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IR^3 SPECIAL ISSUE:

GEOMAGNETIC INTERFERENCE TO RAILWAY TRACK CIRCUITS IN SWEDEN

Editorial Corner

About the Editors

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Dr. Robyn Fiori is a research scientist for the Canadian Hazards Information Service of Natural Resources Canada specializing in space weather. Her research is applied to the development and improvement of space weather tools and forecasts to be used by operators of critical infrastructures and technologies in Canada. As well, it has been published in numerous peer reviewed scientific journals, including the Journal of Geophysical Research, the Journal of Atmospheric and Solar-Terrestrial Physics, and Space Weather. Dr. Fiori received her B.Sc., M.Sc., and Ph.D., from the University of Saskatchewan, Department of Physics and Engineering Physics while studying in the Institute of Space and Atmospheric Studies.

This Issue

Space weather affects many technological systems and considerable work has been done to understand geomagnetic effects on ground systems such as power systems and pipelines. There have also been a few reports from Sweden and Russia of geomagnetic interference to railway systems. Unfortunately, there are only a few papers in the scientific and engineering literature that deal with this topic. Thus, when a Swedish book was found that contained information on geomagnetic interference to railway track circuits, it warranted further investigation.

The book, "Det Tekniska Utförandet av Signalanläggningar vid Statens Järnvägar, Del I: Spårledningsteknik, (The Technical Execution of Signalling Facilities at the State Railways, Part I: Tracking Technology)" by Thelander et al, was published in 1956. It deals with a wide range of phenomena that could affect the operation of railway signalling systems in Sweden. The main text discusses the various issues, but in addition, there are multiple appendices, written by experts in each field, that provide a comprehensive examination of each topic. For geomagnetic effects, there are two appendices:

- Appendix 5f, Åtgärder mot jordmagnetiska störningar I *Hela* likströmsspårledningar för automatiska Vägsignalanläggningar, by E. Alm.
- Appendix 6, Beräkning av jordmagnetiska störningsspänningar I spårledningar, by B. Lejdström and S. Svensson.

There is only one problem (for some of us): it is written in Swedish.

To make the material in the two appendices accessible to a wider audience, it was decided to translate them into English. A professional translator was used to translate the text. The figures from the original Swedish versions were scanned and English translations of all labels in the figures inserted on top of the original image to provide

English versions of the figures. The final translation have been checked by Dr. Risto Pirjola, a space weather expert with knowledge of both Swedish and English. Finally, questions about the railway terminology were referred to Dr. Stefan Niska, an expert in railway signalling at the Swedish Transportation Board (Trafikverket).

The appendices were written for a technical audience in Sweden who would be familiar with track circuits and railway system in Sweden at the time they were written. Consequently, this special issue starts with an introduction to provide some basic information about space weather and track circuit operation to help readers understand the appendices.

The articles that have been translated were originally published in 1956. To acknowledge the original source, while providing a reference to the translations, the articles should be cited as follows:

In the text of a paper, refer to Alm (1956, 2020) and Lejdström and Svensson (1956, 2020).

In the references, cite the articles as:

- Alm, E., Measures against geomagnetic disturbances in the entire DC track circuit for automatic signalling systems, original publication (in Swedish) Appendix 5F, Betänkande: angående det tekniska utförandet av signalanläggningar vid Statens Järnvägar, 1956. Translation (in English), Infrastructure Resilience Risk Reporter, Vol 1, Issue 10, 10-27, June 2020. https://carleton.ca/irrg/journal/

- Lejdström, B. and Svensson, S., Calculation of geomagnetic interference voltages in track circuits, original publication (in Swedish) Appendix 6, Betänkande: angående det tekniska utförandet av signalanläggningar vid Statens Järnvägar, 1956. Translation (in English), Infrastructure Resilience Risk Reporter, Vol 1, Issue 10, 28-51, June 2020. https://carleton.ca/irrg/journal/

Next Issue:

Issue 11 will feature articles from speakers at the 27 November 2019 Infrastructure Resilience Research Group armchair discussion (The Environment: Economic Security, Resilience - Select Industry Response) and Dean's Lecture (The Environment: Past, Present and Future - Sustainability Challenges and Strategies). We invite authors to contribute additional articles for Issue 10 relating to their experience in the field of infrastructure resilience. Draft articles of 2500-4000 words are requested by August 21, 2020. You may not have much time or experience in writing 'academic' articles, but IR^3's editorial board can provide guidance and help. Your experience is valuable and IR^3 provides an ideal environment for sharing it.

Acknowledgements

Dr. Magnus Wik (IRF, Lund, Sweden) found the original Swedish book. I am most grateful to Dr. Felix Kwamena (Low Carbon Energy Sector, Natural Resources Canada) for arranging the translation into English, Dr. Risto Pirjola (NRCan) for checking the translations and Dr. Stefan Niska (Trafikverket) for providing information on railway terminology. Dr. Pirjola, Staffan Viklund (Trafikverket) and Christina Engström (Swedish National Maritime and Transport Museums) provided biographical information about the authors.

INTRODUCTION

During disturbances on the Sun bursts of energy are released in the form of electromagnetic radiation and particles that travel through interplanetary space to the Earth where they cause disturbances in the space environment of the Earth down to disturbances in the Earth's magnetic field seen on the ground. This collection of processes from the Sun to the Earth is referred to as "space weather" and can have a variety of detrimental effects on manmade technology. Enhancement of energetic particles in the space environment can cause problems to satellites ranging from "single event upsets", where the charged particles cause a change of signal in the satellite circuitry, to actual damage to the satellite electronics, in some cases making a satellite inoperable. Energetic particles also penetrate down to the ionosphere, the ionized layers at the top of the atmosphere, where they cause extra ionization that can disrupt high frequency (HF) radio communications and degrade the positioning accuracy from global navigation satellite systems (GNSS). Electric currents flowing in the magnetosphere and ionosphere produce fluctuating magnetic fields seen on the ground as a magnetic disturbance, superimposed on the Earth's main magnetic field. These magnetic field variations induce electric currents in the ground and in long conductors causing problems for power systems, pipelines, communication cables and railways.

During extreme space weather events, the impact on technology can be severe. The "Carrington" storm in 1859 (so-called because the astronomer Richard Carrington reported the first sighting of a solar flare, which turned out to be the precursor for a major magnetic storm a day later) caused world-wide disruption to the telegraph system (Boteler, 2006). Subsequent magnetic storms continued to cause problems for the telegraph, but to a more limited extent (Boteler et al, 1998). A major magnetic storm on Easter Sunday in 1940 produced effects on the telephone and telegraph systems in the United States (U.S.) (Germaine, 1940; Stetson, 1947) and Norway (Harang, 1941); as well as the first reported effects on power systems, with power lines being tripped out in the eastern United States and Canada (Davidson, 1940). Technological problems were again experienced during the magnetic storms during the solar active years from 1957 to 1960 (Axe, 1961; Slowother and Albertson, 1967; Elovaara et al, 1992) and during a major magnetic storm in 1972 (Albertson and Thorson, 1974; Anderson et al, 1974). March 13-14, 1989, saw the largest magnetic storm of the 20th century that produced power system problems across Europe and North America, including the collapse of the Hydro-Quebec power system leaving the 6 million residents of Quebec without power for up to 9 hours (Guillon et al, 2016; Boteler, 2019). Other storms have caused localized power system operating anomalies and the "Halloween" storm of 2003 produced a short power blackout in Malmo, Sweden (Wik et al, 2009). Although the worst effects are infrequent, there is concern that a repeat of a Carrington size event could have widespread impacts on ground-based networks, as well as other technological systems.

A number of countries have recognized the risk from space weather to critical infrastructure and are considering space weather in national risk planning alongside other High Impact Low Frequency (HILF) events. For example, the North American Electric Reliability Corporation

(NERC)[1] has introduced new guidelines that require power utilities to consider the 1-in-100 year magnetic disturbance expected in their location and, using earth conductivity models, determine the geoelectric fields that would occur and use these as input to power systems models to calculate the geomagnetically induced currents (GIC) expected to occur. These can be coupled to engineering models to determine the impact on transformer operation ranging from overheating of the transformer, as well as generation of AC harmonics that can cause misoperation of protective relays and increased power consumption by the transformer that can cause voltage instability in the power network and, in a worst case, power blackouts (Pulkkinen et al, 2017)[2].

Railways are another manmade system using long conductors that can be at risk from space weather. Signalling systems have been affected by geomagnetic disturbances with several countries reporting occasions when signals were incorrectly set to Red, halting train movements for a time. There is also concern that the increasing use of GNSS for automatic train operations is introducing a new vulnerability to space weather. In 2015, a workshop was held in London, UK, to raise awareness of space weather and explore the risks it creates for rail systems (Krausmann et al, 2015). This workshop was organized by the European Community Joint Research Centre, Swedish Civil Contingencies Agency, UK Department of Transport, and NOAA Space Weather Prediction Center. It identified the prime vulnerability as the direct impact of geomagnetic induction on track circuits used to control railway signals. It was also recognized that because of different system architecture, the vulnerability of railways to space weather varies from country to country, and further research is needed to close knowledge gaps so that the systems at risk can be identified.

Track circuits were introduced in 1872 by Robinson in the United States and were quickly adopted around the world (Kichenside, 2009). The basic concept is to divide the railway line into blocks and only allow one train at a time into a specific block. Track circuits are used to detect the presence of a train and control the signals to prevent a following train from entering an occupied block of track. The operation of a track circuit (TC) is illustrated in Figure 1 (from Scalise, 2014). Figure 1(a) shows the track circuit operation in the absence of a train. The TC power unit drives a current down one rail, through the TC relay, and back along the other rail. The current through the relay causes it to "pick up" closing the contacts in the signal circuit to set the signal to Green. Figure 1(b) shows the situation when a train enters the block. The wheels and axle of the train provide a 'short circuit' between the rails, providing a path for the track circuit current instead of through the relay. With no current now flowing through the relay, it "drops out" causing the Green light to go off and turning on the Red light, signalling to any following train not to enter that block. During geomagnetic disturbances, extra electric currents are induced in the rails, potentially causing the track circuit to misoperate. Setting the signals to

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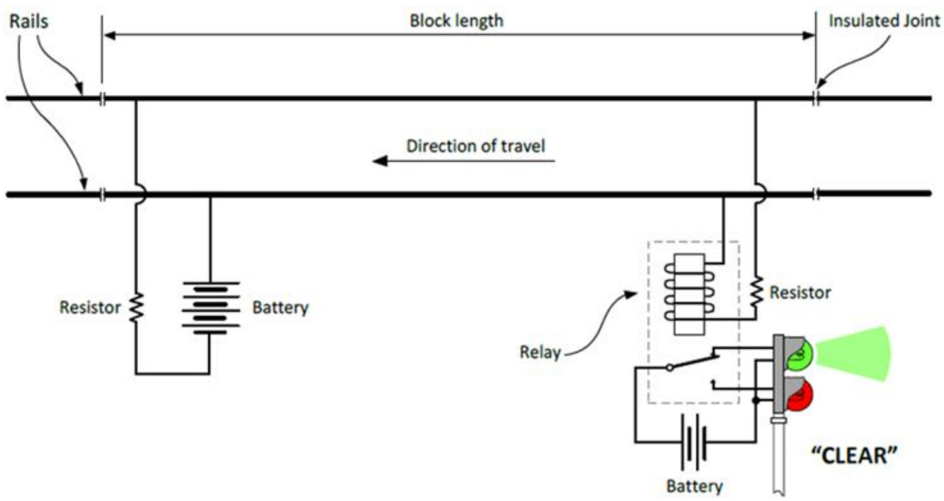
[1] For more information see: https://www.nerc.com/pa/Stand/Pages/TPL0071RI.aspx.

[2] For more information on the risks to large power transformers, the challenges involved in the replacement of one or more failed transformers due to a HILF event, and a discussion of risk mitigation strategies see *Risk Mitigation Strategies for Large Power Transformers* by Kenneth Friedman and Tiffany Choi in Issue 4 of the IR[3] (http://carleton.ca/irrg/wp-content/uploads/Vol-1-Issue-4-IRRG-Journal-FINAL-FINAL.pdf).

Red when there is no train present in that block is termed a “Right Side Failure”; it unnecessarily stops train movement, but is not a safety hazard. The alternate possibility is that the signals are turned to Green even though there is a train already in the block. This is called a “Wrong Side Failure” and is a serious safety concern as it could allow a following train to enter a block that is already occupied.

a) Without a train



b) With a train

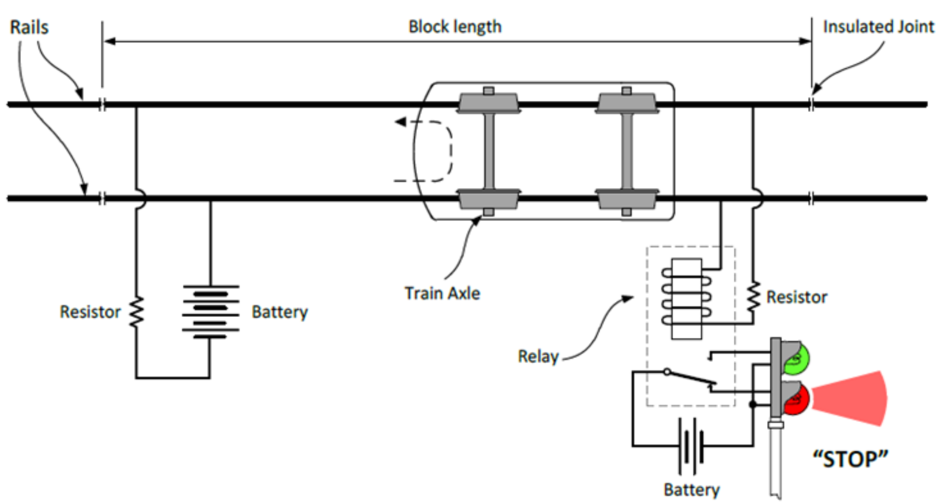


Figure 1. Operation of a track circuit to control railway signals (from Scalise, 2014)

A joint Canadian-Swedish research study has been trying to answer some of the questions about how geomagnetic disturbances affect railway signalling track circuits. Unfortunately, the links between space weather and misoperation of track circuits can be difficult to uncover. However, a study in Russia (Eroshenko et al, 2010) found that unexplained signalling anomalies on certain railway lines occurred during times of high geomagnetic activity. Swedish railways have been more affected by geomagnetic disturbances than other countries. European signalling books (Bailey, 1995) describe special track circuit configuration used in Sweden because of geomagnetic disturbances. In 1982, signals in a 45 km stretch of track in the south west of Sweden were set to Red during a geomagnetic disturbance (Wik et al, 2009). The geomagnetic disturbance was calculated to have produced geoelectric fields of 6 V/km which interfered with the track circuit operation. To fully understand how these geoelectric fields affect signalling requires the ability to model the geomagnetic interference to track circuit operation. Unfortunately, there is little in the published literature on this topic. Thus, the Swedish report by Thelander et al (1956) with the appendices by Alm (1956) and Lejdström and Svensson (1956) is especially important, and it is hoped that making available the translations of their work in this special issue will make it accessible to a wider audience.

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Measures Against Geomagnetic Disturbances in the Entire DC Track Circuit for Automatic Signalling Systems

*Professor E. Alm **

1. Fundamental Features of the Problem

According to the investigations carried out, it is clear that when using DC track circuit relays on single phase lines, in addition to the ordinary AC voltage disturbances, there are certain DC voltage disturbances which, in adverse cases, may cause a false clear. Here, in part, the damped direct voltage (DC) components are relevant, which can occur when the train transformers connects, especially if the train is in the vicinity of a converter station (and if the booster transformers are located near the converter station, then the booster transformers are not enough dimensioned), in part, with geomagnetically induced currents in the rails that vary in intensity with a period of approximately 11 years. (If in the future, grid power transmission with high voltage direct current is used for general purpose, we must also be prepared that a part of the return currents could, through the earth, reach the railway's rail system, and thereby cause currents similar to the geomagnetically induced currents).

For the first type of disturbance, stemming from the connection phenomenon, we could protect ourselves through appropriately dimensioned reactors, which are connected between the track and track relay, and are combined with the parallel resistor connected to the relay (see appendix 3). Eventually, the relay equipment can thereby, also be provided with a time delay, which delays the track relay operation to some extent. A delay of about one second should be enough. In case of a relatively large distance between the transformer station and train, this disturbance will be quite small.

In contrast, it is much more difficult to prevent the effect of earth currents on track circuits and their relays. It is true that they occur quite sporadically and at long intervals, but in spite of this, their impact cannot be neglected. As a rule, the voltages induced in track circuits during high sun-spot years should not exceed 2 to 3 V/km, but values over 6 V/km have, however, been observed, and the fact that even higher values could have occurred, should not be denied. Therefore, interference voltage value must not be set lower than 6 V/km to the ground, for measures that would be adopted for protection hereby, especially for sections in which it has been found in earlier investigations that during the sun-spot years, earth currents can occur (it is possible that the propensity may be different for sections with different directions. On the other hand, the railway network at present is so coherent that, for instance, the North and South sections can also face disturbance due to earth currents).

In our present experience, when using direct current relays, we have the following hypotheses, generally to get an effective protection against the aforementioned disturbances:

a) Centrally supplied track circuits with polarized track relays at both ends of the track circuit and with an extra power cord that connects these relays, so that both the relays are activated to produce a clear signal (see the main statement).

b) Use of code-following relays (see appendix 5B).

As opposed to the first alternative, that the required extra power cord increases the initial cost considerably, if it is not for other reasons (for example line blocking), must be laid out, and this is seldom the case for ordinary signalling systems. With the latter alternative, however, the previously mentioned concerns are relevant.

Noting the great number of track circuit installations that were built before the disturbances in question started being studied. Firstly, we can examine the risks encountered with respect to the disturbance in question, if the track circuits for the signalling systems are built with normal DC relays; and secondly, how by changing the design based on track circuit analysis, we can achieve acceptable operational safety. (In the following, the analysis is limited first to earth current disturbances as these appear to be the most insidious). Specifically for signalling systems at road intersections, there are certain circumstances that reduce the disturbances in this respect.

Specifically, it must be highlighted that in the analyses referred below *fault free* track circuits have been assumed. If rail fracture also occurs, the conditions become considerably more complicated and many of the following conclusions do not apply. For the rest, see appendix 6.

2. For the Right Functioning of Track Circuits With Favourable Conditions in a Railway Signalling System

(a) Earth currents are not constant, rather they appear to vary between positive and negative values.

(b) In railway signalling systems, it is not, as in some other cases, absolutely necessary for the track relay to drop as soon as the train enters the track circuit section. Rather one can, in certain cases, allow the train to run a little bit on the track circuit before the relay drops out; it is important that the warning period at the crossing is sufficiently long for the road vehicles waiting to cross the railway.

(c) The general equipment for a railway signalling system and its way of working is such that the Earth current in the in-and-out rail sections can cause a stop signal in the equipment. This is illustrated in Figure 1 that provides a schematic picture of the currently used track circuit system in automatic signalling systems.

Here, the Earth current is assumed to flow in the rail from left to right. If the voltage drops on the track circuits located on both the sides of the intersection are of the same size as the voltage on the track relays, this voltage drop combines in the left track circuit to cause an increased current in the previously activated left track relay I (both the track circuits are presumed to be unoccupied). In the right track relay II, however, the voltage drop of the Earth current in the line voltage decreases the voltage across the track relay, and if the remaining voltage decreases and becomes equal to the relay's fall voltage or less than that, then the relay drops out. If the Earth current has the opposite direction, instead, the left track relay will drop.

When one of the track relays drops, the warning signal is set off at the intersection, and it continues for about 4 minutes even if no train is approaching, and if a moment later both the track relays are activated. After this time, a time relay starts functioning which tries to disconnect the warning signal. This works if both the track relays are activated, otherwise the warning signal continues.

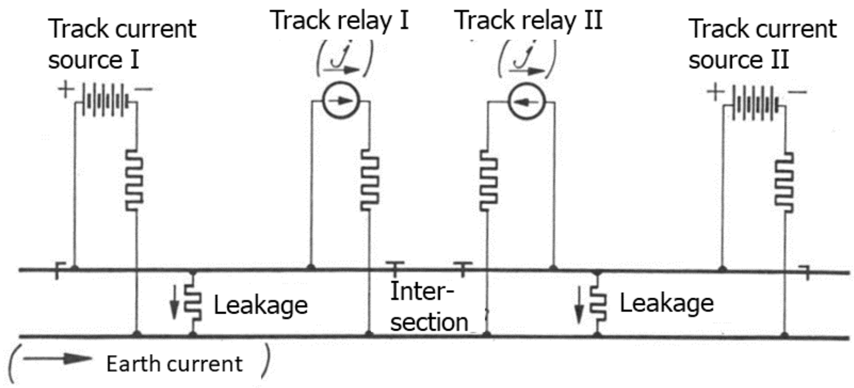

Figure 1. Diagram of the principle for track circuits in railway signalling systems with DC track relays

This also means that if the Earth current is sufficiently large, it helps to some extent to protect the intersection.

In order for the track relays at unoccupied track sections, after the disconnection of the warning signal, be activated and the equipment returned to its rest position, either the interference voltage at unchanged direction of the Earth current has decreased so much that the track circuit battery may decrease, possibly the earth current thrown in direction so that its voltage drop helps to draw the right track relay, or (at neutral track relays) the interference voltage at unchanged direction of the Earth current has become so large that it overcomes the battery voltage and gives an excess pick up voltage, although of the opposite character signal.

If however, during this time, a train enters the right track circuit, the associated track current source is short-circuited, so that only the Earth current's voltage drop can affect the associated track relay. If this voltage drop can reach up to the pick up voltage of the relay and if neutral track relays are used, which are not dependent on the direction of the current, this will reduce and thus show "Clear" despite the fact that the trains are heading toward the intersection. For a train coming from the west, the Earth current voltage needs to reach only the relay's fall voltage for a false clear to be given, so the previously activated track relay is prevented from dropping out even though the train short-circuits the track circuit. Here, other options to reduce the risk of false clear must also be used.

Building upon the above-mentioned first circumstance, the Earth current's variation with time, however, is not possible. From the tests conducted at the Swedish Maritime Administration's Geomagnetic Lab at Lovön, it is evident that such a disturbance in some individual cases can hold an unchanged polarity for up to 7 to 8 minutes. When a train passes through the short track circuit section to an intersection in less than 1 minute, it is clear that in general, one cannot presume that the geomagnetic disturbance may have disappeared (possibly inverse polarity), as the train goes through a small part of the track circuit.

The next circumstance that can be considered, if necessary, is accepting a shorter warning time than the length of the current track circuits related to the railway signalling system, means that the interference voltage in one of the incoming trains' activated track circuit is reduced in proportion to the length between that part of the track circuit that is located between the train and the intersection. If we assume that for a train with the speed 135 km/hour, the warning time can be reduced to 16 seconds, the signalling must be started at the latest of a distance of 600 m. (At the speed of 90 km/h, the warning time is 24 seconds). This means in this case we only have an interference voltage of maximum 0.6 x 6 = 3.6 V on the track circuit in question. Since this track current source is thereby short-circuited, the relay's fall voltage in this case should, therefore, not be less than 3.6 V.

Example. To get an understanding of the consequences that this may have, it would be useful to study a specific case. If we assume the track circuit is dimensioned for a 30 second warning time at 135 km/h (=37.5 m/s), the length of the track circuit would be 1,125 m. When dimensioning the track circuit equipment, one usually presumes that the leakage conductance between the rail sections in unfavourable cases may go up to 1 siemens/km. In the present case, this corresponds to 1.125 siemens, with a rail resistance = 0.135 ohm per double circuit, a track relay of 30 ohm with 0.048 pick up current = 0.144 a, connected in parallel with a protective resistance of 15 ohm, so that the total pick up current = 0.144 A, and a battery of 7.2 V, connected in series with protective resistor of a total of 1.7 ohm, the voltage in the relay end is found to be 2.32 V, voltage at the supply end 2.5 V and current in the supply end 2.765 A. (Therefore an adjustment resistor of 6.1 ohm must be added in series with the relay plus parallel resistor.)

Since it is of special importance to increase voltage at the relay, one must presume that in most cases, it is unnecessary to estimate a large leakage in siemens per kilometre; usually one can assume that the leakage is only approximately one third (ballast resistance is approximately 3 ohmkm). In such a case, voltage at the relay end in the above-mentioned cases is increased to 4.08 voltage. (An external resistor of about 18.3 ohm must therefore be added in series with the relay and parallel resistors)

In direct current relays of normal design, the relation of pick up voltage / fall voltage is approximately = 2, possibly somewhat lower. In such a case, the maximum allowed voltage at the relay end if the relay should drop, at 3 ohmkm, the ballast resistance would be about 2 V. Since we started out with an interference voltage of 3.6 V, the above given track current battery would not be sufficient.

If a fall voltage of about 3.6 V is desired, then with the above given relation between pick up voltage and fall voltage, we would be forced to design the relay equipment for a pick up voltage of about 7.2 V. With an unchanged relay (total pick up current = 0.144 A), the resistance in the relay circuit should be 50 ohm, of which the resulting relay resistance (including parallel resistance) is 10 ohm. The basis of the same prerequisites as earlier, in the supply end, we get a voltage = 7.4 V and a current = 2.88 A. If the protective resistance for the battery increases from 1.7 ohm to 2.43 ohm, the battery voltage would need to be 14.4 V, which is double the one in the previous case. It has therefore become necessary to analyse the options we have that could reasonably be used to reduce the sensitivity of the railway signalling equipment to the impact of Earth currents.

3. Different Equipment to Reduce the Earth Currents' Negative Impact

The following solutions have been discussed:

a) The previously suggested arrangement that the equipment be dimensioned for a leakage of maximum 1/3 siemens per kilometre (ballast resistance of at least 3 ohmkm). If the leakage between the rail sections, in some individual cases (for instance due to strong precipitation) exceed this value, this can certainly lead to a false stop signal at the intersection, but no risky disturbance in the operation would occur.

b) The track relay is built to be polarized, such that it can only be affected by current in one direction. The chances of this disturbance are, hence reduced by at least half.

c) The track relay (with accessories) is designed for a relation between pick up and fall voltage, which is considerably lower than 2 and which is close to the value 1. (To prevent the relay from self-oscillation, as the voltage is close to the pick up voltage value, the relation should be somewhat more than 1 - say about 1.1).

d) The track relay (with accessories) is equipped with equipment (for example an extra series relay) which disconnects the track relay circuit if the relay voltage is more than the battery voltage. (This can be considered the case for the relay, where the interference voltage adds to the battery voltage, particularly if the leakage from the track is low).

e) On the supply side of the track circuit, there must be an ohmic resistor, which limits the size of the current taken from the battery to a reasonable value, as a train short-circuits the track circuit. (In the above-mentioned example, the protective resistance is assumed to be 1.7 ohm). If this resistance is constant, at a relatively large leakage between the tracks, there is a strong impact on the relay voltage. If again, the leakage is small, during wintertime, when the temperatures are below 0°, the relay voltage can be close to the battery voltage. This circumstance, to some extent, weakens the Earth currents' negative impact. If on the other hand, the resistor is such that its resistance declines with increased current (current and voltage dependent resistor), one can expect considerably smaller variations in the relay voltage for varying leakage. This implies a corresponding reduction of the Earth currents' negative impact. On the other hand, this places great demands on the resistor used.

Of these possibilities, we have primarily evaluated how a combination of the alternatives (a) to (c) appear. Consequently, it must be mentioned that in the first attempts, for simplicity's sake, "polarized" common neutral direct current track relays, through dry plate rectifying valves, allowed current only in one direction. This equipment worked as desired, as long as it concerned negative direct voltage. For the alternate voltage disturbances on single-phase tracks, emanating from the track currents' voltage drop in the in-and-out rail sections, the above-mentioned valves, however, seem to be rectifiers and can thereby lead to unexpected additional disturbances. Therefore, this polarization method must be considered omitted in such railway signalling systems/equipment, where alternating voltage disturbances can occur. In our final attempts, for this reason, only magnetically polarized relays have been used.

Furthermore, as the main alternative, it is presumed that the leakage between the tracks is maximum 1/3 siemens per km, from this value; however, it may be expected to decrease to practically zero. Such a reduction in leakage is possible in extreme cold.

Finally, additional measures have been adopted to reduce the ratio between pick up voltage and fall voltage from its normal value, between 1.6 to 2 to about 1.1. This can be done by introducing an additional resistor in the track relays' current circuit, which is connected when the relay is pulled, but short-circuited when the relay drops. Hereby, it is possible to supply a complete continuous current to a dropped track relay so that the relay can be brought to the pull mode. Thus, by connecting the additional resistor, the relay current is reduced to a value that is not significantly higher than the dropout value.

The problem with increasing the track relay's fall voltage, such that it is close to the pick up voltage value, has been solved in two different ways, partly (as suggested by E. Ullerfors) with the use of an auxiliary relay, which provides the connection and disconnection of an additional resistor. In part, such that the track relay can, itself, redirect the manoeuvre in question. In both cases, during the manoeuvre, one must use a pair of track relay contacts.

Figure 2 shows how, with the help of an auxiliary relay, one can increase the track relay's fall voltage so that it is close to the value of the pick up voltage. In parallel with the track relay (and its protective resistance), an extra circuit is added, consisting partly of an auxiliary relay, partly of an adjustment resistor to set the auxiliary relay's pick up voltage to the desired value (for instance 4 to 5 voltage). This circuit also includes a pair of the track relays' *front* contacts. This enables the *auxiliary relay circuit to be connected first if the track relay is pulled*. (In the event of a dropped track relay, the auxiliary relay also drops)

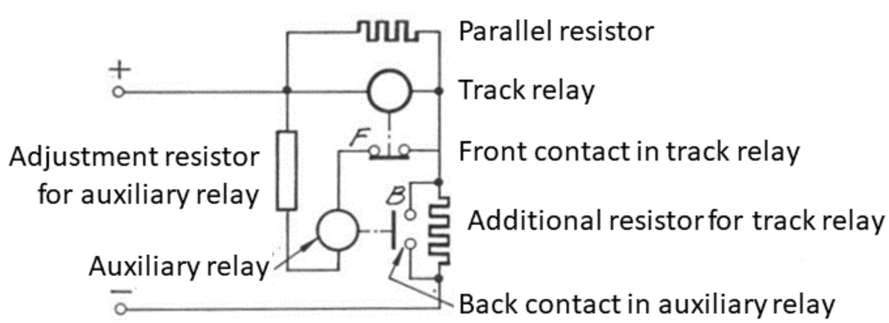

Figure 2. Reduction of the pick up / fall voltage ratio of a DC track relay by means of an auxiliary relay

To increase the necessary additional resistance of the track relay's fall voltage, a pair of the auxiliary relay's back contacts need to be shorted. In the case of a drop in the track relay and thereby also a drop in the auxiliary relay, the track relay on connection always gets a complete continuous current. When the track circuit is pulled, the auxiliary relay circuit is connected, and if its voltage is sufficiently high, the auxiliary relay pulls and connects the track relays' additional resistor.

For the equipment to work in the desired manner, the auxiliary relay must first be brought down so that it reaches the drop mode; otherwise there is a risk of the track relay being pulled again as the relay current increases at the short-circuiting of the additional resistor. Therefore, it may also be necessary to build the auxiliary relay with a delayed drop or adopt other measures to prevent the auxiliary relay from dropping too early.

Figure 3 shows a schematic connection diagram for the cases where we allow the auxiliary relay to automatically take care of the connection and disconnection of the additional resistor. Here, particularly for this manoeuvre, a pair of the track relay's *back* contacts are used. For the equipment to work in the intended manner, the pick up force of the used track relays at the given relay current is increased quite considerably the more the relay armature reaches its final position. To benefit from this circumstance, it is, however, necessary that the back contacts of the short circuit's additional resistor do not disconnect this electric circuit too early. Rather, when the relay armature has reached a certain distance that the increased pick up force combined with the kinetic energy of the armature is sufficient to make the armature go on in a fully drawn mode, even when the short circuit is broken and the relay current is reduced to about the same as the downdraft value.

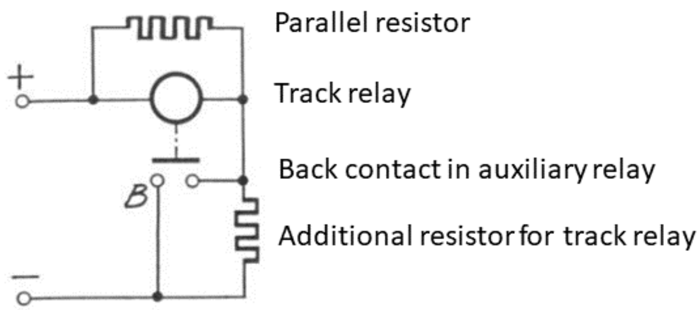

Figure 3. Reduction of the pick up / fall voltage ratio of a DC track relay, achieved by the track relay itself

In this case, in order to facilitate the relay's function in case of acceptable flexibility of back contacts, we must eventually allow a small increase in the pick up voltage, apart from the value that is relevant for the relay, without the additional resistor. (One of the attempts with the value received for a certain relay type on this increase is about 8%; and with another relay type, only an increase of about 2% is needed)

(Another solution worth considering, therefore, is that in parallel with the track relay and its parallel resistor, connect a capacitor of an appropriate size, which tries to hold up the relay voltage, even if the back contacts are disconnected. A closer evaluation shows, however, that the necessary capacitor, due to the discharge circuit's relatively low resistance, would be impractically large).

Compared to the relay connections shown in Figures 2 and 3, Figure 2 has the advantage that, in principle, it does not require any specific adjustment of the contacts included in the auxiliary circuit. In addition, it appears that with the possibility of adjusting the auxiliary relay's pick up voltage, we get somewhat increased protection against unnecessary stop signalling due to the Earth currents than in the case of a connection according to Figure 3. The disadvantage is that in Figure 2 an additional relay is required.

Figure 3 has the advantage of the most possible simplicity from the equipment point of view, but requires, in some cases, an external adjustment of back contacts in the auxiliary relay, which are used for short-circuiting of the additional resistor. In addition, a certain increase in the pick up voltage, besides the value associated with the short-circuited additional resistor, may seem necessary.

4. Test Results With Connections Schematically Shown in Figure 2 (with the auxiliary relay)

The schematic connection drawing shown in Figure 2 demonstrated the practical terms of a model equipment with the same circuit properties as a real track relay of 1125 m length requiring certain supplements. Above all, it is about eliminating the consequences that may occur if the auxiliary relay, under certain circumstances, drops faster than the track relay. As it has been pointed out earlier, this can have a consequence that an additional resistor in the track relay circuit short-circuits too early, that the track relay does not manage to drop completely, but rather returns to pulled mode, when the relay current increases at the short-circuiting of the additional resistor.

The most effective way to protect itself would be using *double* contacts (both front and back contacts) in the track relay and the auxiliary relay. Thereby, it becomes possible that independent of the length of the track relay's dropping time arranged such that the auxiliary relay cannot drop before the track relay completely reaches the drop mode.

Figure 4 shows the connection is schematically used in this case (proposed by T. Törnkvist). As shown, the auxiliary relay can be held, pulled either over its own front contact or through a front contact on the track relay.

As long as the track relay is completely pulled, its front contacts are connected, and thus the auxiliary relays' electric circuit is connected and the relay is pulled. When the track voltage drops below the set fall value and the track relay has begun to drop, its front contacts open one of the auxiliary relay's current flows, but the relay in question still remains pulled over its own front contact until its track relay drops completely so that its back contacts end. Thereby, the auxiliary relay is by-passed so that it is without current and falls. It will thus drop first when the track relay has completely reached the drop mode.

In all the examined cases, it has appeared possible to use a somewhat simpler connection, with just one front contact in the track relay and a back contact in the auxiliary relay, in principle, according to Figure 2. In this context one must arrange such that in the track relay the front contact that disconnects last is chosen. It has mainly appeared that a difference of several seconds in drop time can be achieved, in particular, if the relay voltage is considerably lower than the fall voltage value. Furthermore, it may then be necessary to adopt certain measures to delay the auxiliary relay's drop. For example, on a magnetic path with copper cylinders placed around the relay core, the relay's parallel connection with the capacitor of a sufficient size or similar so that one can securely estimate that the track relay will manage to come to the reverse position before the auxiliary relay short-circuits the additional resistor.

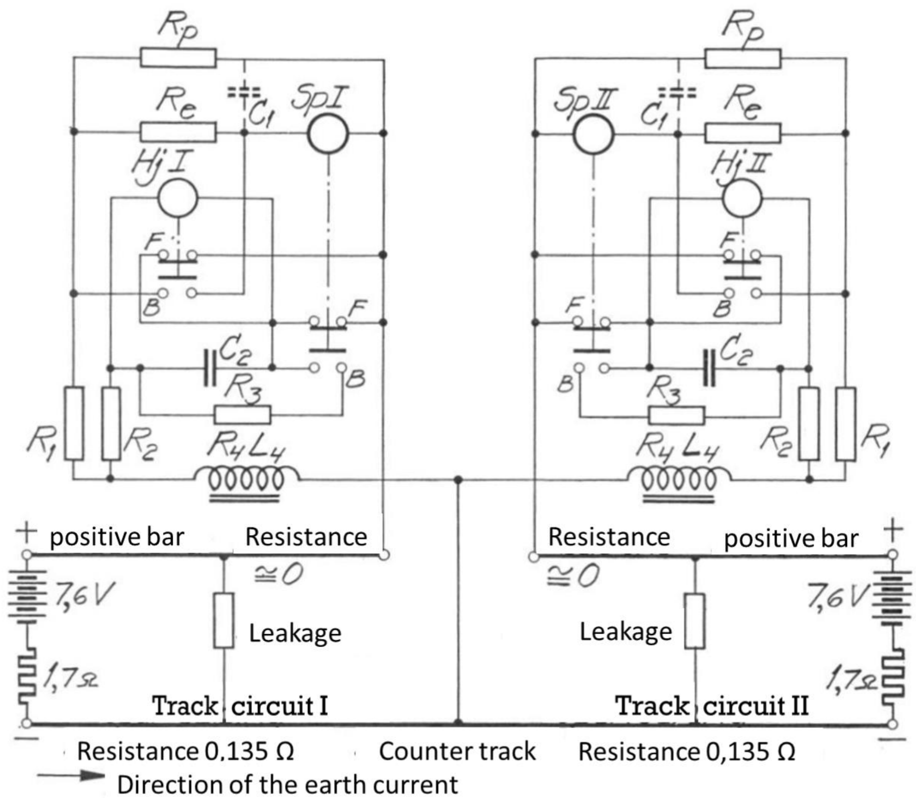

Figure 4. Connection Diagram A for evaluations of the Earth currents' negative impact according to the main diagram in Figure 2. Protection for early dropping of auxiliary relays by means of double contacts in both track relays and auxiliary relay.

<u>Symbols</u>
Sp = Track relay
Hj = Auxiliary relay
Rp = parallel resistor for the track relay
C1 = parallel capacitor for the track relay as an additional protection against AC disturbances, if any
Re = engageable and disengageable additional resistor in the track relay circuit for increasing the fall voltage.
R1 = adjustment resistor for setting the track relay's pick up voltage
R2 = adjustment resistor for setting the auxiliary relay's pick up voltage
C2 = parallel capacitor for the auxiliary relay as protection against AC disturbances (can be possibly replaced or supplemented with a parallel resistor).
R3 = discharge resistor for C2 for protection of the track relay back contact
R4 L4 = protective reactor against AC disturbances
F = front contact
B = back contact

Figure 5 shows a coupling used in which the delay of the auxiliary relay drop occurs, partly with an electrolytic capacitor C_2 coupled in parallel with the auxiliary relay, and partly with a second capacitor C_3 in series therewith and parallel to the front relay contact (with values of 1500 μF each). As long as the other track relay's front contact is connected and thus the auxiliary relay connected, the latter relay and thereby even C_2 have full track voltage, while C_3 is short-circuited and therefore not charging. As the track relay begins to drop and disconnects the auxiliary relay's circuit, this relay however is not immediately without current, but rather receives a discharging current partly from C_2, and partly a charging current, when C_3 is charged. We can also consider that the drop in the auxiliary relay is delayed only through a capacitor of a somewhat increased size being connected in parallel with the relay. Try to show, however, that a division of the capacitor's capacity, according to Figure 5, is somewhat more favourable for the given total capacity. (If auxiliary relay's capacity is somewhat increased on the magnetic path, by means of a copper damping cylinder, we can manage with smaller capacitors, and eventually avoid them completely. With respect to the impact of the AC disturbances, it is, however, desirable to have a capacitor connected in parallel with the auxiliary relay. In this case, capacitor C_2 can be kept, while capacitor C_3 can be removed. For the same reason, it can be desirable to connect a protective capacitor C_1 in parallel with the track relay. Another way to protect the auxiliary relay against the impact of AC disturbances is to connect it in parallel with a resistor of the same value as the parallel resistor R_P for the track relay).

Tests have been conducted on two types of polarized direct current relays. On one hand, relay type A, which is a Swedish make with a 30 ohm resistance winding, a pick up current of 48 mA, and a dropout current of 24 mA. On the other hand, relay type B, which is an American make with a 50 ohm resistance winding, a pick up current of 21.5 mA, and a dropout current of 13.5 mA.

For protection against AC disturbances, the relays have a parallel resistor, R_p, with the resistance of 15 ohm for relay A and 20 ohms for relay B. Both relays are adjusted by means of the resistor R_1, cch, the engageable and disengageable additional resistor R_e for a pick up voltage of 4V, and a fall voltage of approximately 3.6 V. Thereby, each R_e = approximately 34 ohms for relay type A, and 30 ohms for relay type B; and R_1 = 15 ohms for relay type A, and 37 ohms for relay type B.

The auxiliary relay was a common telephone relay with the resistor of 40 ohms resistance in the winding. As is evident from later shown reasons, it is desirable that it does not function with relatively low values on the track voltage – it is through the adjustment resistor R_2 set at a pick up voltage of about 5.1 V. (R_2 during the tests was about 90 ohm). The fall voltage appeared to be somewhat below 2V. In Figure 4, as a protection against the alternating voltage disturbances, an electrolytic capacitor, C_2, of 1500 μF, is connected in parallel. To protect the track relay's back contacts from the ionization currents of C_2, when the contacts are short-circuited, a discharging resistance R_3 of 10 ohms is introduced in the circuit.

In Figure 5, we also have an electrolytic capacitor, C_2, of 1500 μF, connected in parallel with the auxiliary relay. Here, the capacitor must serve, in part, as a protection against alternating voltages and increase the relay's drop time. Moreover, in Figure 5, we see one more electrolytic capacitor C_3 of 1500 μF, used and connected over the track relay's front contacts. As already pointed out, it contributes to increasing the dropping time of the auxiliary relay when it is charged in connection with a contact breaking. As protection against C_3's discharging current, when the track relay is pulled and its front contacts short-circuit C_3, a discharging resistance R_3 of about 10 ohms is introduced in the circuit.

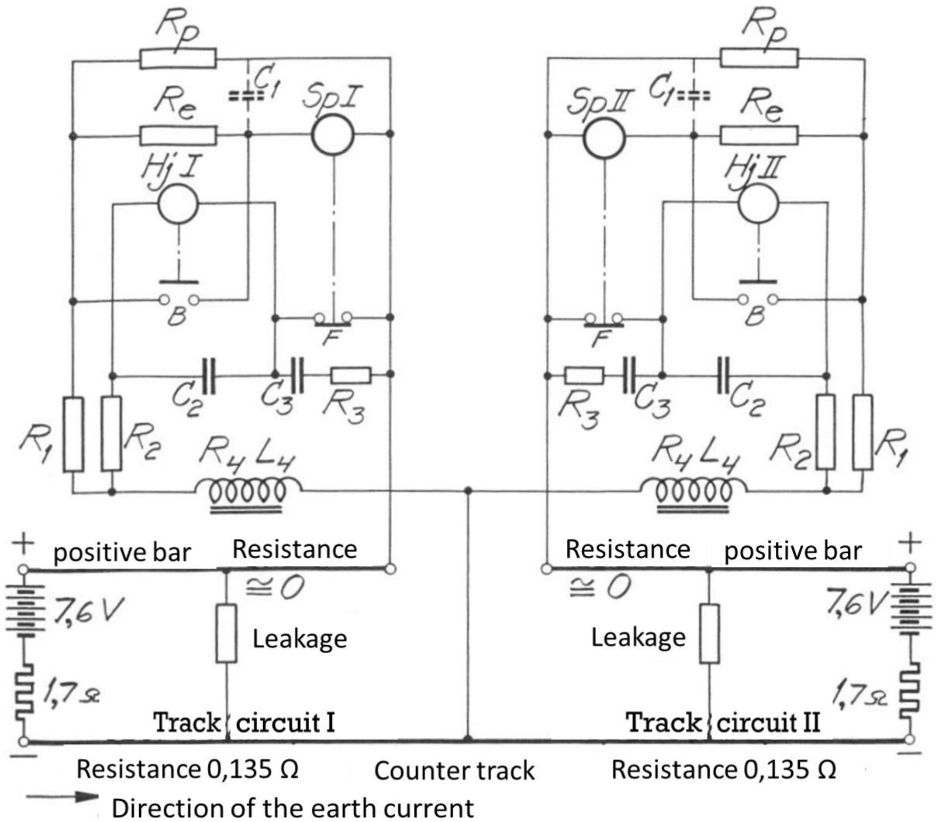

Figure 5. Connection Diagram B for investigations of the Earth currents' negative according to the main drawing in Diagram 2. Protection against early dropping of the auxiliary relays by means of the capacitor C_2 and C_3.

<u>Symbols</u>

S_p = Track relay
H_j = Auxiliary relay, possibly with a delayed drop
R_p = parallel resistor for the track relay
(C_1 = parallel capacitor for the track relay, possibly.)
R_e = engageable and disengageable additional resistor in the track relay circuit for increasing the fall voltage.
R_1 = adjustment resistor for setting the track relay's pick up voltage
R_2 = adjustment resistor for setting the auxiliary relay's pick up voltage
C_2 = parallel capacitor for the auxiliary relay as protection against AC disturbances, partly for increasing the auxiliary relay's drop time.
(C_3= capacitor in parallel to the auxiliary relay's front contact for increasing the auxiliary relay's drop time, alternative system)
(R_3 = discharge resistor for C_3 for protection of the track relay's front contact, if any.)
R_4 L_4 = protective reactor against AC disturbances
F = front contact
B = back contact

The protective reactor (R_4, L_4) located between the minus rail and the relay equipment in the tests referred here, had a direct current resistance R_4 = 2.6 ohm and an inductance L_4 = approximately 4H which at 16 2/3 Hz gives a reactance of about 400 ohms.

Figures 6-9 show the results of the tests conducted on the relay type B. The measurements of the relay type A gave practically the same result which is considered unnecessary to draw up specific curves. Moreover, the connections given in Figures 4 and 5 gave the same protective result, if observed that in Figure 5, the front contact used in the track relay is the one that disconnects last, and is arranged such that the auxiliary relay's drop time is so long that the track relay can safely manage to completely go in the reverse position before the auxiliary relay short-circuits the additional resistor R_e. It is evident from these Figures, in this way, we can achieve 100% protection from the impact of Earth currents if an unusually small leakage between the rails is not needed to be assumed (respectively unusually high ballast resistance).

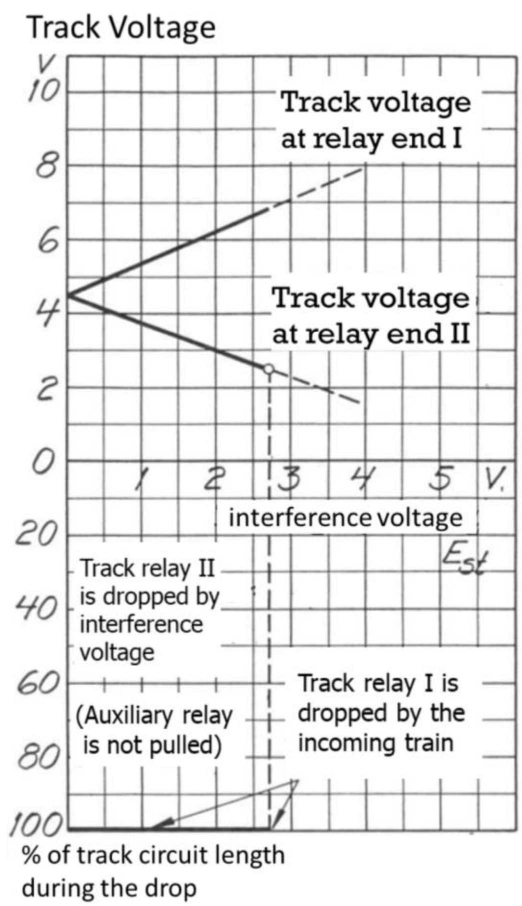

Figure 6. Connection between the interference voltage (E_{st}) and the resulting track voltage at the relay end during the Earth currents. Track circuit length corresponding to 1125 m. Ballast resistance 3 ohms

(Setting up of the track relays: pick up voltage 4 V, fall voltage 3.5 V. Connection drawing according to diagrams 4-5, thus with auxiliary relay, set up for pull at 5.1 V. During this test, the auxiliary relay was dropped from the beginning.)

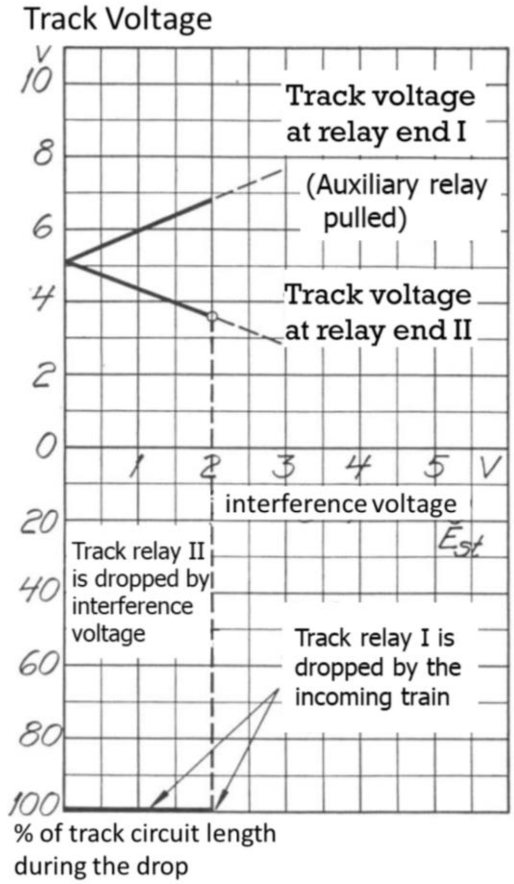

Figure 7. Connection between the interference voltage (E_{st}) and the resulting track voltage at the relay end during the Earth currents. Track circuit length corresponding to 1125 m. Ballast resistance 4.5 ohms

Even in the extreme case, with an endlessly high ballast resistance (Figure 9) where the highest possible voltage, before the railway signalling system is activated, is about 4 V, we need to, in unfavourable cases, only estimate that the warning time for an incoming train is reduced to about 15% (for example from 30 to 25.5 seconds). With the value of the ballast resistance of 9 ohm (Figure 8), the highest possible interference voltage will be 2.85 V before the warning signal is activated: the ballast resistance = 4.5 ohm (and the track voltage in an interference free state = 5.15 V), the highest possible interference voltage would be 2 V (see Figure 7). As the track voltage is about 5 V, the auxiliary relay is usually kept pulled; the additional resistor is thus connected at a pulled track relay. In Figure 6, with the ballast resistance = 3 ohm, as it appears, the track voltage in an interference free state is lower than 5 V, that is the auxiliary relay is dropped the whole time and the additional resistor R_a is also short-circuited. In such a case, the track relay's drop is determined by its normal fall voltage, which in this case was about 2.5 V. This leads to the interference voltage being more than in the previous case, in that it would bring down the track relay at the relay end to about 2.5 V. An interference voltage of about 2.7 V is required according to Figure 6. If the auxiliary relay was instead set for the same pick up voltage as the track relay, or 4 V, so that it could connect and disconnect the additional resistor to give the track relay's fall voltage of about 3.6 V, we would have received a warning signal activated already at about 1.2 V. The use of auxiliary relay for adjusting the additional resistor R_e and its adjustment for a somewhat higher pick up voltage than the track relay's, about 5V, also has the advantage that the track circuit at the lower value for ballast resistance will be somewhat more sensitive to Earth current disturbances.

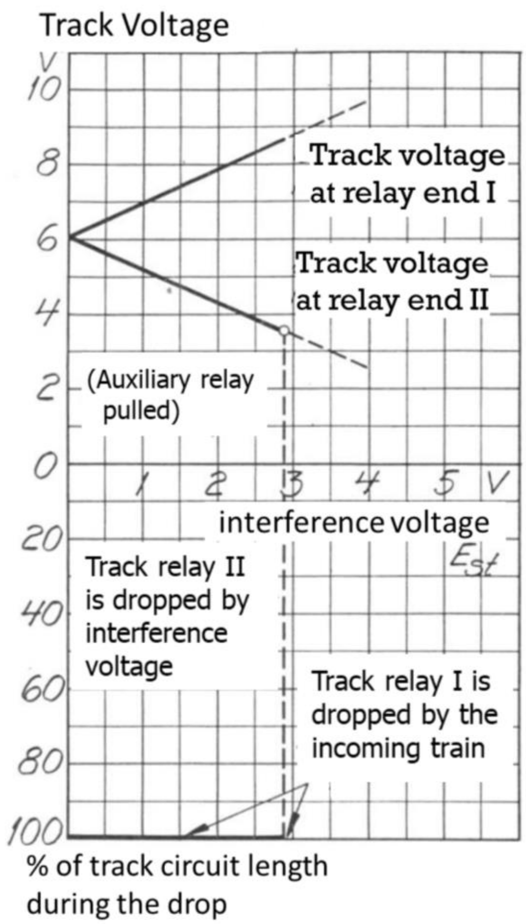

Figure 8. Connection between the interference voltage (E_{st}) and the resulting track voltage at the relay end during the Earth currents. Track circuit length corresponding to 1125 m. Ballast resistance 9 ohms

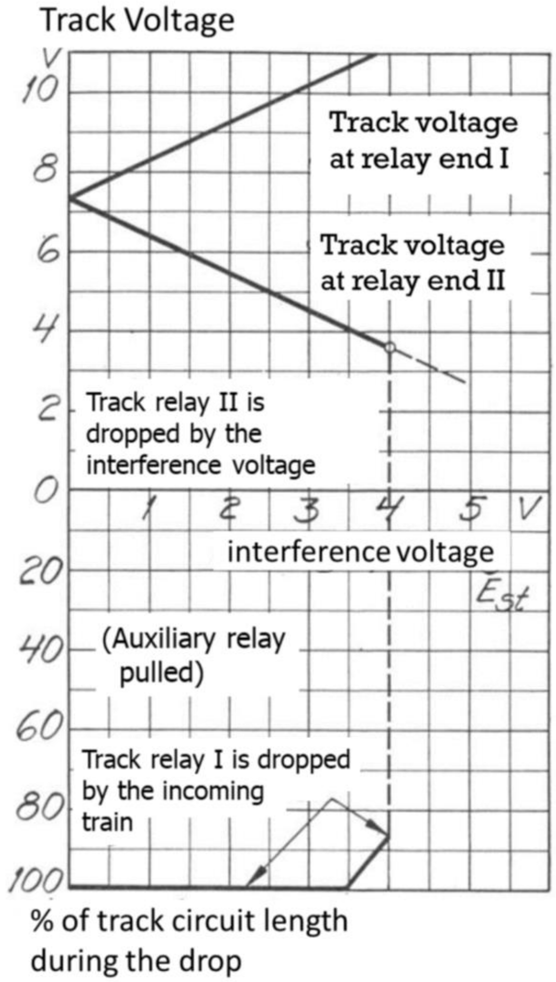

Figure 9. Connection between the interference voltage (E_{st}) and the resulting track voltage at the relay end during the Earth currents. Track circuit length corresponding to 1125 m. Ballast resistance incredibly large

(Setting up of the track relays: pick up voltage 4 V, fall voltage 3.5 V. Connection drawing according to diagrams 4-5, thus with auxiliary relay, set up for pull at 5.1 V. During this test, the auxiliary relay was dropped from the beginning.)

Impact of an interference voltage frequent on rails. In parallel with the examinations mentioned above of how the railway signalling equipment, according to Figures 4 and 5 works with direct current disturbances, the evaluations have also been conducted over the effects of AC disturbances frequency on rails. As was expected, a protective reactor with reactance of approximately 400 ohms reactivity at ground frequency represents a relatively effective protection for the track relay if this relay is provided with an appropriate parallel resistor, which leads the bulk of the relatively weak interference current occurring through the protective reactor beyond the track relay, the reactance of which, for a disturbance frequent on tracks, is comparatively high. However, it appears that if the relay's voltage deviates a little from the fall voltage value, even a relatively insignificant alternating voltage interference can considerably affect the relay. But, if we connect a capacitor of a suitable size in parallel with the relay, the impact of the alternating voltage interference almost entirely disappears.

Apparently, the same applies to the auxiliary relay, which is also vulnerable to the same disturbances as the track relay. It is therefore necessary to equip even this relay with protection against the alternating voltage disturbances. This can be most easily done if we use one more auxiliary relay connected in parallel with a capacitor to increase its drop time; through this we can automatically get an effective shunting of the alternating voltage interference past the relay. We can consider using, just as for the auxiliary relay, an ohmic resistor connected in parallel as a protection against interference, possibly also a combination of resistance and capacitance.

5. TEST RESULT WITH THE CONNECTION SHOWN SCHEMATICALLY IN FIGURE 3 (WITHOUT THE AUXILIARY RELAY)

The advantage of this equipment is that no external relay is needed, rather the track relay supplies itself the necessary connection of external resistor R_e for the increase in fall voltage, as the relay pulls and disconnects the back contacts included in the current circuit. As it has been previously pointed out, the intended effect can be achieved only if these back contacts are so flexible that they disconnect first when the relay anchor has a got high speed and has approached the pulled state to such an extent that it can continue to the completely pulled state, even if the external resistor is connected and has reduced the relay current.

By choosing the back contact on the track relay during the pull disconnects last has shown that of the three examined relay types, it is possible to get two of them to work in the desired manner. For one of these relays, the pick up voltage is required to be increased from 4V to 4.3 V, which is by about 8% before the relay was safely pulled, for the other relay, the required increase in voltage was quite insignificant (about 2%).

The result of these types of tests matched considerably with the curves shown in Figures 6 to 9. The main difference was that at the ballast resistance of 3 ohm, the signalling system could be started at an interference voltage of about 1.2 V. The reason for this has been specified above.

In the case of tests of the third type of relay, however, it was impossible to achieve the desired effect with the connection other than providing the highest possible increase in voltage (about 30% increase). Clearly, the design of the contacts here is unfavourable for the desired effect. It is clear that through a suitable change of the contact device, this relay can also work in the desired manner. If we however assume that completely normal track relays should be used, it seems more appropriate to refrain from the imaginable simplicity of the signalling equipment and, according to Figure 2, allow the auxiliary relay to supply the connection and disconnection of the additional resistor. The tests conducted have undoubtedly shown that the main schematic shown in Figure 3 can also be used if the track relay contacts have a suitable design. Due to lack of available time for these examinations, it has not been possible to conduct a detailed study of how the contact device be designed so that the track relay can function in the desired manner.

6. Conclusions Derived From the Tests

From the tests referred here, it is evident that in a combination polarized relay, comparatively high pick up voltage (about 4 V) and similarly relatively high fall voltage (about 3.5 voltage), can if the track circuits are complete, give a fully satisfying protection for the signalling equipment supplied with direct current against the disturbances which on single phase tracks could have been caused by earth currents in the rails and other similar interfering currents.

The best protection is achieved if the track voltage is not significantly higher than the track relay's pick up voltage. If the track circuit's ballast resistance and thereby also the track voltage is considerably high (in a limiting case full isolation between the rails), we must give up something to meet the requirement that the accompanying track relay would drop as soon as a train enters the track section. It appears, even in such an extreme case, we do not need to estimate more than about 15% shortening of the track circuit's usual warning time (30 seconds at a train speed of 135 km/h).

In this context, it should be highlighted that the difficulties only show up for the track circuit, where the Earth currents' interference voltage adds to the battery voltage. For the other track circuit where the interference voltage shows opposite signs in relation to the battery voltage, the accompanying polarized auxiliary relay always drops as soon as the train enters this track circuit and shortens the signal current source.

Due to the above-mentioned favourable results, the other initially stated possibilities to increase the reliability of the signalling equipment against ground currents at high levels of ballast resistance have not been studied further.

It can perhaps be noted that even the introduction of the required additional resistor R_e (in Figures 4 and 5) for increased fall voltage, and it's adjusting with the contacts of the track relay and auxiliary relay imply an undesired complication, as these contacts, in the event of disturbances, can be vulnerable to greater stresses than the other contacts, where no disturbances arising from the track will occur.

If, however, as is assumed, we have a not too tightly-dimensioned protection reactor connected between the track and the signalling equipment and, in addition, we arrange so that the reduced disturbances coming through the protection reactor are, to a necessary degree, led past the relay windings (for example by means of ohmic resistances or capacitors coupled in parallel with the relays), experiments using disturbance voltages up to 170 V (the highest voltage that can be achieved in laboratory experiments) with railway frequencies have shown that neither the relays nor the contacts affected by the disturbance are harmfully impacted if the above-mentioned protection arrangements are suitably dimensioned. Attempts to detect earth-frequency interference voltages of up to 170 V (the highest voltage that could be achieved in laboratory tests) showed that neither relays nor malfunctioning contacts are adversely affected if the above-mentioned protective devices are appropriately sized. For example, it must be mentioned, if the relays are connected in parallel with the electrolytic capacitors at 1500 μF, at the above-mentioned interference voltage, the voltages over the relays would only be 1.6 and 0.4 V respectively. These values are so low that they can well be adopted for the electrolytic capacitors, without causing any damage to the latter. (For circumstances of rail fracture, see Appendix 6).

About the Author

Johan *Emil* Alm was a Swedish electrical engineer and professor. He was born on October 18, 1878, and graduated from the Royal Institute of Technology, Department of Electrical Engineering, in 1902. From 1903 to 1910, he worked for Asea, the Swedish company that later merged with Brown Boveri to form ABB Ltd. From 1910 to 1917, he was an engineer with Stockholm Electricity Board. During this time he was also assistant of Theoretical Electrical Engineering at the Royal Institute of Technology, moving up to become professor in 1917. Alongside his university teaching, Alm carried on a considerable consulting business. He became a member of the Committee for the Swedish National Railways' Electrification in 1919-1920, committee of the Institute of High Voltage Research in 1932, and the Swedish Royal Academy of Engineering Sciences in 1928. Alm published a considerable number of noted theoretical, as well as practical-theoretical articles on electrical machines in Swedish and foreign journals, among which are noted, among other things, *Some comments when calculating transformers*, *the short-circuit power of AC transformers* and *Protection of Transmission systems*. He made a considerable contribution to understanding geomagnetic interference to railways, including the Appendix in the 1956 report that is translated and published in this special issue. Professor Alm died in 1963.

Calculation of Geomagnetic Interference Voltages in Track Circuits

*B. Lejdström and S. Svensson**

1. Introduction

In the event of magnetic disturbances, as described in detail in Appendix 1, chapter 5, the potential differences have been measured between earthed electrodes going up to several volts per km. These potential differences are related to electric currents in the Earth's surface and in conductors, which are located adjacent to these, for example in rails.

In connection with the Signal Committee's track circuit surveys, the following calculations of the Earth magnetic interference voltages that occur in different types of track circuits have been performed.

During the calculation, the geomagnetic disturbance was assumed to have a voltage of E V/km equally divided along a longer stretch. The same calculation method can, in principle, be applied to either a rail section or two to more rail sections connected in parallel, whereby the resistance along one rail and two in parallel connected rails is assumed to be r ohm/km and the leakage between the rail or rails and the Earth is g_r siemens/km. The voltage between the rail section and Earth is assumed to be U volt and the strength of current in one or several rail sections together is I ampere.

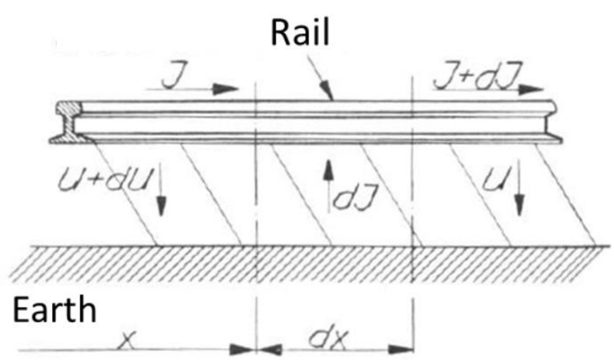

Figure1. Diagram for calculation of interference voltage between the rails and Earth and interference current I in the rails.

For a short section of rails, the following is obtained according to Figure 1

$$U + dU - U = E\ dx - r\ dx\ I \tag{1}$$

$$dI = -g_r\ dx\ U \tag{2}$$

After inserting r $g_r = \gamma^2$ in the equation (2), the following is obtained

$$\frac{dU}{dx} = E\ - r\ I \tag{1a}$$

$$\frac{dI}{dx} = -\frac{\gamma^2}{r}\ U \tag{2a}$$

Differentiating equation (1a) gives

$$\frac{d^2U}{dx^2} = -r\,\frac{dI}{dx} \tag{3}$$

From equation (2a) and (3), the following is obtained

$$\frac{d^2U}{dx^2} - \gamma^2 U = 0 \tag{4}$$

The general solution to this differential equation reads

$$U = C_1\, e^{\gamma x} + C_2\, e^{-\gamma x} \tag{5}$$

Differentiating equation (5) gives

$$\frac{dU}{dx} = C_1\,\gamma\, e^{\gamma x} - C_2\,\gamma\, e^{-\gamma x} \tag{5a}$$

When this expression for $\frac{dU}{dX}$ is inserted in equation (1 a), the following is obtained

$$I = \frac{1}{r}\left(E - \frac{dU}{dx}\right) = \frac{1}{r}(E - C_1\,\gamma\, e^{\gamma x} + C_2\,\gamma\, e^{-\gamma x}) \tag{6}$$

The constants C_1 and C_2 in equations (5) and (6) are determined by inserting the boundary conditions, which will be dependent on the track circuit installations that the calculations should concern.

2. Calculation of Voltage and Current in a Continuous Rail Section of Arbitrary Length

If the continuous rail section is assumed to have the length 2L km and is placed along the *x* axis in a right-angled coordinate system such that the centre point of the rail section is located at zero point, the following boundary conditions are obtained

$$\left.\begin{aligned} I_{x=-L} &= 0 \\ I_{x=L} &= 0 \end{aligned}\right\} \tag{7}$$

After inserting in equation (6), the boundary conditions give

$$\left.\begin{aligned} 0 &= \frac{1}{r}(E - C_1\,\gamma\, e^{-\gamma L} + C_2\,\gamma\, e^{\gamma L}) \\ 0 &= \frac{1}{r}(E - C_1\,\gamma\, e^{\gamma L} + C_2\,\gamma\, e^{-\gamma L}) \end{aligned}\right\} \tag{8}$$

Which gives the constants C_1 and C_2

$$C_1 = \frac{E}{2\gamma \cosh \gamma L} \tag{9}$$

$$C_2 = -\,\frac{E}{2\gamma \cosh \gamma L} \tag{10}$$

When these values are inserted in equation (5) and (6), the following is obtained

$$U = \frac{E\,sinh\ \gamma x}{\gamma \cosh \gamma L} \tag{11}$$

$$I = \frac{E}{r}\left(1 - \frac{cosh\ \gamma x}{\cosh \gamma L}\right) \tag{12}$$

Of special interest are the voltage and current conditions at the centre point and end points of the rail sections, that is for the values at *x* = - *L*, *0*, and *L*.

For the voltage, the following applies

$$U_{x=-L} = -\frac{E}{\gamma} tanh\ \gamma L \tag{13a}$$

$$U_{x=0} = 0 \tag{13b}$$

$$U_{x=L} = \frac{E}{\gamma} tanh\ \gamma L \tag{13c}$$

and for the current, the following applies

$$I_{x=-L} = 0 \tag{14a}$$

$$I_{x=0} = \frac{E}{r}\left(1 - \frac{1}{\cosh \gamma L}\right) \tag{14b}$$

$$I_{x=L} = 0 \tag{14c}$$

From equations (13 a and c) and (14 b), it is evident that if the rail section is infinitely long on both sides, the voltage in these expressions would be $\pm\frac{E}{\gamma}$ volt and the current at its centre $\frac{E}{r}$ ampere.

Figure 2 constitutes a graphical supplement to the above. For small values of γL, U can be written as $\approx Ex$, which is represented in the figure through a drawn line. In the figure, even the Earth's potential relative to the central point of the rails = $-Ex$ has been shown. When $U \approx Ex$ constitutes a short rail section voltage to earth at the point, *x*, the short rail section has approximately the same potential throughout its length and the same as the ground below the centre of the rail.

According to equation (14b), that length can be calculated, which the connected rail section must have so that the strength of current at the centre of the rail section is a certain fraction of this value, which is obtained in an infinitely long rail section. If this fraction is chosen, for example 90%, the following is obtained

$$\frac{E}{r}\left(1 - \frac{1}{\cosh \gamma L}\right) = 0.90\ \frac{E}{r}$$

$$\frac{1}{\cosh \gamma L} = 0.1$$

$$\cosh \gamma L = 10$$

$$\gamma 2L = 5.986$$

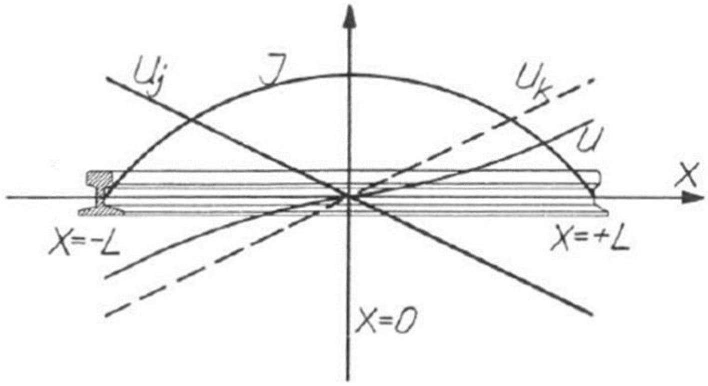

Figure 2. Current and voltage conditions in a continuous rail section of the length 2L km.

Symbols

I = strength of current in the rail section $= \frac{E}{r}\left(1 - \frac{\cosh \gamma x}{\cosh \gamma L}\right)$

U = rail section's voltage to Earth $= \frac{E \sinh \gamma x}{\gamma \cosh \gamma L}$

U_j = the Earth's potential relative to the rail section centre = - Ex.

U_k = approximate value on the short rail section's voltage to Earth = Ex.

For a continuous rail section with connections to an overhead return line, it can be estimated that g_r varies between 0.02 S/km and 2.86 S/km. For the Swedish alternating current electrified railway lines, normally a return conductor is found, which is connected, at intervals of 5.6 km, to the continuous rail section. Resistance r is thereby reduced from 0.06 ohm without return conductor to 0.042 ohm/km with return conductor connected in parallel with the rail section. Corresponding values of γ are then 0.0346 and 0.414 respectively without the return conductor, and 0.0290 and 0.347 respectively with the return conductor.

Without the return conductor, for the smallest leakage, the following is obtained

$$0.0346\,.2L = 5.986$$
$$2L = 173 \text{ km}$$

and for the largest leakage

$$0.414\,.2L = 5.986$$
$$2L = 14.5 \text{ km}$$

With the return conductor, the values for the smallest leakage would be

$$0.0290\,.2L = 5.986$$
$$2L = 206 \text{ km}$$

and for the largest leakage

$$0.347\,.2L = 5.986$$
$$2L = 17.3 \text{ km}$$

In a rail section, which is infinitely long on both the sides, the strength of the geomagnetically induced current according to the equation (14b) = $\frac{E}{r}$. The value of E is estimated as a result of the observations conducted so far as being able to go up to a maximum of 7 V/Km, while the value of r for a rail section is 0.06 ohm/km, which gives an estimate of the maximum strength of the current as $\frac{7}{0.06}$ = 117 ampere.

As the return conductor is connected, at equal intervals, in parallel with one rail section, where the track circuits are found, or with both the rail sections, where there are no track circuits, a geomagnetically induced current will flow forward even through the return conductor, and this current is determined by the return conductor's resistance r_a which is 0.143 ohm/km if consideration is also given to the direct current resistance in the connected booster transformers. When E = 7 volt/km, the strength of the current in the return conductor is $\frac{7}{0.143}$ = 49 A.

On sections, where track circuits are not found, both the rail sections are continuous. If this is the case for a long section in both directions, the above-calculated strength of current is obtained in each rail section.

For an uninterrupted infinitely long rail section, the voltage to the earth = 0 according to equation (13b).

3. Calculation of Voltage and Current in a Rail Section, Which is Interrupted in the Middle, and Infinitely Long on Both Sides of the Interruption

The rail section is assumed to be placed along the x-axis in a right-angled coordinate system, such that the centre of the rail section, that is the interruption, is located at the zero point. The following boundary conditions apply

$$\left.\begin{aligned} U_{x=\pm\infty} &= 0 \\ I_{x=0} &= 0 \end{aligned}\right\} \qquad (15)$$

after inserting in equations (5) and (6), the boundary conditions give

for $x \leq 0$

$$\left.\begin{aligned} 0 &= C_1 e^{-\gamma\infty} + C_2 e^{\gamma\infty} \\ 0 &= \frac{1}{r}(E - C_1 \gamma 1 + C_2 \gamma 1) \end{aligned}\right\} \qquad (16)$$

for $x \geq 0$

$$\left.\begin{aligned} 0 &= C_1 e^{\gamma\infty} + C_2 e^{-\gamma\infty} \\ 0 &= \frac{1}{r}(E - C_1 \gamma 1 + C_2 \gamma 1) \end{aligned}\right\} \qquad (17)$$

from equation (16), the constants C_1 and C_2 are estimated to

$$\left.\begin{aligned} C_1 &= \frac{E}{\gamma} \\ C_2 &= 0 \end{aligned}\right\} \qquad (18)$$

From equation (17), the following is obtained

$$\left.\begin{aligned} C_1 &= 0 \\ C_2 &= -\frac{E}{\gamma} \end{aligned}\right\} \qquad (19)$$

when the values on C_1 and C_2 are inserted in the equations (5) and (6), the following is obtained for $x \leq 0$

$$U = \frac{E}{\gamma} e^{\gamma x} \tag{20a}$$

$$I = \frac{E}{r}\left(1 - e^{\gamma x}\right) \tag{21a}$$

for $x \geq 0$

$$U = -\frac{E}{\gamma} e^{-\gamma x} \tag{20b}$$

$$I = \frac{E}{r}\left(1 - e^{-\gamma x}\right) \tag{21b}$$

From the equations, it is evident that the voltage at the interruption of the rail section is $\pm \frac{E}{\gamma}$ volt and the current at a great distance from the interruption is $\frac{E}{r}$ ampere. The current voltage conditions are shown graphically in Figure 3.

To get an understanding of the impact of the leakage to earth on the current and voltage curves' shape, *U* and *I* are calculated in the equations (20a) and (21a) respectively for E = 7 volt/km, r=0.06 ohm/km and g_r alternatively = 0.02 S/km and = 2.86 S/km. The values obtained from this are presented in the following tables and reproduced graphically in Figure 4.

At an interruption in an infinitely long rail section, for example in the case of a rail fracture, the voltage to the Earth at the free ends is $\frac{E}{\gamma}$ and - $\frac{E}{\gamma}$ respectively, according to equation (20a) and (20b). The voltage U_b across the interruption between the free ends is

$$U_b = \frac{E}{\gamma} - \left(-\frac{E}{\gamma}\right) = \frac{2E}{\gamma} \tag{22}$$

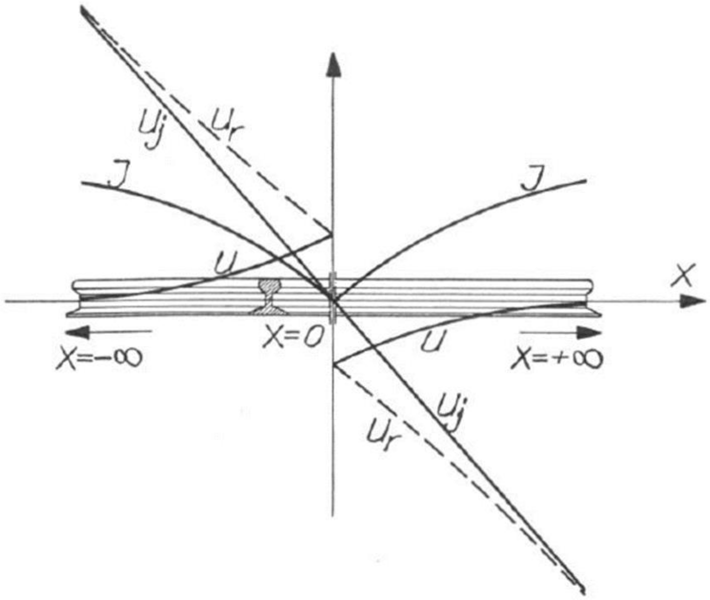

Figure 3. Current and voltage conditions in a centrally interrupted, on both sides, infinitely long rail section.

Symbols

I = strength of current in the rail section $= \frac{E}{r}(1 - e^{\gamma x})$ for $x \le 0$ and $= \frac{E}{r}(1 - e^{-\gamma x})$ for $x \ge 0$

U = rail section's voltage to Earth $= \frac{E}{\gamma} e^{\gamma x}$ for $x \le 0$ and $= -\frac{E}{\gamma} e^{-\gamma x}$ for $x \ge 0$

U_j = the Earth's potential relative to the rail section centre = $-Ex$.

U_r = rail section's potential relative to the potential that the Earth has right below the rail section's centre.

Alt II. $\gamma = \sqrt{r\, g_r} = 0.414$

x km	U_{II} volt	I_{II} ampere
0	16.9	0
-0.5	13.7	21.8
-2.9	11.2	39.5
-5	9.1	54.0
-7.6	7.4	65.7
-10	4.9	83.0
-15	2.1	102
-20	0.0	117
-∞	0	117

Alt I. $\gamma = \sqrt{r\, g_r} = 0.0346$

x km	U_{I} volt	I_{I} ampere
0	202	0
-0.5	199	2.0
-2.9	183	11.1
-5	170	18.5
-7.6	156	27.0
-10	143	34.1
-15	120	47.2
-20	101	58.3
-∞	0	117

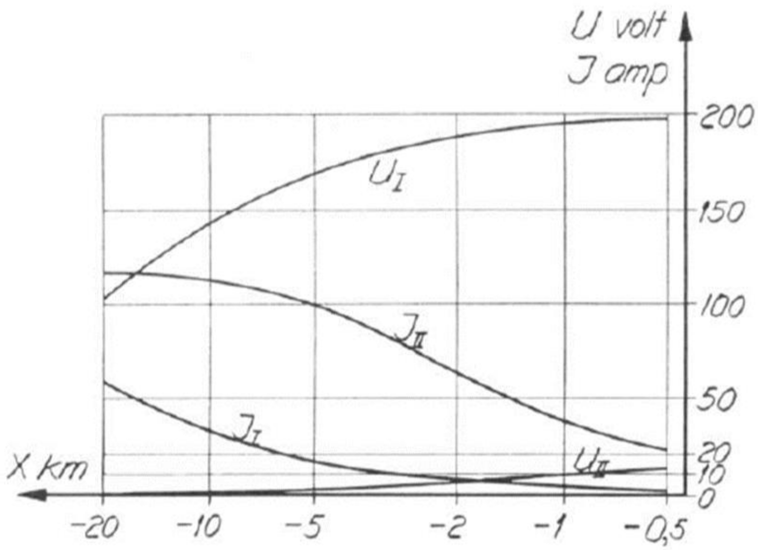

Figure 4. Graphic presentation of the current (I_I and I_{II} respectively) and the voltage (U_I and U_{II} respectively) for an infinitely long rail section, which is interrupted in the centre, on both the sides, for two different values of the rail section's leakage to earth, namely gr_I = 0.02 and gr_{II} = 2.86 S/km. The interruption is located at x = 0.

This voltage will be large for low values of the leakage. For example, if the values E=7 volt/km, R = 0.06 ohm/km and g_r = 0.02 S/km are used in equation (22), the following is obtained

$$\gamma = \sqrt{0.02 \cdot 0.06} = 0.0346$$

and

$$U_b = \frac{2E}{\gamma} = \frac{2 \cdot 7}{0.0346} = 405 \text{ volt}$$

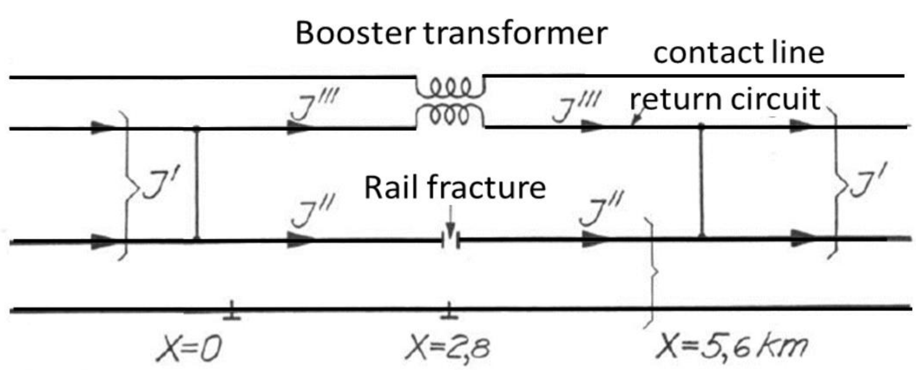

Figure 5. Schematic diagram for calculation of voltage over a rail fracture in a continuous rail section, where the rail fracture is located at the centre of two points, by which the return conductor is connected with the rail section.

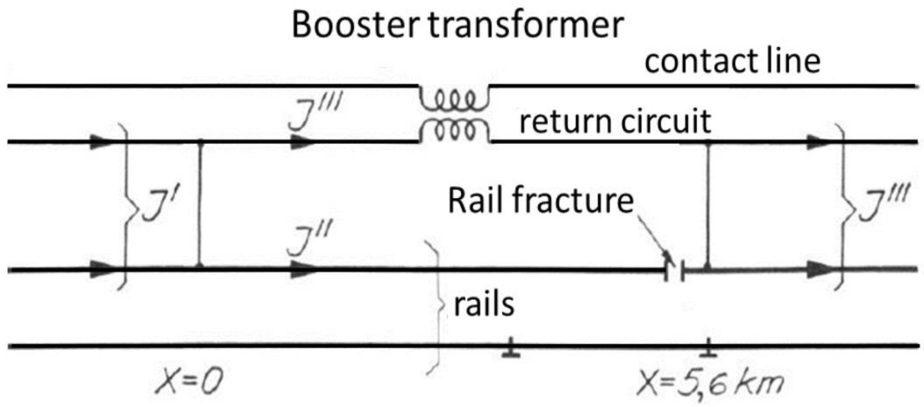

Figure 6. Schematic diagram for calculation of voltage over the rail fracture in a continuous rail section, where the rail fracture is located next to the point where the return conductor is connected to the rail section.

For the highest value of the leakage g_r = 2.86 S/km, γ = 0.414 and

$$U_b = \frac{2E}{\gamma} = 34 \text{ volt}$$

If there is a return conductor that is connected with the continuous rail section at every 5.6 km, lower voltages over the rail fracture are obtained.

The size of the voltage will depend on, to some extent, where the rail fracture occurs in relation to the point where the return conductor is connected with the rail section. The voltage therefore has been calculated in one part for the case where the rail fracture has occurred in the middle of these connection points (Figure 5), and in the second part for the rail fracture immediately alongside such a connection point (Figure 6).

If I' symbolizes the total of currents in the continuous rail section and in the return conductor according to Figure 5 and the resistance in the rail section connected in parallel with the return conductor makes up r_1 ohm/km, then $I'_{x=-\infty} = \frac{E}{r_1}$. If these boundary conditions are inserted in equation (6), the following is obtained

$$\frac{E}{r_I} = \frac{1}{r_I}(E - C_I'\gamma_I 0 + C_2'\gamma_I \infty)$$

where

$$\gamma_1 = \sqrt{r_1 g_r}$$

This equation is satisfied only by C'$_2$ = 0, whereby according to equations (5) and (6), the following is obtained

$$U_{x=0} = C_1 \tag{23}$$

$$I'_{x=0} = \frac{1}{r_1}(E - C'_1\gamma_1) \tag{24}$$

Insertion of boundary condition $I''_{x=2.8} = 0$ in equation (6) gives

$$C''_2 = C''_1 e^{5.6\gamma_2} - \frac{E}{\gamma_2} e^{2.8\gamma_2}$$

Where $\gamma_2 = \sqrt{r_2 \; g_r}$ and r_2 constitutes resistance in the continuous rail section. The expression is inserted for C"$_2$ in equation (5) and (6), the following is obtained

$$U_{x=0} = C''_1 \left(1 + e^{5.6\gamma_2}\right) - \frac{E}{\gamma_2} e^{2.8\gamma_2} \tag{25}$$

$$I''_{x=0} = \frac{1}{r_2}\left[E\left(1 - e^{2.8\gamma_2}\right) - C''_1\gamma_2 \left(1 - e^{5.6\gamma_2}\right)\right] \tag{26}$$

If the return conductor's resistance for 5.6 km length is symbolized with R$_a$, the following is obtained

$$I''' = \frac{U_{x=0} - U_{x=5.6} + 5.6E}{R_d}$$

First for symmetry reasons, it is understood that $U_{x=5.6} = -U_{x=0}$ of which follows

$$I''' = \frac{2U_{x=0} + 5.6E}{R_d} \tag{27}$$

From equations (23) and (25), the following is obtained

$$C'_1 = C''_1\left(1 + e^{5.6\gamma_2}\right) - \frac{E}{\gamma_2} e^{2.8\gamma_2}$$

According to Figure 5, the following applies

$$I'_{x=0} = I''_{x=0} + I'''$$

Using these values for I', I'' and I''' according to equations (24), (26) and (27) and C'$_1$ according to the above, an expression for C"$_1$ is obtained.

Furthermore, the following applies

$$U_b = 2\, U''_{x=2.8} = 2\left(C''_1 e^{2.8\gamma_2} - C''_2\, e^{-2.8\gamma_2}\right)$$

If C"$_2$ is eliminated by inserting the relation between C"$_2$ and C"$_1$ as per above, the following is obtained

$$U_b = 4\, C''_1 e^{2.8\gamma_2} - \frac{2E}{\gamma_2}$$

Thus, when the expression for C''_1 is inserted, the following is obtained

$$U_b = \frac{2E}{\gamma_2}\left[1 - \frac{2\left[\frac{1}{r_2}\left(e^{2.8\gamma_2}-1\right)-\left(\frac{1}{r_1}-\frac{5.6}{R_d}\right)e^{2.8\gamma_2}+\frac{\gamma_1}{\gamma_2 r_1}+\frac{2}{\gamma_2 R_d}\right]}{\frac{1}{r_2}\left(e^{5.6\gamma_2}-1\right)+\left(\frac{\gamma_1}{\gamma_2 r_1}+\frac{2}{\gamma_2 R_d}\right)\left(e^{5.6\gamma_2}+1\right)}\right] \quad (28)$$

Insertion of E = 7 volt/km, r_1=0.042 ohm/km, r_2=0.06 ohm/km

R_d = 0.8 ohm, g_r = 0.02 S/km, $\gamma_1 = \sqrt{r_1 g_r}$ = 0.0290,
$\gamma_2 = \sqrt{r_2 g_r}$ = 0.0346 give U_b = 111 volt

For g_r = 2.86 S/km then γ_1 = 0.347 and γ_2 = 0.414 and U_b = 32.5 volt

Even in this case, when the rail fracture occurs alongside a point where the return conductor is connected to the rail section (see figure 6), equations (23) and (24) apply

$$U_{x=0} = C'_1 \quad (23)$$

$$I'_{x=0} = \frac{1}{r_1}\left(E - C'_1\gamma_1\right) \quad (24)$$

In equation (6) in this case, when the boundary condition $I''_{x=5.6} = 0$ is inserted, the following is obtained

$$C''_2 = C''_1 e^{11.2\gamma_2} - \frac{E}{\gamma_2} e^{5.6\gamma_2}$$

$$U_{x=0} = C''_1 \left(1 + e^{11.2\gamma_2}\right) - \frac{E}{\gamma_2} e^{5.6\gamma_2} \quad (29)$$

$$I''_{x=0} = \frac{1}{r_2}\left[E\left(1 - e^{5.6\gamma_2}\right) - C''_1\gamma_2\left(1 - e^{11.2\gamma_2}\right)\right] \quad (30)$$

Inserting boundary condition $I'''_{x=\infty} = \frac{E}{r_1}$ in equation (6) gives condition $C'''_1 = 0$, by which the following is obtained

$$U'''_{x=5.6} = C'''_2 e^{-5.6\gamma_1} \quad (31)$$

$$I'''_{x=5.6} = \frac{1}{r_1}\left[E + C'''_2\gamma_1 e^{-5.6\gamma_1}\right] \quad (32)$$

If the return circuit's resistance for the length of 5.6 km is R_d, the following is obtained

$$I''' = \frac{U_{x=0} - U'''_{x=5.6} + 5.6E}{R_d} \quad (33)$$

in equations (23), (31), (32) and (33), U and C_2 are eliminated

$$I''' = \frac{C_1' + \left(\frac{1}{\gamma_1} + 5.6\right)E}{R_d + \frac{r_1}{\gamma_1}} \tag{33a}$$

According to Figure 6, the following applies

$$I'_{x=0} = I''_{x=0} + I'''$$

In this expression, the I values are inserted according to equations (24), (30) and (33a). Since C' is eliminated through equations (23) and (29), hereby an expression for C''_1 is obtained.

Furthermore, the following applies

$$U_b = U''_{x=5.6} - U'''_{x=5.6} \tag{34}$$

According to equation (5), the following applies

$$U''_{x=5.6} = C''_1 e^{5.6\gamma_2} + C''_2 e^{-5.6\gamma_2}$$

Eliminating C_2 gives

$$U''_{x=5.6} = 2\, C''_1 e^{5.6\gamma_2} - \frac{E}{\gamma_2} \tag{35}$$

According to equations (23), (29), (31), (32) and (33a), the following is obtained

$$U''_{x=5.6} = \frac{C''_1\left(e^{11.2\gamma_2}+1\right) - \frac{E}{\gamma_2}e^{5.6\gamma_2} + \left(5.6 - \frac{R_d}{r_1}\right)E}{\frac{\gamma_1}{r_1}R_d + 1} \tag{36}$$

Inserting the same values as used above in equation (28), the following is obtained

For $g_r = 0.02$ S/km, $U_b = 110.8$ volt; and for $g_r = 2.86$ S/km, $U_b = 29.0$ volt

For both the values of the leakage, clearly a somewhat lower value of the voltage is obtained in this case where the rail fracture occurs alongside a point where the return conductor is connected to the rail fracture than when the rail fracture occurs in the centre of two such connection points, where the corresponding values on U_b made up 111 and 32.5 volt respectively.

4. Calculation of Geomagnetic Interference Voltages Over the Track Relay in a Single Insulated End Supplied Track Circuit

a) Faultless Track Circuit

If the continuous rail section is assumed to be infinitely long on both the sides, its voltage against the Earth = 0 (compare with equation 13b), from which follows that a voltage drop along this rail section is equal to the voltage drop of the Earth surface. Both sets of rails in a faultless, L km long track circuit according to Figure 7, are assumed to be shorted by the train at x = 0. For the values of L that usually occur for track circuits, the strength of current in the insulated rail section and thereby the voltage drop along it is relatively small. The relay equipment is moreover assumed to have such a large resistance that the strength of current through it is relatively small. The voltage over the track relay equipment is then

$$U_r \approx E\ L \tag{37}$$

When the value U_r = 1.1 V (the relay's fall voltage) and E = 7 V/km, the following is obtained, $L \approx$ 0.15 km, which is the maximum allowed value on the length of the track circuit. To the extent that higher values of U_r can be selected, a corresponding increase in track circuit length may be allowed.

b) Rail Fracture in the Continuous Rail Section

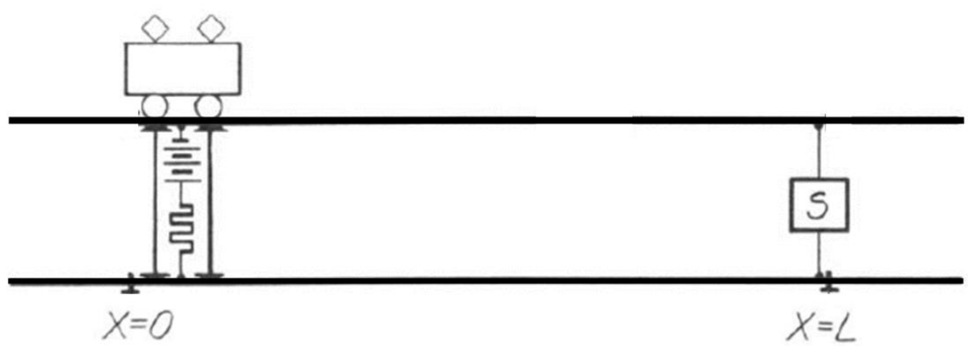

Figure 7. Schematic diagram for calculation of voltage over the track relay equipment (S) in a single insulated, faultless, L km long track circuit, the supply equipment of which is short-circuited by a train.

In a track circuit according to Figure 8, where the supply equipment is shorted by an incoming train on the track circuit, a rail fracture is assumed to occur in the proximity of the track relay in the continuous rail section, which possibly continues uninterrupted and infinitely on both sides of the rail fracture.

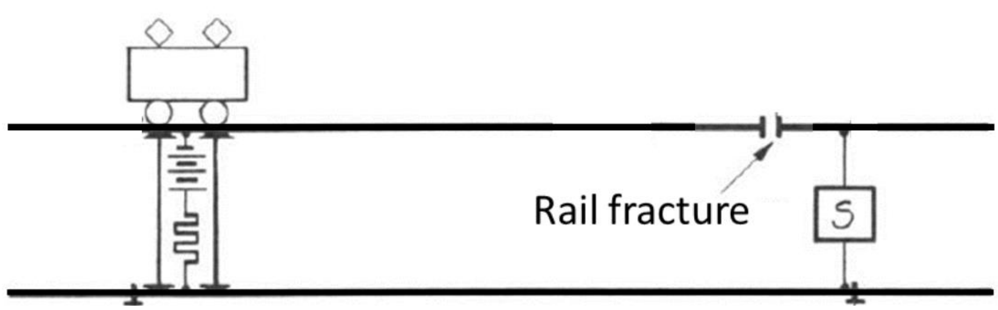

Figure 8. Schematic diagram for calculation of voltage over the track relay equipment (S) in a single insulated, faultless, long track circuit, the supply equipment of which is short-circuited by a train, and the continuous rail section of which is interrupted at the relay end.

The track relay equipment in this case will be connected in parallel with the rail fracture through the two rail stretches up to the supply end and the short-circuited train. The voltage over the track relay equipment U_r can be calculated on the basis of the following formula, which is derived from Thevenin's theorem.

$$U_r = U_b\left(1 - \frac{2\gamma}{2\gamma + Rg_r}\right)$$

(38)

In this expression, R is the track relay equipment resistance and U_b is the voltage over the rail fracture.

For typical values of R, the expression within the parenthesis is close to 1, particularly if the value for the leakage conductance g_r is not too little. This means that the voltage over the relay will be almost equal to the one according to the equation (22) and (28) respectively, the calculated voltage over the rail fracture U_b.

These voltages are so large that the track circuit's function is at risk, even for considerably lower and more frequent values of the geomagnetic interference voltage E than the adopted maximum value 7 V/km.

5. Calculation of Geomagnetic Interference Voltages in a Double Insulated, and Supplied Track Circuit

a) *Faultless Track Circuit*

If the leakage to Earth is the same for both the rails, the track circuit in this case is symmetrical, so no ground magnetic interference voltage occurs over the track relay equipment. On the other hand, if both the rails have a different leakage to Earth, symmetry is eliminated. According to Figure 9, the following boundary conditions are obtained (relay equipment's resistance is assumed to be relatively large).

$$I'_{x=L} = I''_{x=L} = 0$$

$$I'_{x=0} + I''_{x=0} = 0$$

$$U'_{x=0} = U''_{x=0}$$

Through these boundary conditions, the constants in equations (5) and (6) are determined to be suitable for each of the two rails.

Moreover, voltage over the relay equipment is calculated according to the formula

$$U_r = U'_{x=L} - U''_{x=L}$$

(39)

As extreme values of the leakage for one of the sets of rail sections $g_{r1} = \frac{1}{2500}$ S/km is inserted, and for the other $g_{r2} = \frac{1}{7}$ S/km and the resistance r = 0.06 ohm/km is inserted, which gives γ_1 = 0.0049 and γ_2 = 0.093. For L = 2 km and E = 7 V /km, then U_r will be = 0.035 V. The voltage thus becomes harmless, despite the widely different values of leakage for the two rail sections, the values of which apply as extreme values and may not be possible to occur simultaneously on one and the same track circuit.

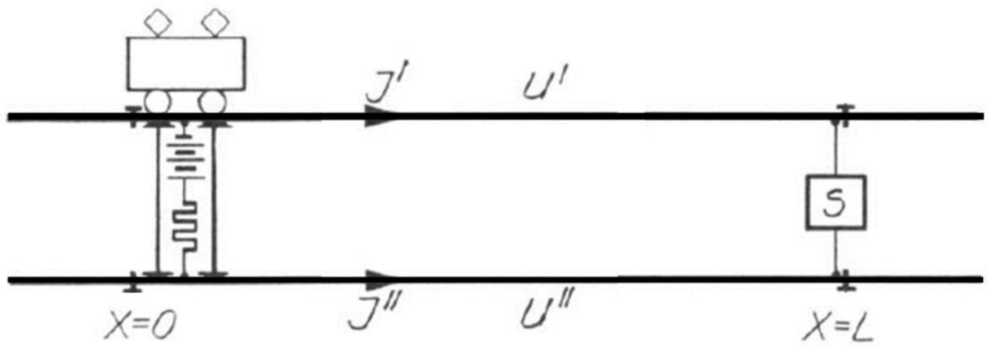

Figure 9. Schematic diagram for the calculation of the voltage over the track relay equipment (S) in a double insulated, faultless, L km long track circuit, the supply equipment of which is short-circuited by a train.

As the insulation junctions at the supply equipment are shorted by the train according to Figure 10, larger voltages are obtained. In this case, the boundary conditions are

$$I^{-}_{x=L} = I^{=}_{x=L} = 0$$

$$I'_{x=-\infty} = I''_{x=-\infty} = \frac{E}{r}$$

$$U'_{x=0} = U''_{x=0} = U^{-}_{x=0} = U^{=}_{x=0}$$

$$I'_{x=0} + I''_{x=0} = I^{-}_{x=0} + I^{=}_{x=0}$$

The voltage over the relay equipment U_r is calculated in a corresponding way as the above given equation (39). For γ_1 = 0.0049, γ_2 = 0.093, L = 2 km and E = 7 V/km, U_1 = 2.21 V, is obtained.

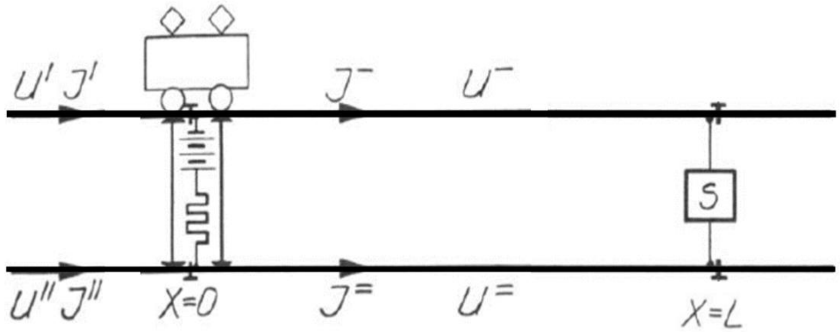

Figure 10. **Schematic diagram for the calculation of voltage over the track relay equipment (S) in a double insulated, faultless, L km long track circuit; its insulation junctions at the supply end are short-circuited by a train.**

As it has been stated above, one must not apprehend that such large differences could occur between the leakage values for both rail sections in a track circuit, which in this example is taken into consideration. The interference voltage over the relay equipment would therefore be considerably lower than the above given value. Against the voltage U_r = 1.1 V, is thereby a leakage g_{r1} = 1/25 S/km for one rail section and g_{r2} = 1/7 S/km for the other rail section that is a relation of 0.28 between both the rail sections. Even this difference between the leakage values is so large that it cannot be expected to occur. In case of a rail fracture on the other hand, a considerably larger voltage is obtained, as the insulation junctions are short-circuited, which is shown in the next section.

b) Rail Fracture in One Rail Section

In the event of a rail fracture in one rail section according to Figure 11, the interference voltage is calculated with some approximation in the following manner.

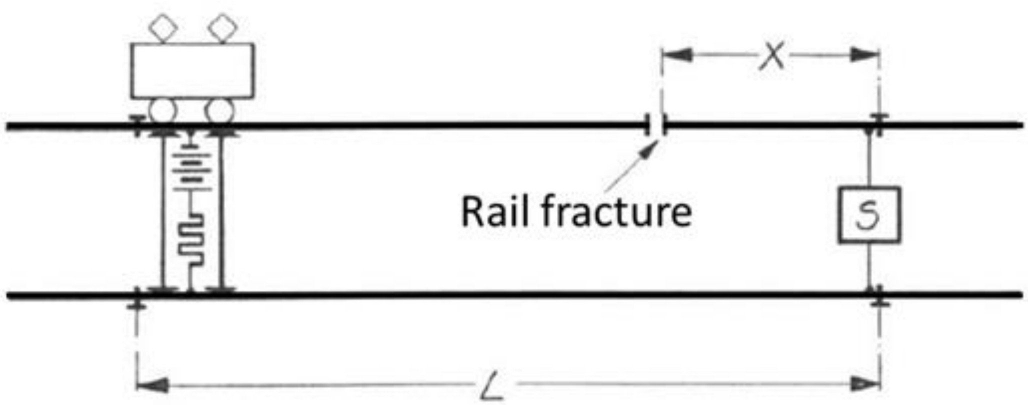

Figure 11. **Schematic diagram for calculation of voltage over the track relay equipment (S) in a double insulated, L Km long track circuit, the supply equipment of which is short-circuited by train, and one rail section of which is interrupted by the distance x km from the relay end.**

On *one side* of the track relay equipment, two of the train's emfs are connected in parallel. In connection with Figure 2, emf against Earth is calculated to:

$$\frac{E(L+x)}{2} \quad \text{and} \quad \frac{E\,L}{2}$$

If the leakage to Earth for the entire rail section is assumed to be $\alpha\, g_r$ S/km and for the broken g_r S/km kilometre, the corresponding resistance to Earth against the given emfs would be

$$\frac{1}{g_r(L-x)} \quad \text{and} \quad \frac{1}{\alpha g_r L}$$

The resulting emf is thereby calculated as

$$\frac{E}{2} \cdot \frac{L^2(\alpha+1)-x^2}{L(\alpha+1)-x}$$

and the resulting resistance to Earth as

$$\frac{1}{g_r[L(\alpha+1)-x]}$$

On the *other side* of the track relay equipment, an emf works towards the earth, expressed as

$$\frac{E\,x}{2}$$

with the resistance to earth

$$\frac{1}{g_r\,x}$$

In parallel with the track relay equipment with the resistance *R* ohm, the leakage works between the rail section *g* S/km, which for the section x corresponds to the resistance

$$\frac{1}{g\,x}$$

With this the geomagnetic interference voltage over the track relay equipment is calculated as U_r

$$U_r = \frac{\left(\frac{E L^2(\alpha+1)-x^2}{2\;L(\alpha+1)-x} - \frac{Ex}{2}\right)\dfrac{R\frac{1}{gx}}{R+\frac{1}{gx}}}{\dfrac{R\frac{1}{gx}}{R+\frac{1}{gx}} + \dfrac{1}{g_{r[L(\alpha+1)-x]}} + \dfrac{1}{g_r x}} \qquad (40)$$

After implementing the assumption based on the experience that $g_r = \frac{2}{7}g$, equation (40) can be written in the form

$$U_r = ELRg\frac{x(L-x)(\alpha+1)}{Rgx[9L(\alpha+1)-2x]+7L(\alpha+1)} \tag{40a}$$

When E = 7 V/km, L = 2 km, the following is obtained

$$U_r = 14Rg\frac{x(2-x)}{Rgx\left[18-\frac{2x}{\alpha+1}\right]+14} \tag{40b}$$

This equation can be converted to

$$Rg = \frac{14\,U_r}{-\left(14-\frac{2U_r}{\alpha+1}\right)x^2+(14-9U_r)2x} \tag{40c}$$

From equation d(Rg)/dx = 0, we obtain (Rg)max for

$$x = \frac{14-9U_r}{14-\frac{2U_r}{\alpha+1}} \tag{41}$$

When this value is inserted on x in equation (40c), the following is obtained

$$(Rg)_{max} = \frac{14U_r\left(14-\frac{2U_r}{\alpha+1}\right)}{(14-9U_r)^2} \tag{42}$$

When U_r = 1.1 volt and g = 0.5 S /km, the following is obtained for α = 1, α = 0.5, α = 0.1 and α = 0.0028 (1/2500:1/7)

α	*(Rg)* $(Rg)_{max}$	R_{max} Ohm
1	11.8	23.6
0.5	11.5	23.0
0.1	11.0	22.0
0.0028	10.8	21.6

For the interference voltage over the relay equipment not to exceed 1.1 volt, the resistance of the relay equipment must not exceed the given value of R_{max}. From equation (42), it is evident that the product $(Rg)_{max}$ will be infinitely large, if U_r is chosen as $= \frac{14}{9} = 1.56$ volt.

Thereby, an arbitrary value can be used for the resistance of the track relay equipment.

As the insulation junctions at the supply equipment are shorted by a train, a considerably large interference voltage is obtained. The voltage over the relay equipment can then be calculated by the expression (similar leakage has been adopted for both the rail sections)

$$U_r = \frac{\left(\frac{E}{\gamma} - \frac{Ex}{2}\right) \frac{R\frac{1}{gx}}{R+\frac{1}{gx}}}{\frac{R\frac{1}{gx}}{R+\frac{1}{gx}} + \frac{1}{g_r x}} \tag{43}$$

As above, with the inserted value $g_r = \frac{2}{7}g$, equation (43) can be written as

$$U_r = 2ERgx\frac{\frac{1}{\gamma} - \frac{x}{2}}{9Rgx+7} \tag{43a}$$

This equation can be converted to

$$Rg = \frac{7U_r\gamma}{-\gamma Ex^2 + (2E - 9U_r\gamma)x} \tag{43b}$$

From the expression $\frac{d(Rg)}{dx} = 0$, $(Rg)_{max}$ is obtained for

$$x = \frac{1}{\gamma} - \frac{9U_r}{2E} \tag{44}$$

With this value inserted in equation (43b), the following is obtained

$$(Rg)_{max} = \frac{\frac{7U_r}{E}}{\left(\frac{1}{\gamma} - \frac{9U_r}{2E}\right)^2} \tag{45}$$

Inserting the values $\gamma = 0.093$, $U_r = 1.1$ V and $E = 7$ volt/km, in equation (44) gives $x = 10.1$ km. This value is unreasonable, as such long track circuits normally do not occur, and the rail fracture could also occur outside the track circuit. Instead insert in equation (43b) for example $x = 1$ km and in general same values, $R_g = 0.057$ is obtained, that is an unreasonably low value. For example, $R = 16$ ohm, $x = 1$ km, $g = 0.5$ S/km and $E = 7$ volt/km and $\gamma = 0.093$, so according to the equation (43a) $U_r = 14.6$ V is obtained.

The voltage can be limited, if an extra pair of insulation junctions are inserted outside the track circuits supply end at such a distance from the end that both the pairs of insulation junctions cannot be simultaneously spanned by the longest approaching train. Reasonable values on the voltage can then be obtained if the resistance of the relay equipment is chosen according to the equation (42), the length of which L is estimated as the distance from the track circuit relay to the extra pair of insulation junctions outside the supply end.

In some cases, a combination of track circuits has been used, where only one rail section is insulated between the track circuits according to Figure 12. In this case, the insulated junctions are found on both sides of the track relay equipment, on one side at distance *L* and on the other side at distance y. The leakage is assumed to be the same for both the relay sections.

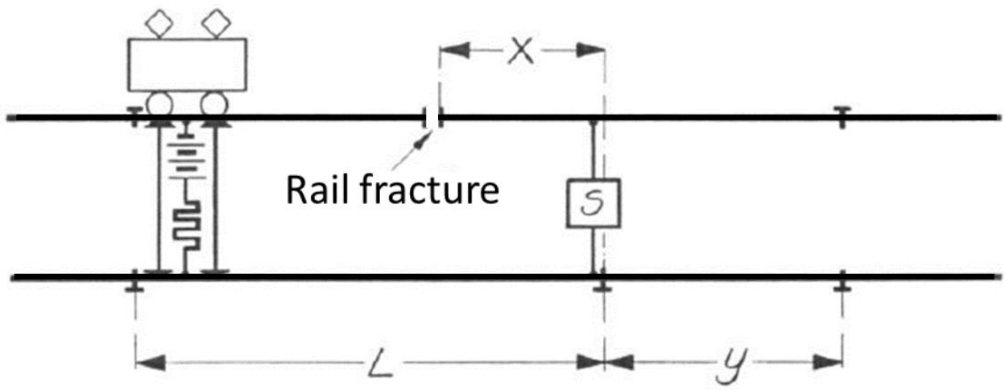

Figure 12. Schematic figure for calculation of voltage over the track relay equipment (S) in one of the two adjacent L and y km long double insulated track circuits at the extreme ends, where the first mentioned track circuit's supply equipment is short-circuited by a train and it's one rail section is interrupted at the distance x km from the relay end.

The expression for U_r is presented in an analogical way as equation (40).

$$U_r = \frac{\left(\frac{E(2L^2 - x^2)}{2(2L-x)} - \frac{E(y-x)}{2}\right) \frac{R\frac{1}{gx}}{R + \frac{1}{gx}}}{\frac{R\frac{1}{gx}}{R+\frac{1}{gx}} + \frac{1}{g_r(2L-x)} + \frac{1}{g_r(x+y)}} \tag{46}$$

This expression can be simplified to

$$U_r = ERg\frac{[2L(L-x) + y(2L-x)](x+y)}{Rg[2(2L-x)(x+y) + 7x(2L+y)] + 7(2L+y)} \tag{46a}$$

When the values, *L* = 2 km and *E* = 7 V/km are inserted, the following is obtained

$$U_r = 7Rg\frac{[4(2-x) + y(4-x)](x+y)}{Rg[2(4-x)(x+y) + 7x(4+y)] + 7(4+y)} \tag{46ba}$$

This equation is converted to

$$Rg = \frac{7(4+y)U_r}{-(28+7y-2U_r)x^2+(56-36U_r-5U_ry-7y^2)x+8y(7-U_r)+28y^2} \quad (47)$$

From equation d(Rg)/dx = 0, we obtain $(Rg)_{max}$ for

$$x = \frac{56-36U_r-5U_ry-7y^2}{2(28+7y-2U_r)} \quad (48)$$

When U_r = 1.1 volt, the following is obtained

$$x = \frac{16.4-5.5y-7y^2}{2(25.8+7y)} \quad (48a)$$

If this expression for *x* is inserted in equation (47), a very complicated expression for $(Rg)_{max}$ is obtained. Instead of having *x* values calculated for certain values of *y* and thereafter have associated values of *x* and *y* at U_r = I.I volt inserted in equation (47). The result of this calculation is given in the following table.

For values of U_r, greater than 1.1 V, *x* = 0 is already achieved for small values of *y* and for U_r = 1.56 volt, *x* =0 is achieved for *y*= *0*. If even greater values on U_r are inserted, negative values are obtained for *x* from the equation (48). Since the given expressions do not apply for negative x values, these are set in this case to *x* = 0.

Y km	X km	$(Rg)_{max}$	R_{max} ohm (for *g* = 0.5 S/km)
0.0	0.318	11.8	23.6
0.01	0.316	10.1	20.2
0.02	0.314	8.8	17.6
0.1	0.298	4.3	8.6
0.2	0.276	2.6	5.2
0.4	0.229	1.4	2.8
0.8	0.120	0.7	1.4
1.187	0.000	0.4	0.8

If the values $x = 0$ and $U_r = 2.1$ volt are inserted in equation (47), the following associated values of y and R are obtained.

Y km	$(Rg)_{max}$	R_{max} ohm (for g = 0.5 S/km)
0.02	74.4	148.8
0.1	14.4	28.8
0.2	6.9	13.8
0.4	3.2	6.4
0.8	1.4	2.8
1.0	1.1	2.2

It appears from the calculations that if we should obtain reasonable values of R_{max}, the length y must be limited.

6. Calculation of Geomagnetic Interference Voltages in a Double-Insulated Centrally Supplied Track Circuit in the Event of Rail Fracture in Both the Rail Sections

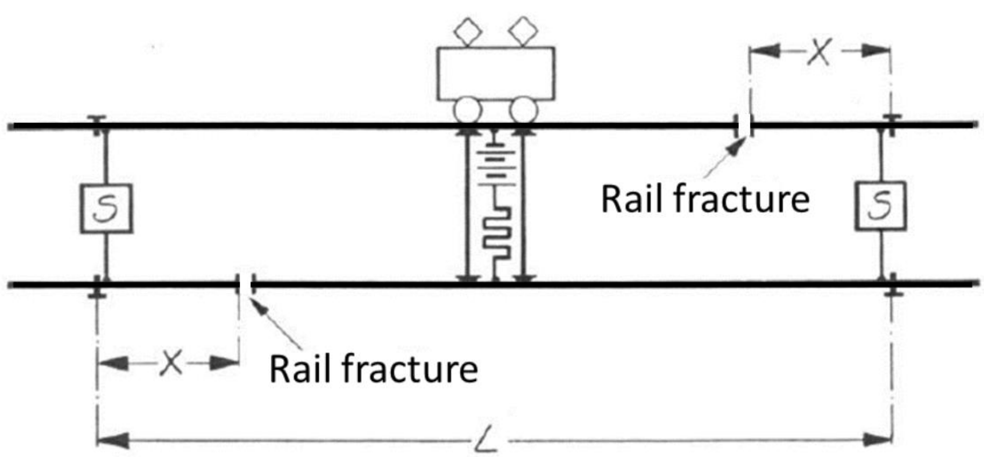

Figure 13. Chematic figure for calculation of voltage over each of the track relay equipment (S) in a double insulated, centrally supplied, L km long track circuit, the supply equipment of which is short-circuited by a train and the rail sections of which are interrupted, one at the distance of x kilometer from one relay end, the other at a distance of x km from the other relay end.

In a centrally supplied track circuit of normal design, both the track relays must attract simultaneously for the track circuits' safety function to be risked. Therefore, the most difficult case occurs where the rail fracture shown in Figure 13 occurs in each rail section at the same distance from the relay equipment and as the leakage to Earth is equally large for both the rail sections.

For each track relay, the expression for U_r is obtained in an analogical way as in equation (40)

$$U_r = \frac{\left(\frac{E}{2} - \frac{Ex}{2}\right) \frac{R\frac{1}{gx}}{R + \frac{1}{gx}}}{\frac{R\frac{1}{gx}}{R + \frac{1}{gx}} + \frac{1}{g_{r[L-x]}} + \frac{1}{g_r x}} \tag{49}$$

This expression can be simplified to

$$U_r = ERg\frac{2x(L-x)^2}{-11Rgx^2 + 18LRgx - 7x + 14L} \tag{49a}$$

This equation can be converted to

$$Rg = \frac{7U_r(2L-x)}{2Ex^3 + (11U_r - 4EL)x^2 + (2EL^2 - 18LU_r)x} \tag{50}$$

From equation d(Rg)/dx = 0, we obtain $(Rg)_{max}$ for

$$4Ex^3 + (11U_r - 16EL)x^2 + (16EL^2 - 44LU_r)x - 4EL^3 + 36L^2U_r = 0 \tag{51}$$

In this equation, the values U_r = 1.1 volt, E = 7 volt/km and L = 1.5 km, L = 2 km, L = 2.5 km, L = 3 km and L = 4 km. When equation (51) is solved, the values of x, given in table below, are obtained. Corresponding values of Rg_{max} are obtained by inserting in equation (50).

L km	x km	$(Rg)_{max}$	R_{max} ohm (for g = 0.5 S/km)
1.5	0.03	830	1660
2.0	0.22	17.7	35.4
2.5	0.40	5.1	10.2
3.0	0.59	2.4	4.8
4.0	0.96	0.9	1.8

If the track relay equipment's resistance is chosen $R \leq R_{max}$ according to the table, U_r will be maximum 1.1 volt, independent of where the rail fracture has occurred. To the extent that higher values of U_r can be allowed (higher fall voltage), even a higher R can be chosen.

About the Authors

Sten *Birger* Lejdström was born in 1920 near Stockholm and passed away in 2015. He studied electrical engineering at the KTH (Royal Institute of Technology), in Stockholm, and took his degree as a Master of Science in the early 1950s. After university, he started work at SJ (the Swedish state railway) where he was involved in the development of signal technology. In the 1960s, the extensive expansion of the railway system required a new interlocking system for traffic management and Birger Lejdström was chosen to be the project manager for this work. No suitable interlocking system was available at the time so Lejdström's team developed a brand new interlocking system that was completely relay-based. This new "CST" system went into service in 1964 and continues in operation today where it still competes with today's computer-based installations in terms of speed, performance and technical sophistication. Lejdström retired from SJ in 1985, but continued his involvement with railways, working as a traffic controller at Stockholm Traffic Centre. He remained alert until the end and passed away at the age of 94.

Sven Erik Svensson was born on 10th August 1914 in Gnosjö, in southern Sweden, and passed away on 28th December 2001 in Vällingby, near Stockholm. He graduated from Chalmers University of Technology, Gothenburg, in 1940, after which he began a long career with SJ (the Swedish State Railways). He obtained permanent employment as an engineer in the Electro Technical department in 1942, and, in 1947, Sven was promoted to deputy engineer. Later he became deputy director at SJ's Electro Technical Agency that took care of the effects of solar storms on the interlocking system in the railway. In this role, he was regularly quoted by Swedish newspapers in articles about the geomagnetic effects on the railways that occurred in the 1950s.

Recommended Reading

Krausmann, E., Andersson, E., Russell, T., Murtagh, W., *Space Weather and Rail: Findings and Outlook*, *JRC Science and Policy Reports*, JRC98155, 22 pp, 2015. doi:10.2788/211456 https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/space-weather-and-rail-findings-and-outlook

Power System and Railroad Electromagnetic Compatibility Handbook: Revised First Edition. EPRI, Palo Alto, CA, Oncor Energy Delivery Services, Dallas, TX, The National Grid Transco Company, Warwick, UK, Association of American Railroads (AAR), NW, Washington DC and American Railway Engineering and Maintenance-of-Way Association (AREMA), Landover, MD: 2006. 1012652. https://www.epri.com/#/pages/product/000000000001012652/?lang=en-US

Chronology of Space Weather Effects on Ground Systems Such As Power Systems, Pipelines, and Communication Cables: https://www.spaceweather.gc.ca/tech/se-chr-en.php.