How Effective Are Automatic Grounding Devices at the Floating Negative Rail System of a DC Powered Rail Transit System?

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Abstract: Currently most modern dc rapid transit systems around the world use running rails or a negative rail as the negative return circuit for the dc traction current. These rails are intentionally kept ungrounded from ground (earth) by using insulating material between the rail and earth to minimize dc stray current. This configuration of return current rail develops varying voltage with respect to ground along the entire length of the rail when trains are in operation. Probability of dc or ac power system faults exist in the vicinity of the rail tracks which leads to coupling of fault voltage to these rails. This varying voltage of the return rail at the train location gets transferred to the train vehicle shell due to design configuration of the vehicle propulsion system injecting negative current to these rails. To minimize the unpredictable threat of electric shock hazard, automatic negative rail grounding (N_{RG}) devices that continuously monitor return rail voltage with respect to ground are implemented at appropriate locations such as substations, passenger stations and at other accessible locations. This paper provides recommendations to establish a uniform application approach for N_{RG} devices in the transit industry with a clear understanding that it is the dc current through the human body and not the dc rail voltage that poses electric shock hazard.

Key words: Automatic grounding device, electric shock, floating negative system, running rail, touch voltage

I. INTRODUCTION

With help from Paul Forquer, the author sent a survey questionnaire to North American transit professionals on their application experience on negative rail grounding (N_{RG}) devices and real life incidents of electric hazard of rail-to-earth voltage (V_{RE}). One professional provided a survey table from 16 transit agencies asking a) is V_{RE} limit used as a system design criteria and b) have they applied N_{RG} devices. The answer to a) was: 9 yes, 2 no, 5 no response and answer to b) was: 8 yes, 5 no, 3 no response. The settings were different for those who applied N_{RG} devices, 50 V limit being more common. An excellent brief study on N_{RG} devices and a review of several manufacturers' N_{RG} literature was provided by Benjamin Stell. A comprehensive list of other professionals who showed interest in the subject is included in the acknowledgement.

The survey response indicated no fatal incident directly related to rail-to-earth voltage, different transit properties used different N_{RG} devices with different settings and criteria. This paper first describes a simple dc traction power system to explain continuous changing V_{RE} due to continuous changes of operating trains. Then it reports that V_{RE} may get additional changes due to ground fault on both ac and dc power systems. Lightning can also inject transient overvoltage on the negative rail. Next paper expresses how important it is to minimize the risk of hazard from elevated V_{RE} during ground faults by application of N_{RG} devices. Then a description of human body current as result of contacting the negative rail or the vehicle at elevated V_{RE} (which may lead to risk of injury) is included. For the heavy rail transit system, estimated dangerous probability time of V_{RE} voltages is included for managing the electric hazard risk. Finally the paper provides recommendations with a clear understanding that the negative rail-to-earth voltage monitoring devices appear to be the primary protection devices to manage the concern of electric hazard risk of elevated negative rail-to-earth voltage. Real life incidents are included in the Appendix.

II. DC POWER SYSTEM CONFIGURATION

The basic simplified dc traction power distribution circuit is shown in Fig. 1 to show design parameters that are responsible for continuously changing the negative circuit voltage with respect to ground. These parameters are train current and dc power distribution system resistances including uniform distributed rail-to-earth leakage resistance on a per unit length [13] [14]. It is clear that to minimize dc stray current (I_S) during train operation the equivalent rail-to-ground leakage resistance values R_L and R_S at the load and the source respectively should be kept as high as practical. For a dc power system there are practical limits of distances between the substations, negative rail linear resistance values which contribute to rail voltage drop E_N for given values of train operating currents. Rail-to-earth voltage at any location, such as vehicle (load) location voltage E_{GL} will be positive with respect to earth and at the source (rectifier substation) location voltage E_{GS} will be negative with respect to earth. These voltages change continuously as the train location and train current change continuously due to dynamic load of the multiple trains on the cross-bonded negative rails. Intentionally keeping negative return rail system ungrounded is called floating dc power system.

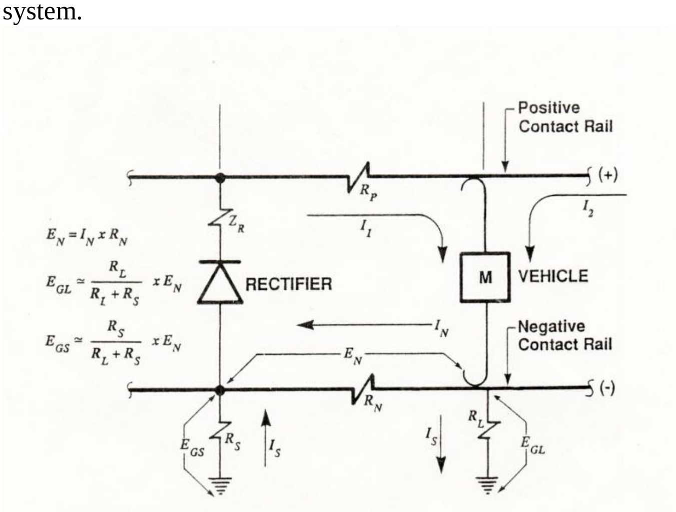

Fig. 1 Equivalent circuit for determination of rail voltage with respect to ground

This paper will discuss only rail-to-earth varying voltage risk management by application of N_{RG} devices at the rail which will short the rail to earth for a short duration upon sensing voltage higher than the set limits and other criteria of monitoring flow of current between rail and earth.

III. RAIL-TO - EARTH VOLTAGE (V_{RE})

Rail-to-earth voltage should be controlled so that there is almost no probability of lethal incident. From Fig. 1, it is clear that varying V_{GL} or V_{GS} is the function of interrelated parameters, train currents through the negative rail, and negative rail resistance. For the simplicity of this paper and for discussion purposes this varying rail-to-earth voltage is abbreviated as V_{RE}. Many technical papers describe dc power system modeling for analysis of V_{RE} [11] [12] [15]. For simplicity Fig. 1 does not show coupling of ac and dc power system fault voltages or coupling of lightning surges voltage to rail which makes additional changes to V_{RE} upon occurrence of such incident during train operation.

a) Estimation of probable total exposure time and probable dangerous time to all patrons from dc varying rail potential V_{RE}

For systems with isolated right-of-ways, the maximum time duration of unpredictable threat of train touch potential V_{RE} due to train operating currents only may be estimated by expressions (1) and (2) below.

$$T_E = CxHxN_PxD_TxT_HxD_F \qquad (1)$$

Where:

- T_E total exposure time of patrons to V_{RE} each day
- N_P number of platforms in the entire transit system
- C a factor (say 1.25) to account for increased exposure time as the patron may touch the moving train before or after its complete dwell time at the platform
- D_T average dwell time of each train
- T_H number of trains per hour
- H hours of train operation/day
- D_F diversity factor of the trains at the platforms among all N platforms

Within this exposure time (T_E) which may vary from day-to-day train operation, there can be certain dangerous probability time T_G ($T_G < T_E$) where V_{RE} may be higher than so called maximum acceptable voltage limit. This is the voltage where N_{RG} devices may be set. This time T_G may be different on each day. It is this time which is controlled by N_{RG} devices to make a risk free operation. T_G on a specific day of trains operation may be estimated by the probability function indicated by expression (2).

$$T_G = P\ (V_{RE}, D_F, A_S, T_B, C_R, V_D) \qquad (2)$$

Where

P	probability function of variables listed in the bracket
A_S	abnormal time of TPSS operation – TPSS out of service during train operation
T_B	train bunching time intervals during train operation
C_R	crush or maximum train (load) - current
V_D	dangerous set voltage range plus or minus - volts

Since it is the dc current through human body and not the touch voltage V_{RE} that needs to be lowered, other methods such as use of high resistivity insulating pads at the platform along with high insulating material on the outer shell of the train vehicles should be promoted in the design criteria for the transit system. This V_D should be recorded both in magnitude as well as time duration to make proper settings of N_{RG} devices.

b) Unpredictable threat of dc and ac power system faults and rail-to-earth voltage

High V_{RE} may be caused by a multitude of ac and dc power system faults and other sneak circuits which are numerous to predict or list. Many of these faults are "external" to the dc transit system and thus are not under the control of the TPSS protection scheme. These faults may be of longer duration (See incidents in Appendix). N_{RG} devices can clamp rail-to-earth voltage caused by predictable or unpredictable external faults.

IV. VARIOUS TRANSIT SYSTEMS

Accessible locations of various transit systems based upon their design configurations are described below.

a) Heavy Rail System (3rd Rail System)

These systems use separate rights-of-way from which all other vehicular and foot traffic are excluded. Therefore passengers are exposed to V_{RE} only at the passenger stations whereas maintenance crew may get exposed at any work location near the tracks during train operation. Overhead ac distribution lines close to transit system may not be of much concern if proper design is implemented not to let ac broken line fall on rails. Application of N_{RG} devices still come into play to mitigate the hazard of rail potential although use of insulating rubber pads etc can raise the set voltage limit for N_{RG} devices.

b) People mover

It appears that most such systems use separate guided right-of-ways and rubber tires where power conductors and rails, if used are only accessible to maintenance crew. Patrons are subject to rail touch voltage through vehicle body contact at the passenger station platforms for any bodies not made of fiberglass. N_{RG} devices application can provide protection required for the patrons and the maintenance crew and may help in minimizing damage to equipment. Application of insulating pads and dedicated grounding rail can reduce the risk of shock hazard, however, increased risk of dc stray current should be evaluated in case of dedicated grounding rail.

c) OCS powered light rail system

In certain areas of this system it is not possible to exclude access to return rail by vehicular and foot traffic. Underground ac power distribution system or an overhead ac distribution lines in close proximity to transit tracks may get negative rail involved during their ac ground faults. Although negative rails are usually embedded in earth, the design requires appropriate insulating material to make rails isolated from ground as much as practical. This isolation sets the stage to have high rail voltage posing the risk of electric hazard especially to children who may be stepping on the rail and puddle of water near the tracks. Application of N_{RG} devices makes less risk from shock hazard at the expense of increase in dc stray current and should be evaluated.

d) DC Powered Monorail System or DC Powered Rubber Tired Vehicles with Negative Rail System

These systems do not share their guide way system with other vehicular and foot traffic and power rails may not be exposed directly to any person other than the maintenance crew. In Seattle Alweg monorail had a car body grounded to the negative power conductor for 42 years. This caused numerous non fatal shocks to maintenance crew and finally contributed to a near lethal fire incident. The car bodies are now floating and protected by a hot coach detector similar to trackless trolleys.

V. CURRENT THROUGH HUMAN BODY AND SHOCK HAZARD.

Current through human body touching the negative rail can be simplified by an equivalent circuit comprising of a voltage source V_{RE}, source resistance and human body resistance to complete the circuit. The source resistance is the equivalent rail-to-earth leakage resistance which depends upon the rail-to-earth leakage resistance of the insulation system and the length of the negative rails which is in the range of 5 to 10 Ω and is small compared to human body resistance.

Dalziel's equation for current through human body is indicated in expression (3) [3] [5].

$$I = \frac{K}{\sqrt{t}} \qquad (3)$$

Where

I is the body shock current in amperes at the threshold of fibrillation

t is the duration of the flow of that current in seconds

K is a constant, which Dalziel determined below

For 0.05% of a large population group, the minimum value for current I, at 60 Hz, was found to be 95 mA for 70 kg body weight and 65 mA for 50 kg body weight. From the experimental data, a value was found for K at 3 seconds as 0.165. Most people are aware that there is danger in touching an energized object. Few really understand, however, just how small a quantity of electric energy is required for a fatal incident. This energy is estimated by squaring expression (3) and multiplying with body resistance R_b and time t which is indicated by expression (4) below.

$$Energy = R_b I^2\, t = K^2\, R_b \quad watt.seconds \qquad (4)$$

Using body resistance R_b value of 500 Ω, the lower value of energy required to produce fibrillation was found to be 13.6 watt seconds for 70 kg body weight (*K* value of 0.165). There may be harmful currents below the fatal current limits shown in Fig. 2 depending upon many factors related to condition of the person and duration of the current through the body. Note that dc current is more likely to freeze muscles than ac, but ac will cause heart fibrillation at lower voltages than dc. Equal N_{RG} protection for ac and dc faults may require lower settings for ac faults as implied by Table 1.

A detailed discussion of the research of electric shock hazard by Dr. C.F. Dalziel and W.R. Lee is included in the papers [3] [4] [5]. Dr. Massimo Mitolo's paper [7] provides a basic holistic approach and definition of probability that may be applied for further research to transit system risk of shock hazard from rail-to-earth voltage.

Nearly 20 years after Dalziel, Biegelmeier and Lee provided further analysis and explanation of experiments to establish the threshold of fibrillation in humans; these researchers postulated that there was a relationship between fibrillating currents and the timing of the heart cycle. A 'normal' heart beat duration was taken to be 600 ms (100 beats per minute). They found a mathematical relationship between the lower threshold and upper threshold creating a graph drawn with a slope of -1 indicated in Fig. 2 [1] [2] [3] [4] [10]. These are shown in ac rms. currents by lines 'a', 'b' and IEC interpretation of ac rms. current by line 'c1', the data for dc traction current in shown by a line between lines 'b' and 'c1' in Fig. 2 based upon the current in Table D.3 [1].

Fig. 2 current v/s time graphs may lead a conclusion that that the rail voltage V_{RE} is such that current and time does not exceed above the line for the dc current and this N_{RG} devices are not needed. Please note the time and current may increase during ac and dc faults especially dc power system protection may not be very sensitive to high impedance fault at remote from the traction power substation. In addition, Fig. 2 graphs indicate currents which are likely to cause fatal incidents. We are dealing with currents and their duration below all these lines in Fig.2 which may cause varying degree of shock hazard and consequent injury to human from negative rail potential.

What is the probability of an ac or dc ground fault adding to the normal IR drop voltage at the time a person is exposed? What time duration will make this dangerous? The answer to second part of the probability question was provided by Lee and Biegelmeier in their research on heart physiology [5]. They found that the probability of a fibrillating current occurring in the first one third of the heart cycle (200 ms) was 30%. The first part of the probability question is much more difficult to answer, and it has a significant legal risk attached.

a) DC Traction Power System Voltage Limits

IEEE Standard 80, IEEE Guide for Safety in Substation Grounding, is the grounding standard commonly referenced in the USA for design of electrical facilities including DC traction power system. This guide only provides guidance on the tolerable ac step and touch potentials based upon the tolerable human body Current

Limits on Dalziel's equation that gives the body current that can be survived by 95% of persons weighing 110 lbs (50 kg). This statement when used with other assumptions leads to ventricular fibrillation voltage expression (4). Simple statement indicated in IEEE 80 that dc current can be 3 times higher than ac will lead to expression (6) for dc tolerable touch voltage.

(5)

Where *t* is the duration of the shock current in seconds. These expressions are valid for 0.03 to 3 seconds and were intended for isolating the faulted power system in the time duration for the protection device. A simple statement indicated in IEEE 80 that dc current can be 3 times higher than ac will lead to expression (6) for dc tolerable touch voltage.

(6)

Rail-to-earth voltage may last more than 3 seconds and thus published data indicated in reference [1] and shown in Table 1 for the accessible voltage should be considered.

Shock Duration (Seconds)	Permissible Voltage and Current Limit (rms.)			
	AC Systems		DC Systems	
	Voltage (Volt)	Current (mA.)	Voltage (Volt)	Current (mA)
0.05	935 V	500	770 V	410
0.1	842 V	442	660 V	340
0.5	225 V	100	395 V	195
1.0	80 V	50	170 V	150
1-300	65 V	41*	150 V	132.4*
> 300 (continuous) (See Note)	60 V	37.5*	120 V	105.6*

Table 1 – Maximum permissible touch voltage and human body current for threshold of fibrillation

Note: In shops, the EN 50122-1 maximum permissible continuous +voltage limits are 25 V ac and 60 V dc. Please note that the touch voltages in Table 1 have been increased by adding voltage drop across the old wet shoes having 1000 Ω resistance value. The voltage and current values indicated in Table 1 are those indicated in tables D 3.1 and D 3.2 from page 54 of BS EN 50122-1:1998 [1]. Tables D.1 and D.3 of [1] contain more voltage points than those shown here for simplicity. Indicated currents with * are estimated values not indicated in reference [1]. For values in the range of 50 V dc the current value may be in the range of 40 mA and this current value should be considered for shock hazard [8] [9].

Present industry accepted value for the threshold of fibrillation current through the human body is shown in Fig. 2 by line c1 is for the 60 Hz ac [6] and the line above c1 is for the dc traction power current which is based on the data indicated in Table 1 [1]. This data may help in clarification of the upper limits of lethal currents from elevated rail voltage.

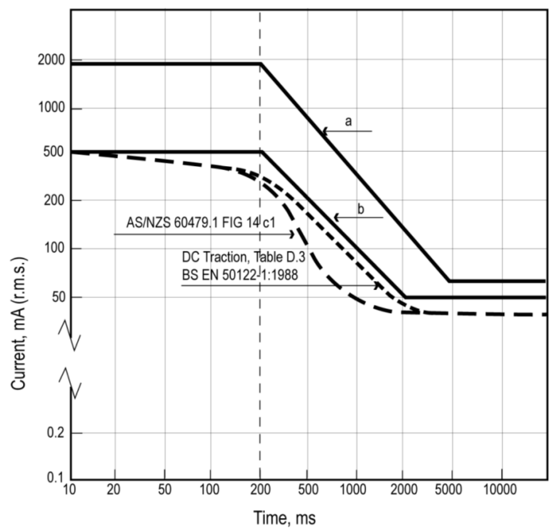

Fig.2 - Threshold of fibrillation – body currents

VI. MANAGING THE RISK OF V_{RE} HAZARD

The answer to the question of how effective are N_{RG} devices lies both in the approach to their appropriate locations in the dc power system and in their setting criteria which can minimize the risk even when the rail-to-earth voltage may be low but may last long enough to cause shock hazard and injury. Many factors come into play for the unpredictable threat of touch potential and its subsequent implications. Best approach to minimize the rail-to-earth voltage risk is to review all of the factors listed below and optimize the design approach to apply N_{RG} devices.

- Design the system using rail-to-earth voltage as a design criterion.

- Review special locations that result in maximum rail-to-earth voltages during power system analysis.
- Apply insulating rubber mats and promote the application of insulating car body in addition to application of N_{RG} devices.
- Review the idea of a dedicated grounding rail for the entire length of the platforms especially for the people movers.
- Promote uniform approach of design and application of N_{RG} devices among the suppliers and transit agencies.

VII. N_{RG} APPLICATION DISCUSSION

One of the design criteria is to keep $\mathbf{V_{RE}}$ as low as practical during substation spacing and ratings analysis of designing traction power system. Software programs [11] [12] are used to determine the expected magnitude of dc stray current as a result of this varying voltage. Abnormal system operation when a TPSS is out of service is also considered to determine the maximum expected rail-to-earth voltage especially at the passenger stations. As the system gets older the rail-to-earth voltage may change due to deterioration of the rail insulation system or lack of maintenance, however, it is the author's opinion that it has little effect on the rail-to-earth touch voltage consideration with the exception that the N_{RG} devices setting may require re-evaluation as slightly higher current may flow between the rail and earth.

For proper application of N_{RG} devices, high accuracy rail-to-earth monitoring devices should be used during pre-revenue service and then later during actual system operation of trains under all operating scenarios including one substation out of service successively to record voltage profile of V_{RE} at specific locations. Although such a monitoring system may not be able to provide a rail voltage profile under a rare train bunching operation, it will provide enough data for N_{RG} device application and settings.

Design of the station platform and vehicle shell should implement use of insulation material to increase the safe rail touch voltage to patrons. The use of personnel protective grounding (PPG) is recommended for electric safety of the maintenance crew whether they work during train operation or during night when no trains are in operation but the TPSS are energized. The type of PPG used in the rail industry is another subject that requires uniform design approach and operating procedures. Simultaneous contact with grounded metallic structures such as switch machines or other metallic barriers and the negative rail should be avoided.

There is no other practical solution other than to manage such risk by use of appropriate N_{RG} at appropriate locations even if the operation of such devices may lead to some increased dc stray current. It may be stated in some technical papers that the touch voltage of the negative rail is below the acceptable maximum touch voltage which in the author's opinion is a false sense of risk management. N_{RG} devices are recommended from other considerations indicated in this paper.

It appears that there is a lack of applicable published probability analysis and data for the dc transit system in the industry. This may prove to be a false interpretation under the circumstances of rail-to-earth voltage due to dc ground faults outside dc switchgear enclosures that may last longer than the rail-to-earth voltage developed by operating train current. Since the probability of risk will not be zero, it is the author's opinion that the general public and the court have high expectations for the transit system to provide safe dc electrical system which requires N_{RG} devices. How to quickly detect power system ground faults transferred potentials coupling with rails and to remove the risk seems to be a fundamental design requirement instead of estimating probability and therefore N_{RG} devices are needed for all transit systems.

VIII. N_{RG} DEVICE SETTING CRITERIA

The setting criteria indicated below is author's opinion based upon the data presented in Fig 2 and should be further evaluated based upon the design capability of N_{RG} devices and understanding of the V_{RE} characteristics and other considerations of minimizing the current through the human body. Currently many suppliers of such devices are complying with IEC and EN standards such as EN- 50122-1 and EN 50123-5, limitation of touch voltage and accessible voltage to meet both the transient over voltages due to lightning as well slow changes in rail-earth voltage due to changes in train voltages of other ac and dc faults. Review device ratings, limitations and settings with the supplier of the device.

1. For heavy-rail system with insulated rubber mats, maximum voltage settings may be higher as compared to LRT systems. Should measure flow of current between rail and earth upon shorting, if current does not stop, then trip all feeder breakers at adjacent TPSSs.
2. For LRT and street cars settings should not be more than 50 V. NRG device activation time should be as

low as practical. Device should stay activated for few seconds and then open if there is no current, if there is current then trip all DC feeder breakers in adjacent TPSSs. System availability is enhanced whenever NRG can control fault voltage to a safe level and avoid substation trips.

IX. RECOMMENDATIONS

1. There are many ac and dc faults sources not controlled by the TPSS, therefore application of N_{RG} devices is very important in all transit systems.
2. The N_{RG} devices must be installed and working from the first day the new street railways, light rails, and street cars electrification projects are tested or put in to revenue operation. These devices should be installed at locations where insulated tracks are mingled with vehicles and pedestrians in city streets.
3. Application of insulated rubber mats and additional grounding rails may be useful in addition to use of N_{RG} devices in dedicated right-of-way applications.
4. In addition to application of N_{RG} devices, the risk management of V_{RE} should start with reducing dc current through the human body by considering other methods such as the use of rubber mats of high resistivity at the platform edges, grounding rail at the platforms, and use of PPG for the maintenance crew.

X. FUTURE RELATED WORK

It appears there is a need for future work by all who are involved in the subject of N_{RG} device developments and applications.

1 Calculations of dc stray current with and without N_{RG} devices and recommendations for reducing corrosion due to dc stray current.

2. Method to ensure fail-safe response by N_{RG} devices. Time response of N_{RG} devices sufficiently fast to suppress ac power line faults and lightning surges.
3. Calculation of IR voltage peaks with and without N_{RG} devices using IGBT current control to equalize and reduce IR peaks
4. Calculation of transit system availability with and without simple or advanced N_{RG} devices, i.e. nuisance trip shut downs. Minimize TPSS trips and lock outs whenever possible.

XI. APPENDIX

a) Incident No. 1: Cross coupling between the grounded yard system and floating main line 700 V DC Light Rail System.

The 64V device at TPSS did not work and was never tested. Due to the wrong placement of a catenary no-bo-insulator, a train leaving the yard caused main line catenary to earth grounded, causing rail-to-earth voltage of - 750 V dc. This could be sustained for as long as the train sat and waited for street traffic to clear. This faulted condition could last for minutes.

This fault condition was not detected for several years until N_{RG} device was installed at TPSS which alarmed every time a train left the yard. The N_{RG} was successful in both identifying and clamping the fault voltage to a safer level. In an associated situation, track switches had been failing with dielectric breakdown. Dielectric failure which was occurring at track switches could have caused another “external fault source’ by coupling utility power system potential to the rail.

b) Incident No. 2: 750V DC Transit Systems.

There are two different systems operating in the city, failure of one system effected the other system operation. Trolley overhead dc system crossed the street car dc cantenary system at many street intersections. Many times trolley arcs commutated to the street car catenary due to lack of sufficient insulation barriers. The two separate dc power systems could be cross-coupled due to a wire pull down or wire damage due to trolley poles in the overhead system, which is not uncommon. The street car substations tripped off due to 64V leaving the street cars stranded and both the streetcar body and the street car rail at plus 700V DC in the case of a sustained fault. Most faults have been temporary and short duration, with only the continual nuisance tripping and street car shutdowns.

The street car had no control over the trolley system, whatsoever. At present, there are plans to install $N_{RG.}$ Currently there is a temporary set up of multiple solid grounding of the negative rail to achieve voltage safety at the expense of probable increased risk of corrosion.

c) Incident No. 3: Utility overhead power line fallen on trolley wires.

High voltage utility lines across the trolley caused damage to TPSS equipment on two different occasions, without any other casualty. Trolley buses are double insulated and trolley wires cannot be contacted by the public. There have also been feeder cable faults which have caused the negative contact wire to go well below earth ground. This is not too much of a problem in the trackless trolley system, but the same thing will occur with light rail and street cars, which have more exposure to the public.

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