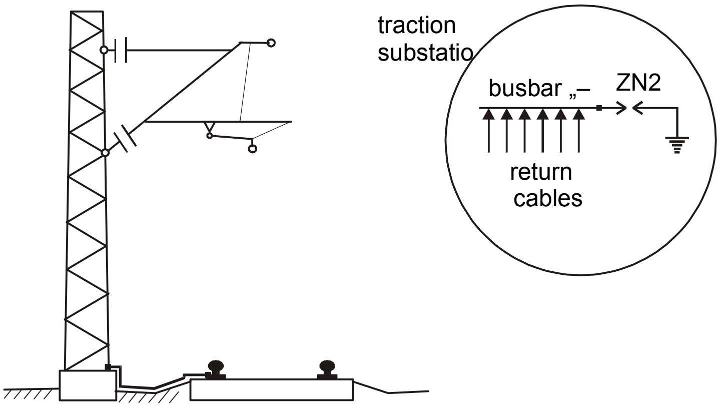

Fig. 5: A scheme of the system with direct bonding of the support structures and open connection (via a voltage limiting device –ZN2) of the negative busbar in the traction substation to the earth is applied.

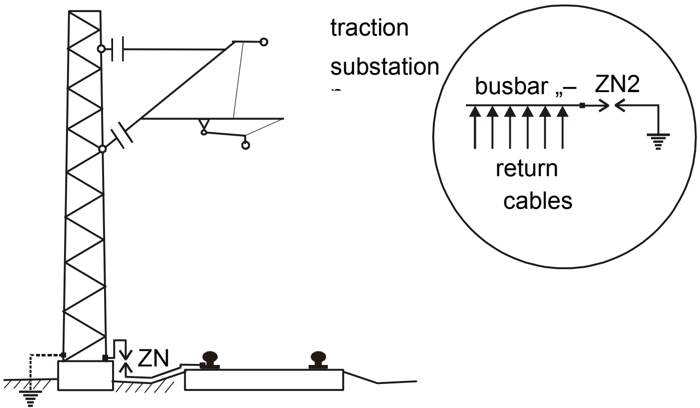

Fig. 6: A scheme of the system with an indirect bonding of the support structures (via ZN-a voltage limiting device) and an indirect connection (via ZN2) between the negative busbar of the traction substation and the earth.

Standards [14,15] do not recommend the direct bonding of the grounded conducting parts of structures placed in the catenary and pantograph zone. It is suggested an usage of indirect connections to the rails via voltage limiting devices (ZN), which during normal operating conditions separate the constructions from the rails. In a case dangerous voltage appears at the indirectly bonded to the rails construction, the connection is changed into a direct one, allowing clearing the fault. Similarly, the voltage limiting device (ZN2) is used to connect the negative busbar with the earthing system in a traction substation. This solution fulfils the requirements of simultaneous protection against electric shock, an effective short-circuit (including short-to-ground) clearing and stray currents mitigation. The voltage limiting device (ZN2) used to connect the negative busbar to the substation earth is more complicated then this one (ZN) used to bond indirectly the support structures to the rails. ZN2 should have an option to trigger the power switches of the substation in a case a short-circuit to ground is not switched-off by the adequate high-speed breaker.

There are used in the overhead catenary power supply systems different means of protection against indirect contact (an additional anti-shock protection) and stray currents mitigation improving in the same time the short-circuit conditions. These solutions are as following:

- improving of reliability of isolation of catenary (double isolation),
- equalisation (during failures) of the potential of rails, support structures and the local earth by using indirect connections via voltage limiting devices or spark-gaps and shields,
- decreasing longitudinal voltage drops in the return network by installing additional, connected to the rails return wires, which decrease global resistance of return network,

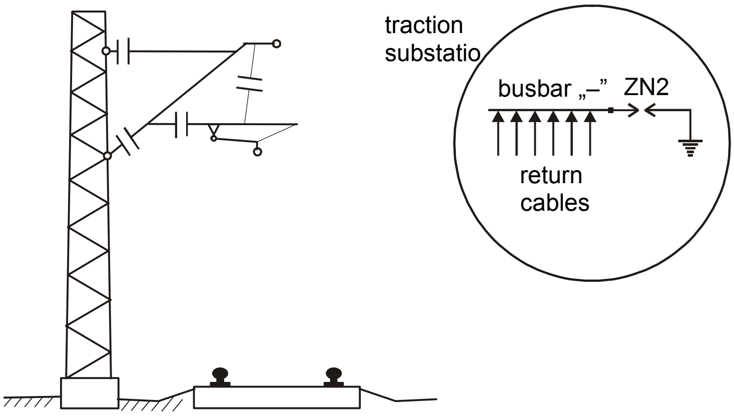

Fig. 7: A scheme of the system with the double isolation of catenary and indirect connection of the negative busbar in the substation via a voltage limiting device ZN2.

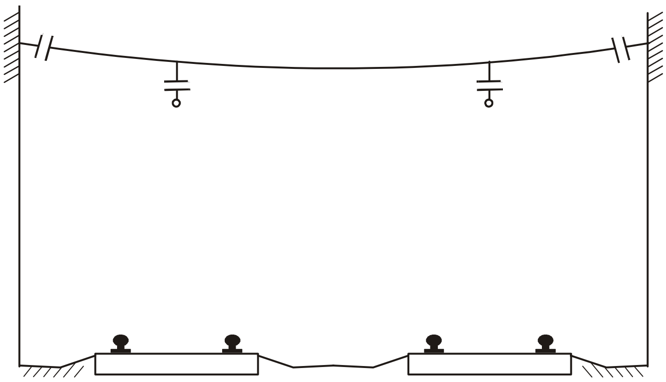

Fig. 8 Elastic catenary suspension with the double isolation

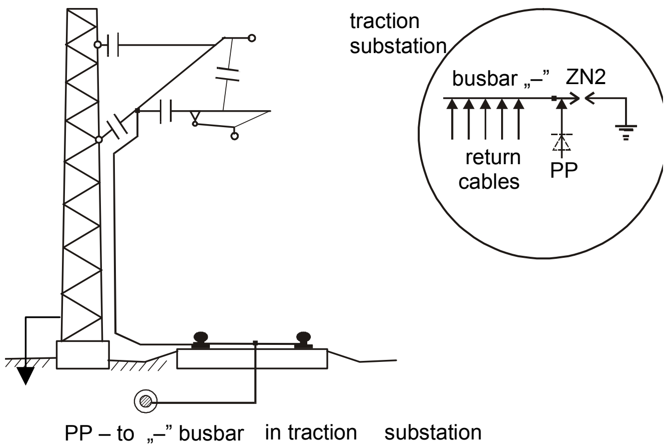

Fig. 9: A scheme of the system with an additional isolated return wire PP (connected to the negative busbar in the traction substation, typically via a diode) and a double isolation of the catenary with the direct bonding of the neutral section (conducting) to the rails, the support structure is directly earthed; the negative busbar in the traction substation is connected indirectly to the earth via ZN2 (the voltage limiting device).

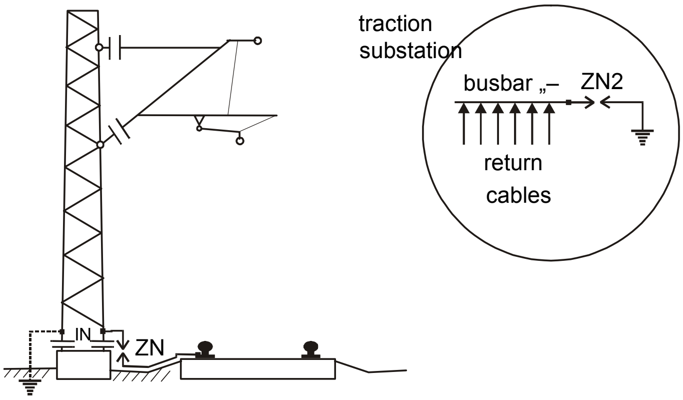

Fig. 10: A scheme of the system with the indirect bonding of the support structure to the rails (via ZN), the support structure is isolated from its base (IN – low voltage isolation) and earthed using an additional earthing rode; the negative busbar in the traction substation is connected indirectly to the earth via ZN2 (the voltage limiting device).

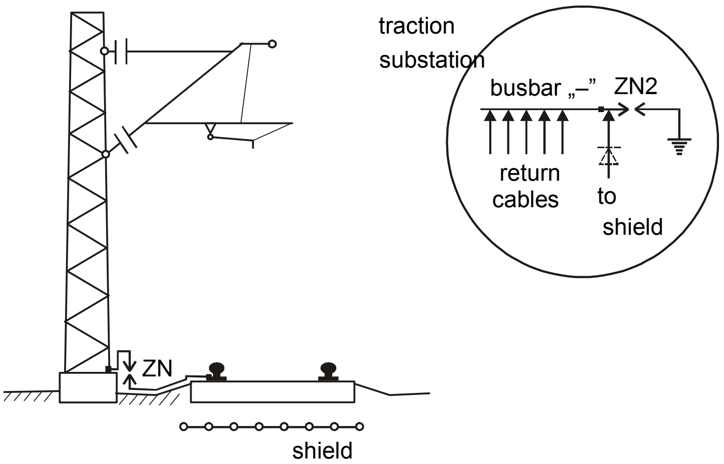

Fig. 11: A scheme of the system with the indirect bonding of the support structures via ZN, the indirect connection of the negative busbar to the earth in the traction substation via ZN2 and a special stray currents shield connected (via a diode) to the minus busbar in the substation.

The solutions of that kind, starting from the simplest ones used in Poland are presented in Figures 7 and 8. More refined solutions, applied are as follow:

- with an additional return wire and bonding of the isolated (neutral) section of a cantilever, applied in the agglomeration rail in Seul (Fig. 9),
- with the indirect bonding of the isolated from its base the support structure (additionally earthed) by ZN (new, so called 'group bonding system' applied by PKP) [8],(Fig. 10),
- with a special stray currents shield, connected via an additional wire and a diode to the negative busbar in the substation, the support structures are indirectly (via ZN) bonded to the rails (the system used in UK), (Fig.11),

4. Conclusions

1.The return networks of rail urban transport systems cause significant problems due to safety and stray currents issues.

2. Proper technical solutions (earthing and bonding system) and maintenance of return networks, according to the appropriate standards can assure fulfilment all the requirements: safety and low impact on the technical infrastructure (mitigation of stray currents and

compatibility with the other systems). The choice of the protection system should take into account local conditions.

3. The configuration and the parameters of the return network have a great influence on the operation of the power supply system of urban rail transport. So the application of simulation methods of calculations and analysis of power supply system makes a powerful tool widely used for sizing its parameters and the configuration. It allows not only to fulfil the technical requirements but as well to fit the support structures and catenary to the urban architecture.

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