Electrical Safety of DC Urban Rail Traction Systems

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***Abstract*—In this paper the electrical safety of DC urban traction systems is analysed, with particular focus on fault current detection and on dangerous voltages which could arise in case of fault. For the discussion the tram network of Turin, Italy, is used as a case study. Firstly the structure of the DC traction power supply is described; then the safety of the system is analysed, examining possible types of fault. In particular, ground faults inside the substation and along the line are analysed in detail. Fault currents and dangerous voltages are calculated thanks to a simplified circuital model of the traction system. Finally, the consequent risks for the people are examined and some conclusions are presented.**

I. Introduction

Urban DC traction systems are common mass transport systems employed in many towns worldwide. The terminology used to identify them may vary, the most common terms being: light rail, street car, tram or trolley. We can consider these terms as synonyms.

The Traction Electrification System (TES) for trams is usually constituted by:

- power substations, containing transformers, AC/DC converters and protective devices;
- an Overhead Contact System (OCS);
- positive feeder cables, connecting the OCS with the positive busbars in the substations;
- negative return conductors, collecting the return current from the rails and bringing it back to the negative busbar in the substation.

It is worth noting that there is a huge difference between these tram systems, running along public urban streets, in a meshed network, and normal rail systems running on separate rights of way, without public access and with mostly straight sections [1]. In the former, in fact, the risk due to electric hazards is higher because of the presence of the public in strict contact with the TES, possibly exposed to dangerous voltages in case of fault. In addition to this, the protection of these systems is more difficult, due to the meshed structure of the network and to the high number of vehicles running at the same time.

The difficulty of protection of DC urban tram systems is due to the problem of distinguishing a fault current from the currents related to the normal operation, mainly because of the following factors:

- fault currents can be small, due to high impedance ground faults;
- in standard heavy rail systems the lines are divided in straight sections, and in each section, for safety reasons, only one train is allowed to run at the same time; in urban tram systems, instead, the network is meshed, and also the sections are meshed: more than one tram can be running at the same time inside the same section, resulting in higher currents in normal operation;
- the tram networks were designed for trams driven by DC motors. Modern trams are instead driven by asynchronous motors, fed by the DC OCS through IGBT DC/AC converters; these trams have completely different absorbed current profiles during acceleration and much higher peak values.

For these reasons, using standard protection principles, such as instantaneous and time-delayed over-current protections is not sufficient. Different studies have been performed on innovative protection schemes for TES [2], [3], but are mainly focused on railway systems that, as said before, are quite different from tram systems.

In Europe the main requirements for what concerns electrical safety in traction systems are provided by Standards EN 50122-1 *Railway applications - Fixed installations - Electrical safety, earthing and the return circuit. Part 1: Protective provisions against electric shock* [4] and EN 50122-2 *Railway applications - Fixed installations - Electrical safety, earthing and the return circuit. Part 2: Provisions against the effects of stray currents caused by d.c. traction systems* [5]. The main problems covered in these Standards are:

- protective provisions against indirect contact and impermissible rail potential;
- stray currents and rail to earth conductance.

The two objectives of reducing both stray currents and dangerous voltages in case of fault are contrasting, and the results depend on the choices regarding the grounding of the different elements of the TES [6], [7].

Object of this paper is the analysis of the electrical safety of DC urban traction systems, with particular focus on fault current detection and on the dangerous voltages which could arise in case of fault. For the discussion the tram network of Turin, Italy, is used as a case study.

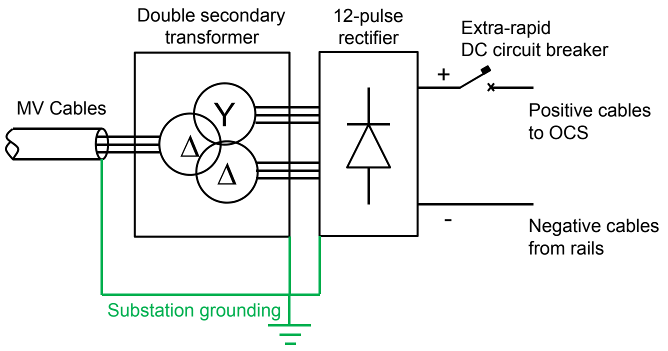

Fig. 1. Power substation for DC traction.

The rest of the paper is organized as follows: firstly the structure of the DC traction power supply is described, with reference, in particular, to the Turin tram network; then the safety of the system is analysed, examining possible types of fault, fault currents, dangerous voltages and consequent risks for the people. Finally some conclusions are presented.

II. Structure of the DC traction power supply

Fig. 1 presents the typical scheme of a substation feeding the DC traction system in Turin. MV cables connect the substation to the rest of the urban MV distribution network. A double secondary transformer lowers the voltage to $470\,V$ and feeds a 12 pulse rectifier. The output nominal voltage is $600\,V$ DC.

Each substation can feed 6 or 7 OCS zones: every zone is fed through a positive cable and is protected by an extra-rapid DC circuit breaker. The settings of the circuit breakers can vary in the range between $3000\,A$ and $4500\,A$, depending on the size of the zone and on the forecasted number of vehicles in it.

The negative cables allow the current return to the rectifier, connecting it to the rails. While the OCS is divided in zones, and each zone is fed by only one substation at a time, the rails and negative cables constitute a unique meshed city-wide network. The negative cables are not connected to the substation grounding system, in order to limit the stray currents dispersed by the rails into the ground.

In the tram network in Turin, the positive feeder and negative cables have a typical cross section of $1000\,mm^2$, while the OCS has a cross section of $95\,mm^2$.

III. Safety of DC traction systems

Different types of faults can happen on the DC urban rail traction systems, among which (Fig. 2):

1) ground fault in the substation;
2) short circuit in the substation;
3) fault to a pole (to ground) along the line;
4) short circuit along the line (can happen on a vehicle);
5) ground fault along the line.

When a short circuit happens in the substation, the fault current magnitude will be high enough to make the extra-rapid circuit breaker trip. But in case the short circuit happens outside the substation, for example on a vehicle, or in case a ground fault happens, the current would be limited by the circuit resistances, resulting in a current comparable with normal operation ones. In this case dangerous voltages can last for long periods without any maximum current protection intervention. For this reason new, and more sophisticated, relays are being installed, and should be properly set in order to recognize fault currents.

In general, the workers can be subject to risk of electric shock inside the substation, and people outside the substation, in case a fault is not recognized and interrupted in a time interval shorter than that allowed by Standard EN 50122-1 (section 9.3.2.2 regarding the maximum permissible effective touch voltages as a function of time duration) [4].

In this paper the focus is on ground fault inside the substation (fault 1) and ground faults along the line (fault 5).

TABLE I
Rail to ground conductance - measurement results

Rail section	Section length $[m]$	g $[S/km]$
1	45	1.48
2	300	2.03
3	85	1.58
4	240	1.77

IV. Circuital model of the traction electrification system

In order to study fault currents and dangerous voltages, a simplified model of the TES has been developed, based on literature review and on experimental measurements. In the following sections the models for rails, rectifier and substation grounding system are presented. Finally a simplified fault circuit is described.

A. Rails model

Rails can be modelled as a distributed parameters line, with a longitudinal resistance r and a shunt conductance to ground g. For railway tracks with open formation, many studies report typical values for the required parameters [8], [9]. For rails with closed formation (typical of urban traction systems) a few data can be gathered from literature. The longitudinal parameter can be evaluated knowing the cross section of the rails and the resistivity of the constitutive material. For the rails in Turin, it was calculated $r = 0.013\,\Omega/km$. For what concerns the conductance to ground, four measurements were performed on short sections of rails, not used any more and disconnected from the rest of the network: the results are presented in Table I. The measured values, with an average of $g = 1.6\,S/km$, are compatible with the reference limit value provided by Standard EN 50122-2 ($g \leq 2.5\,S/km$) [5].

For the study of the ground faults in the substation and along the line, it is also important to evaluate the equivalent ground resistance R_{tg} of all the city-wide tracks network; the rails and negative cables constitute in fact, as previously described, a unique meshed city-wide network. The value of R_{tg} changes

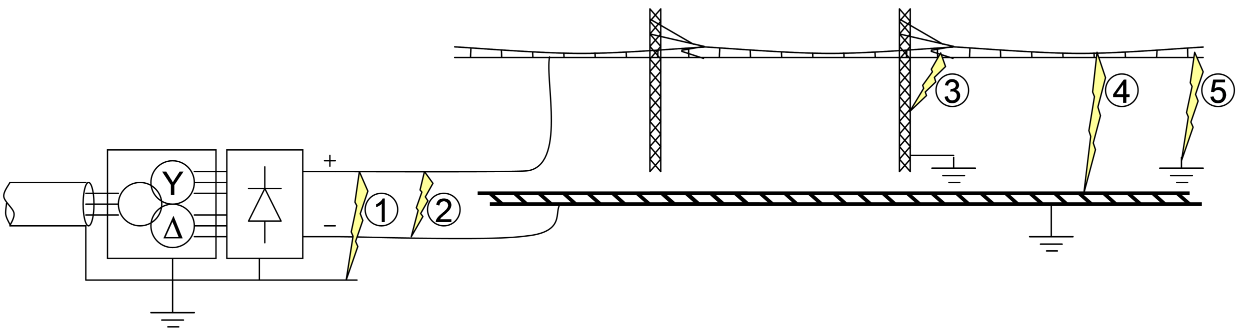

Fig. 2. Possible faults on DC traction systems.

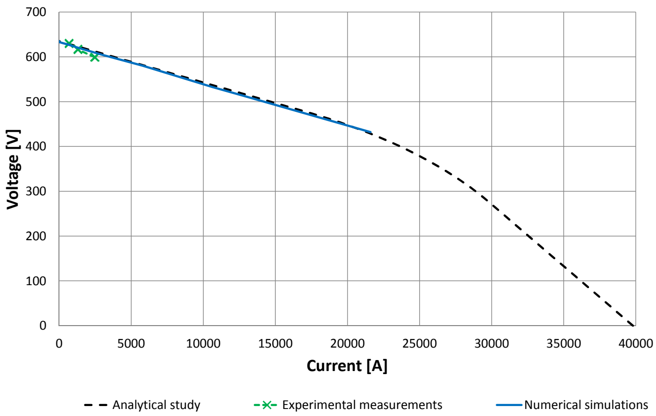

Fig. 3. Transformer-rectifier characteristic.

depending on the considered point and is difficult to evaluate. It is however possible to estimate a range in which R_{tg} should be included. For the purposes of this study, it was estimated $0.02\,\Omega \leq R_{tg} \leq 0.2\,\Omega$.

B. Transformer and rectifier model

The model of the transformer and rectifier group has been determined by means of an analytical study, experimental measurements in a substation and numerical simulations (fig. 3).

In the case of ground faults, both in the substation and along the line, the rectifier works in the first part of the characteristic, with relatively high voltages and low currents. As we are interested in the steady state condition and not on the transient, and as the first part of the characteristic is linear, the transformer/rectifier group has been modelled as an equivalent voltage source $V_{eq} = 635\,V$ in series connection with an equivalent resistance $R_{eq} = 0.0167\,\Omega$.

C. Substation grounding system

The grounding system of the substations is constituted by a typical configuration of a ring electrode with four rods. The typical ground resistance can vary in the range from 5Ω to 15Ω depending on the soil characteristics. However, the grounding system of each substation is connected to the neighbouring ones by means of the MV cables sheaths and, in Turin, of bare conductors buried in contact with the soil together with MV cables. For this reason, the equivalent ground resistance that can be measured from each substation is mostly independent from the ground resistance of the single substation and from the distance between substations: it has a typical value around $R_{sg} = 0.06\,\Omega$ [10].

TABLE II
SUMMARY OF MODEL PARAMETERS

Parameter	Value range
V_{eq}	635 V
R_{eq}	0.0167 Ω
R_{sg}	0.06 Ω
R_{tg}	$0.02\,\Omega \div 0.2\,\Omega$
R^-	$1.7 \cdot 10^{-4}\,\Omega \div 1.7 \cdot 10^{-3}\,\Omega$
R^+	$1.7 \cdot 10^{-4}\,\Omega \div 1.7 \cdot 10^{-3}\,\Omega$
R_{ocs}	$0\,\Omega \div 0.1\,\Omega$

D. Fault circuit

Having defined the simplified models for the different components of the system, it is possible to draw the equivalent circuit for the ground fault in the substation or along the line (Fig. 4). In the figure, R^-, R^+ and R_{ocs} represent, respectively, the resistance of the negative cables from the substation to the rails, of the positive feeder cable from the substation to the OCS and the resistance of the overhead line.

The ranges for the values of the different parameters are summarized in Table II.

V. RESULTS

Currents and voltages have been calculated on the simplified circuit, varying the different parameters in the ranges that have been presented in the previous sections.

In the case of ground fault in the substation, the fault current is injected into the ground through R_{sg} and flows through R_{tg} and the negative conductors back to the rectifier. In the case of ground fault along the line, instead, the fault current flows to the ground through the fault and flows back to the substation through the ground resistance of the rails network R_{tg}, without involving the grounding system of the substation. It was noticed that the value of the current absorbed by vehicles (i.e. the pre-fault condition) does not affect considerably the results

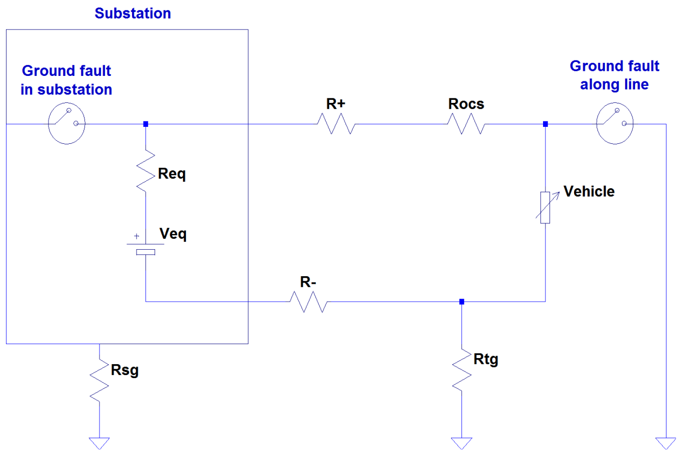

Fig. 4. Fault circuit.

of the study. The same remarks are valid for the length of the negative and positive cables: the variation of the value of R^{-} and R^{+} does not affect considerably the results. The main parameters which instead influence the fault current magnitude and the voltages are the resistance R_{tg} of the rails network and the resistance R_{ocs} of the OCS.

In Fig. 5 a summary of the results for the ground fault in the substation is presented. The fault current can be compared with the settings of the over-current protection to see if it will trip: typical settings of over-current protections are in the range from $3000\,A$ to $4500\,A$, marked with the green vertical lines in Fig. 5. On the left side of the vertical lines the circuit breaker trips, while on the right side it does not, as it does not recognize the fault current, leaving dangerous voltages on the exposed conductive parts (ECPs) and between ECPs and return conductors in the substation. Dangerous voltages are also present on the rails, accessible to the public. The conventional limit of $120\,V$ for long-term conditions (to be considered if the circuit breaker does not recognize the fault) is in fact highlighted in the figure with the horizontal red line and for all the range of possible values of R_{tg} the analysed voltages are above this limit.

Also the ground fault along the line has been studied. Two different cases are analysed: a ground fault along the line near the substation and a ground fault along the line far from the substation. In particular in the second case, the resistance of the OCS contributes to the limitation of the fault current, making it difficult for the over-current protection to recognize the fault. The two analysed cases are presented in fig. 6 and fig. 7.

Following the same scheme described before for the ground fault in the substation, we have highlighted also in fig. 6 and fig. 7 the typical setting range of the over-current protections (green vertical lines) and the maximum permissible effective touch voltage (horizontal red line). In the case of fault along the line, the fault currents are higher than in the case of ground fault in the substation, if the fault is close to the substation

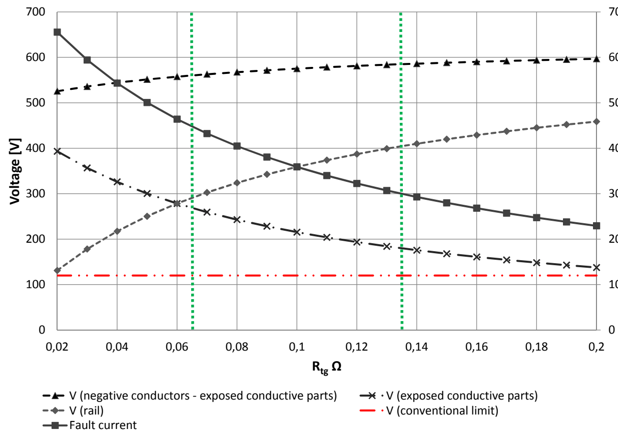

Fig. 5. Ground fault in the substation - results.

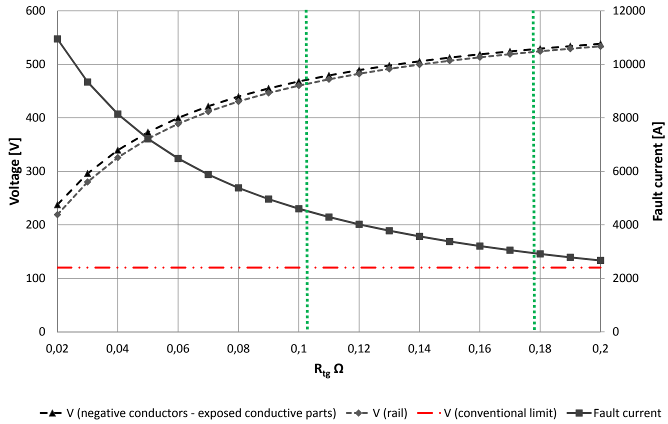

Fig. 6. Ground fault along the line close to the substation - results.

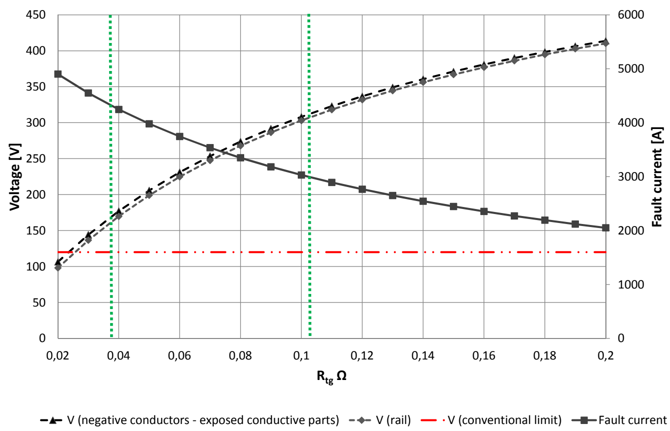

Fig. 7. Ground fault along the line far from the substation - results.

itself (fig. 6), as they are not limited by the ground resistance R_{sg}. In case instead the fault is far from the substation, as previously said, the resistance of the OCS strongly limits the fault current. In particular in this case, there are again situations in which the fault current is not big enough for being recognized by the over-current protections, and dangerous

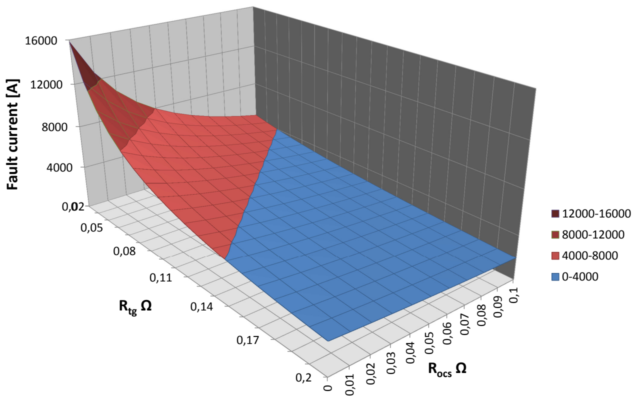

Fig. 8. Fault current for a ground fault along the line.

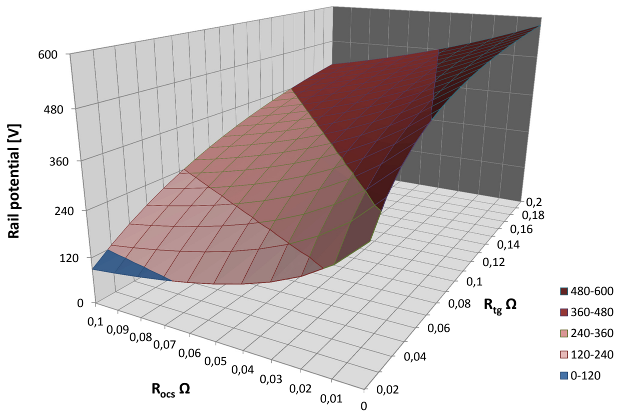

Fig. 9. Rail potential for a ground fault along the line.

voltages can last for a long time on the rails and inside the substation between negative conductors and ECPs.

It is interesting to analyse the effect of the variation of the two main parameters, R_{tg} and R_{ocs}, at the same time, on the fault current magnitude and on the rail potential, in case of ground fault along the line.

Fig. 8 shows a 3D representation of the variation of the fault current as a function of R_{tg} and R_{ocs}. If we assume an average setting of the over-current protection of $4000\,A$, the circuit breaker will trip if the fault is in the lower (blue) area of the 3D plot. For all the other combinations of R_{tg} and R_{ocs}, the circuit breaker will not detect the fault.

Fig. 9 presents instead a 3D representation of the variation of the rail potential as a function of R_{tg} and R_{ocs}. The 3D plot shows that there is only a small portion of the variation range, the lowest part, coloured in blue, where the rail potential is below the safety limit of $120\,V$.

It is interesting, at this point, to put together the pieces of information provided separately by fig. 8 and fig. 9. For this purpose, the two colour plots, projected on the R_{tg}-R_{ocs} plane, are superimposed exploiting transparency. The result of the combination of the two figures is presented in fig. 10.

By comparing the fault current magnitude with the setting of the over-current protection and the rail potential with the safety limit, it is possible to identify three different areas, highlighted by the coloured borders in fig. 10:

- the small area at the top left, surrounded by the green dotted line, where the over-current protection recognizes the fault, where therefore the circuit-breaker trips, even if no dangerous voltages are present because the rail potential is below $120\,V$;
- the area on the left, surrounded by the yellow dashed line, where dangerous voltages are present because the rail potential is above $120\,V$ and the circuit breaker trips because the fault current is above the setting of the over-current protection;
- the big area on the right, surrounded by the red solid line, where the rail potential is above the safety limit, but the circuit breaker will not trip, as the fault current is too small to be detected by the over-current protection.

Analysing in particular the third area, the one surrounded by the red solid line, it is clear that, in particular in case the ground fault along the line happens far from the substation, dangerous voltages can last for long periods on the rails, accessible to the public, without any tripping of the protections.

VI. Conclusion

If only over-current protections are adopted, in urban rail traction systems potentially dangerous situations can be originated. In fact, the ground fault currents can be lower than the protection settings, both for ground faults inside the substations and for ground faults outside the substations, along the line. In these cases dangerous voltages can last for a long time on the rails, accessible to the public, and inside the substations, on exposed conductive parts and between exposed conductive parts and negative conductors. It is therefore of utmost importance that innovative relays are installed and properly set, in order to recognize short circuit currents from normal operation ones.

The analysis that is presented in this paper has been performed considering a negligible fault impedance. In case the fault impedance is not negligible, the fault current could be even smaller, and therefore more difficult to be detected by common over-current protections.

One partial provision that could improve safety, even if not totally sufficient, would be the installation of a voltage limiting device, which connects the grounding system of the substation with the negative conductors in case the voltage between them is above a certain threshold. This provision would certainly be beneficial for the ground fault in the substation, but would be partially beneficial also for the ground fault along the line.

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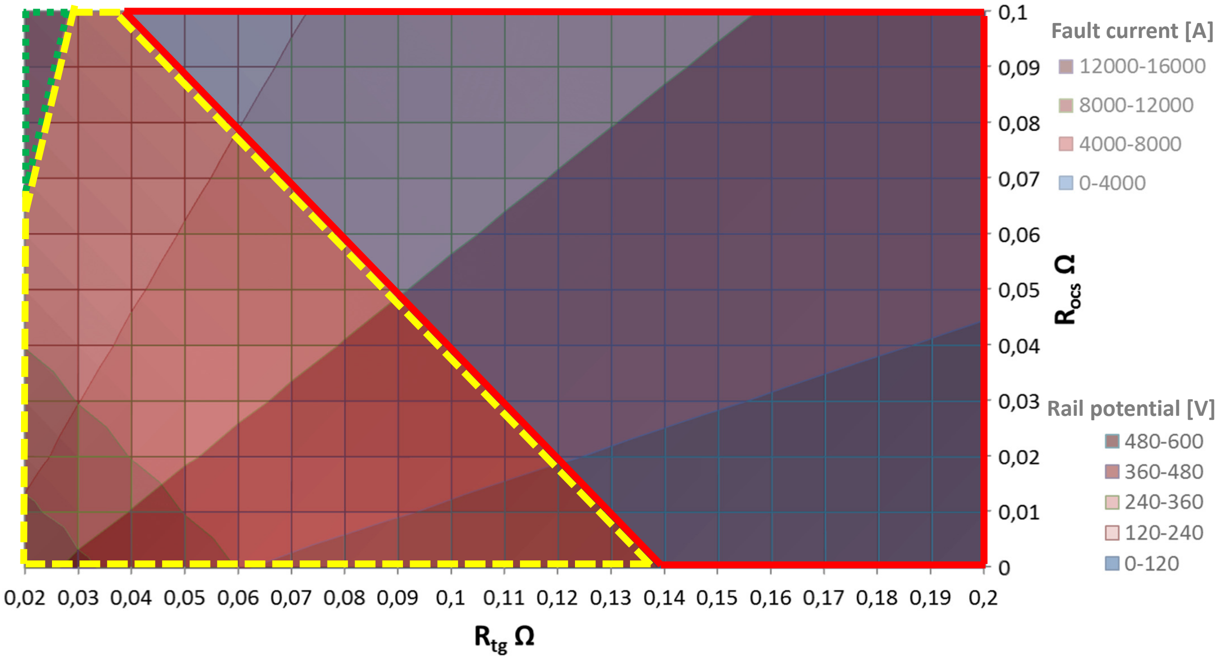

Fig. 10. Fault current and rail potential for a ground fault along the line.

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