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Evaluation and Mitigation of Electromagnetic Interference Between Railways and Nearby Power Lines: A Review

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ABSTRACT A railway running near power lines is subjected to electromagnetic interference from power lines, which can adversely affect normal operation of the railway's communication and signaling system, resulting in safety hazard on the railway equipment and personnel. Therefore, it is very important to assess such electromagnetic interference issues to ensure the railway system's reliability and the public safety. In this paper, a literature review is conducted on electromagnetic interference between railways and nearby power lines, which has not been widely researched in the past. Although IEEE Standard 2746-2020 has raised the importance of such electromagnetic interference, but it only offers very basic information without an in-depth coverage. This paper provides a review, where critical aspects of electromagnetic interference between railways and power lines are summarized and the future research direction in this area is recommended.

INDEX TERMS Communication and signaling system, electromagnetic interference, inductive coupling, power lines, railway safety.

I. INTRODUCTION

Railways offer essential transportation services that carry considerable passenger and cargo traffic in Canada. Efficiency and safety of the railway transport largely depends on the reliability of the rail signaling, communication and control systems. Railway tracks serve as signal transmission medium due to their conductive nature to ensure safety and regularity in rail traffic. A signaling failure may result in interruption or delays of the railway transport in most situations but it could also cause damage of cargo and railway infrastructure, and injuries or losses of human life. Due to the load growth in power systems, limited available right-of-way and the public engagement, a power line often needs to share a joint corridor with other infrastructures, such as railway. However, such arrangement raises equipment and personnel safety concerns by both electric utility and railway companies due to AC electromagnetic interference between railway and nearby power lines.

When an alternating current (AC) flow in a conductor, it creates time-varying electric and magnetic field around

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it. Any nearby metallic objects, such as railway tracks, are subject to this electric and magnetic field and can create induced voltage and current. When a power line is under fault conditions, it can also create earth current that conductively couple into the railway system. Electromagnetic interference between railways and nearby power lines pose two main concerns: 1) personnel safety in the form of electrical shock hazards when touching or standing nearby the rail track; and 2) signal-system compatibility, which is related to the proper operation of signaling and protection systems of a railway.

Many track circuits have the working frequency of 50-60 Hz, the induced voltage and current from nearby power lines at the same frequency range may affect the detection and signaling system of the train [1]. The interference of a high voltage power line running parallel to a railway had caused malfunction of the track signaling circuits in Netherland in 1970 [2], damages to the crossing system circuit card was also reported in [3].

In 1936, Association of American Railroads (AAR) and Edison Electric Institute (EEI) published an important report – the inductive coordination of electrical supply and communication system, and it had been revised and updated in 1977 and is now known as “Principles and Practices for

Inductive Coordination of Electric Supply and Railroad Communication/Signal System” [4]. This document is commonly known as the “Bluebook” and is frequently used by Railway engineers.

In 1980s, AAR and the American Railway Engineering and Maintenance-of-Way Association (AREMA) funded a project with Electric Power Research Institute (EPRI) to study the electromagnetic compatibility of railways and two reports were published: 1) Mutual Design of Overhead Transmission Lines and Railroad Communication/Signal Systems [5]; and 2) Utility Corridor Design: Transmission Lines, Railroads, and Pipelines [6]. In Canada, the only available standard to address the interference issue between power lines and railway is CSA C22.3 No. 3-98 [7]. This standard embodies the principles and practices applicable for the purpose of effecting electrical coordination between organizations that operate electric supply or communications systems, where interference exists or is expected to exist. However, this standard covers very limited information on the railway’s signaling and communication systems.

Most recently, IEEE published a new guide for evaluating AC interference on linear facilities co-located near transmission lines, IEEE Std. 2746-2020 [8]. This standard documents some common guidelines/limits on the AC interference issue including pipeline, railway and fence, which does not offer in-depth coverage for railway systems.

Most of the prior work on the interference study between railways and nearby power lines were focused on the design criteria, system allowable limits and the simulation methodology. Nowadays, such study relies on the finite element simulation, which needs extensive training and expertise to conduct. These finite element simulation studies are usually conducted case by case during the detailed design stage but ignored during the route planning stage for power lines due to lack of information. Unlike pipeline standards, none of the existing Canadian standards provide clear guidelines on the minimal separation distance between the railway and power lines.

To provide proper evaluation and mitigation of such electromagnetic interference between railways and nearby power lines, further research is urgently needed to fill in this research gap. In this paper, we have conducted a literature review to summarize the current status of this unique, important but less studied subject area, and recommend the future research directions.

The paper is arranged as follows: in Section II, the common vulnerable railway communication and signaling equipment is reviewed and introduced; in Section III, different types of electromagnetic interference on railway systems are discussed; in Section IV, the present design, equipment and safety limits used by the railway industry to evaluate the electromagnetic interference issue are summarized; in Section V, the commonly used mitigation options to tackle the interference issue are presented; and conclusions are drawn in Section VI.

II. RAILWAY COMMUNICATION AND SIGNALING EQUIPMENT

As a complex system, it is essential that the railway communication system can operate reliably, accurately and safely. In the beginning, railway communication systems were designed to improve the public safety. Overtime, with expanding railway networks and the increasing train traffic, it was recognized that the railway signaling systems could have significantly impact on the railroad productivity and profitability. Although the railway communication system and signaling has been improved continuously to adapt the society’s development, its framework and major functions remain unchanged to ensure safe and efficient rail traffic [22]:

- Maintain safe separation between trains;
- Detect unsafe conditions in the track ahead of a train, on cars and locomotives; and
- Increase the traffic capacity of a railroad by centralized traffic control and automated terminal control systems.

Among all railway communication and signal components, the track circuit and motion detector/sensor are the most common system components that are particularly vulnerable to AC interference from adjacent power lines, the design limit of AC interference study between power line and railway is set to ensure the proper operation of the railway communication system and public safety. Those limits is determined either by industrial standard, such as AREMA, or by the equipment manufacturer itself. Therefore, it is important to understand how the typical railway communication component works so both power line and railway system can be modeled and studied properly in the AC interference study. This section will explain the major railway communication components in Canada.

A. TRACK CIRCUITS

Among many railway communication systems presently in operation around the world, to ensure safety of the train traffic, track circuits are the most popular systems by providing critical information about the position and movements of trains. If track circuits fail or malfunction, the operation of trains may become unreliable, leading to delays or even accidents of trains. In its simplest form, a track circuit is a low-voltage direct current (DC) electrical circuit, which uses railroad mechanical components, such as rails, wheels and axles, as its electrical conductors. These mechanical components used in conjunction with a relay and a battery connected to the tracks, the presence of railroad axles, cars or locomotives in the track circuit can be detected [11] [23].

To control the switches operation, wayside signals, flashing red lights, bells, gate arms and other vital relays, the track circuit controls signaling systems at wayside signal locations, interlockings and some crossings. The automatic block system (ABS) was introduced: at one end of the rail, the terminals of a battery are connected at each rail; and at the other end of the rail, the coil of a relay is connected across the rails and the energy from the battery is received through both rails. When the track has no train present and is unoccupied,

the relay coil receives most of the energy from the battery, which is enough for the coil to be energized and build up magnetism, attracting the armature of the relay towards the coil. When the train enters the track, the wheel and axle of the train effectively shunt the rails, depriving the relay coil of energy, demagnetizing and releasing the armature of the relay coil. The location of the train can be determined and various signal equipment, such as wayside signals, cab signals, or grade crossing warning systems, can be controlled based on this operation principle [11], [18], [23].

Another important characteristic of the track circuit system is the ability to detect the broken rail, loose connection, and dead battery, etc. These situations will tend to de-energize the track relay and indicate an occupied rail (train present).

In railway operation, a track is divided into a series of blocks that are sized to allow a train to stop within a block (ensuring a train has time to stop before getting dangerously close to another train on the same line), and the rule is only one train may occupy a block at a time [9]. The block lengths vary based on local conditions, and the maximum length varies in the range of 0.8 - 3.6 kilometers for practical operation. To successfully operate a track circuit, the bonding, ballast, drainage and local climate all play a role. A shorter block offers economical and reliable operation under all weather conditions without needing constant attention or adjustment, where the effect of foreign current can be greatly eliminated, and the broken rail protection is increased. A longer block minimizes the number of control circuits, and reduces the required maintenance and the number of failures caused by line breaks. Considering today's technology development in the railway industry, such as the increasing mileage on the stone ballast, better drainage designs, new technologies on rail manufacturing and better robust bonding materials, using longer track circuits on new installations may be feasible, however, the length of a block should always been determined based on local conditions and planned operations [11], [18], [23].

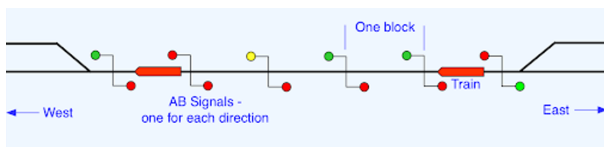


FIGURE 1. An example of the ABS system [10].

In an ABS system, the track is divided into a series of consecutive blocks of a varied length, and most ABS systems use a three or four block system. An example of an ABS system is shown in Fig. 1, where the red/yellow/green are the universal signaling system block status (Red indicates an obstructed block; yellow indicates that an obstructed block is ahead; and green indicates that no obstruction is expected). In Fig. 1, the right train faces a green wayside signal at the top portion for two blocks, and then encounters a yellow wayside signal on the third block indicating the next block is obstructed as shown with a red wayside signal. Similar to in a single track, each block entrance is controlled by wayside

signals, in which the operation is automatically controlled solely based on the presence or absence of preceding trains. ABS systems use long insulated cables and bare conductors to transmit signals from one block system to another. These conductors are usually supported by wood poles beside rail tracks.

The AC interference on an ABS system depends on the specific type of track circuits and the type of signal conductor used, and bare conductors are more susceptible to AC interference than shielded cables [11], [18], [23].

B. CROSSING MOTION DETECTORS

A crossing motion detector system is activated as soon as it detects trains by rail shunting, and can accurately predict the speed of the oncoming train to activate the crossing at a pre-determined time. It provides the vehicular traffic a consistent and appropriate amount of warning time before the arrival of trains with widely varying speeds at a level crossing [11], [18]. Fig. 2 shows a typical setup of the crossing motion detector system.

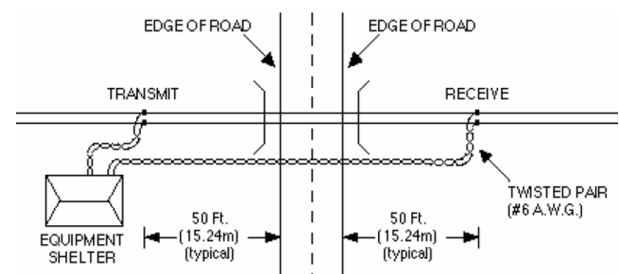


FIGURE 2. A typical setup of a crossing motion detector system [10].

In order to detect in coming train traffic on a crossing, a track circuit known as “approaches” are commonly installed at about 50 feet from the roadside at both sides. The installation location is determined by the level of road traffic, pedestrian and train. The distance of the approaches will also enable the train to have adequate time to travel at a safe speed and appropriate for the area it is passing through. Usually, an allowance of 20–30 seconds is allocated for pedestrians and vehicular traffic to react appropriately for the incoming train. Another track circuit called “island” is located about the middle of the road span. Warning devices are activated when either “approaches” detects a presence of a train, and will be deactivated when the “island track” is disengaged followed by the “approaches track”. In the event of train backing away and not reaching the “island track”, a timer with several minutes duration will be triggered. Once the timer has expired, the warning devices will be turned off [11], [18]. The operation principle of the crossing motion detector/ predictor systems is explained below: when a train's wheels and axles shunt railroad tracks, the lead axle is a moving termination shunt, which causes the electrical impedance of the track circuit to change during the movement, depending on the distance between the shunting lead axle and the measurement point. The track resistance decreases as the track circuit shortens when the train

approaches the island track. Both the track circuit impedance and the rate of change of the track circuit impedance with respect to time are measured by the crossing predictor system. When the lead axles of the train is at the edges of the level crossing, the track impedance is equal to zero. By dividing the measured track impedance by its measured rate of change, the time for the track impedance equal to zero can be calculated. When the calculated remaining time for the train to reach the island track is less than the desired warning time, the level crossing warning system is activated [10], [11].

A pattern of decreasing values in the track impedance indicates that a train is approaching the crossing; on the other hand, a pattern of increasing values in track impedance means that a train is leaving or moving away from the crossing. The magnitude of the impedance is proportional to the position of the nearest axle of the train within the approach. Therefore, the exact distance between a crossing and an approaching train and the train's velocity can be measured [11], [18].

A crossing motion detector/predictor is able to work satisfactorily for continuously moving trains approaching a level crossing. However, there are certain situations that might cause some difficulties. For example, the approaching train has already activated the crossing motion detector and its warning signals, and then the train stops before reaching the crossing, which will create a traffic backlog on the vehicular road. To avoid this issue, a timer can be added in the level crossing predictor system. When a crossing predictor is activated by an approaching train and then no longer seeing an inbound motion or changes in the track impedance, a timer begins to run. If the train resumes its approach to the level crossing after the stop, the timer is overridden by the crossing predictor system's normal operation. If the timer completes its cycle before the train starts to move, the level crossing's warning system will be shut off by the level crossing predictor system [11], [18].

With regards to vulnerability to AC interference from foreign sources, crossing predictor systems and motion sensors are the most sensitive, and this is because how these systems operate. Other systems works by having a signal source at one end and a receiver on the other. However, crossing predictor systems and motion sensors works by computing the rate of change in the track circuit impedance. The addition of interference effects on these systems could change how the controlled signals behave and operate [11].

III. ELECTROMAGNETIC INTERFERENCE

Metallic facilities, such as railways, located near energized power lines are susceptible to AC interference, which might cause both equipment issues (equipment corrosion, degradation or malfunction) and personnel safety concerns (shock hazards to humans) [8]. The railway modernization increases the effect of AC electromagnetic interference between the railway communication and signaling system and adjacent power lines, and AC interference must be evaluated to ensure the safety and reliability of railway systems. For railway systems, ac interference may result in unintended/impaird

operation of an electrical or electronic system when the induced voltage or current exceeds allowable limits.

In general, electromagnetic interference involves three types of mechanisms: conductive coupling, capacitive (electric field) coupling, and inductive (magnetic field) coupling.

A. CONDUCTIVE COUPLING

Conductive coupling occurs when time-varying electric fields are present in energized power lines, and a voltage gradient and electrical current are established within conductors. Conductive coupling can result in significant energy transfer and cause severe damage [8].

Unbalanced faults, especially single-line-to-ground faults, typically represent the greatest risks to personnel and equipment [8]. When a power line is under a single-line-to-ground fault condition or a lightning strike, a portion of the fault current or the lightning current will flow through the local tower grounding electrode and produce a ground potential rise (GPR) around the faulted structure. If a railway track is located within the zone of influence of the fault or lightning, the fault current might find its way into railway facilities, such as the signal house. The ballast also provides a conductive path from the earth to the rail circuit. When the power line runs in parallel with a railway in a shared corridor, there can be numerous grounds in closed proximity, providing a number of possible conducting paths for the current between the two systems. It is important to consider conductive interference during normal operation of the power system, as well as during faults when very large fault currents enter the earth. It is essential to preserve proper operation of railroad facilities for both cases to prevent damage to equipment or injury to personnel as a result of elevated voltages during power system faults.

The conductive coupling is illustrated in Fig. 3, which shows the current flow due to conductive coupling between a power line in parallel to the railway under a single-line-to-ground fault condition [11].

When a power line crosses the railway at a 90° angle, conductive coupling becomes the only concern as both inductive and capacitive couplings are minimal in this case.

B. CAPACITIVE COUPLING

Capacitive coupling occurs when time-varying electric fields are present within energized power lines, forming the capacitively coupled systems, where time-varying electric fields from the energized power lines interact through free space, resulting in a voltage on the nearby railway facilities. If the capacitively coupled voltage is at a sufficiently large magnitude, the nearby railway poses a shock hazard to personnel or causes interference in sensitive electrical equipment [8].

The railway tracks are sitting on top of the ballast. Fig. 4 shows the major railway structure and components, including the ballast. The typical ballast is made of crush rocks with higher resistivity than the local ground. This configuration makes the railway track semi-isolated from the

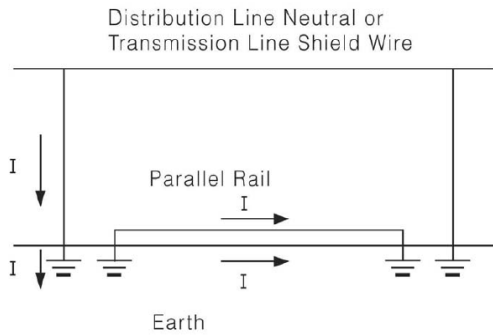


FIGURE 3. The current flow due to conductive coupling between power lines and railways [11].

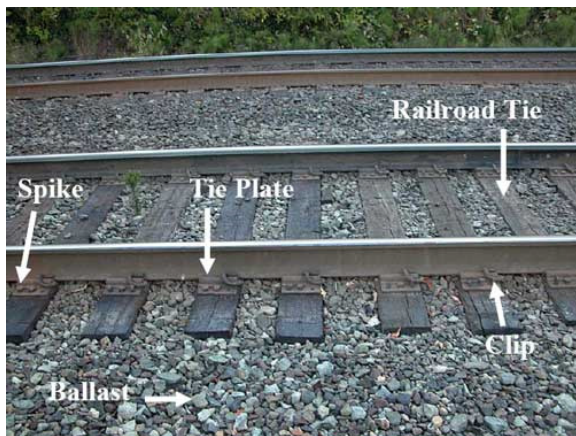


FIGURE 4. Major railway structure and components [11].

earth. Therefore, the capacitive coupling exists when a railway is situated in close proximity of power lines [11]. In this case, several capacitances are formed: 1) phase conductors and the track form an equivalent mutual capacitance (C_{12}) with an air dielectric; and 2) the self-capacitance (C_{20}) is created between the track and the ground. Fig. 5 shows the two types of capacitors formed due to capacitive coupling [8]. The voltage difference between the overhead phase conductor and the ground divides across these capacitors in an inverse proportion to the faradic value of the two capacitors. The induced voltage on the railway track is a direct function of the overhead phase conductor voltage to earth, inversely proportional to the distance between the railway and the overhead conductor [21].

The capacitive coupling may result in a high open-circuit voltage, but only a small current at the mA level. Comparing to inductive coupling, capacitive coupling has less impact on the railway signaling and communication system [21].

C. INDUCTIVE COUPLING

Inductive coupling occurs when time-varying current passes through a power line and produces a time-varying magnetic field around the path, and when a power line is in parallel with other nearby continuous conductive pathways, such as railway, mutual inductive coupling between the systems occurs. For inductively coupled systems, time-varying current in one conductive pathway (a power line) induces voltages and currents in the nearby railway [8].

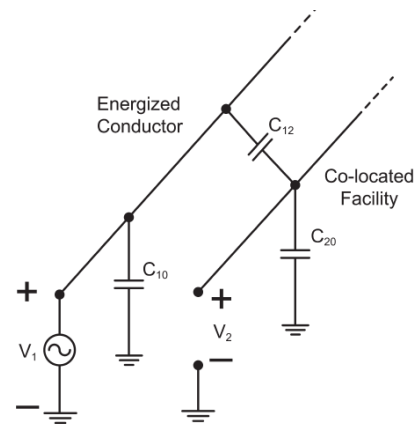
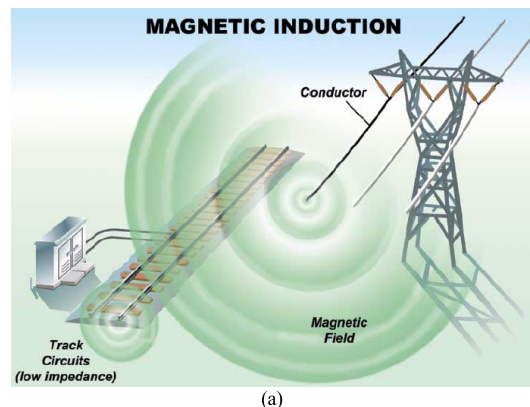
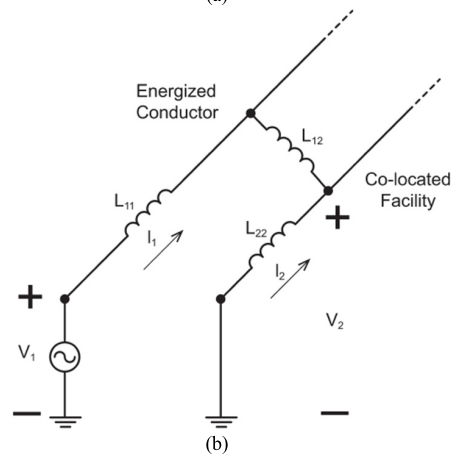


FIGURE 5. Capacitive coupling between power lines and railway [8].



(a)



(b)

FIGURE 6. (a) Inductive coupling between a power line and the railway [11]; (b) Inductively coupled systems [8].

Inductive coupling is the dominant type of AC interference when a power line runs in parallel with a railway track in a significant distance. The induced electromotive force (EMF) causes the current circulation in the railway track and builds up the voltage between the railway and the surrounding earth. Fig. 6 (a) shows the inductive coupling between power lines and a railway [11]; while Fig. 6(b) shows inductively coupled systems between an energized conductor and a nearby facility (railway), where a mutual inductance (L_{12}) exists between them, providing both a current (I_2) and a voltage (V_2) onto that railway facility [8].

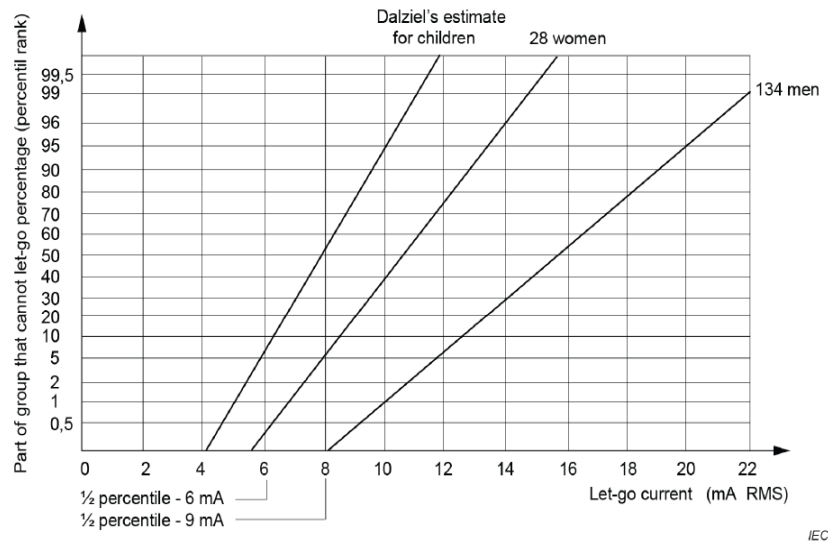


FIGURE 7. The let-go current for 60 Hz sinusoidal current [12].

Each phase conductor of power lines carries certain amount of current, which produces a time-varying magnetic field. The strength of this field is dependent on phase currents and the separation distance. In an ideal situation, currents on three phases are perfectly balanced and the net magnetic field at the location is zero when its distance to each phase is identical, i.e., the magnetic field generated by each phase cancels each other. However, in real life, separation distances are not the same and phase currents are always not perfectly balanced, creating an inductive coupling.

In inductive coupling, the maximum potential values occur at the end or interruption in either the power line or the railway, such as the transposition of power lines or where the railway turning away from power lines. When the two systems are interacting, bending points or discontinuities create rapid transformation in separation between the railway and power lines. The strong discontinuity of the EMF at the end points of the railway track forces a large leakage current, resulting in a large potential on railway tracks [11].

It is important to consider magnetic field induction under both normal operation and during faults of the power system. Much higher voltages are induced during faults because not only the greater magnitude of the fault current than a normal load current occurs, but also there is the extreme unbalanced loading on power lines during unbalanced faults.

IV. AC INTERFERENCE LIMITS AND CRITERIA

When AC interference becomes a concern on the railway system, there are two major categories of design limits to be considered: 1) the safety limits under both steady state and fault conditions of power lines; and 2) the operation/equipment limit to avoid either malfunction or permanent damage of equipment due to excessive induced voltages or currents. This section will discuss both design limits and criteria.

A. SAFETY LIMITS UNDER STEADY STATE POWER LINE OPERATION

Under power line steady-state operating conditions, the railway system is subjected to both electric induction and magnetic induction. The capacitive coupling is related to the voltage induced on the railway system by electric field. The object under electric field has to be isolated from the ground so it can collect the electric charges and build up the voltage. When people touch this object, human body will create a grounding path to discharge the energy into the ground. In this case, the steady-state current should not exceed the threshold of let-go current limit [7], [11].

The let-go current limit is the maximum value of touch current at which a person holding electrodes can let go of the electrodes. The threshold of let-go depends on several parameters, including the contact area, and the shape and size of electrodes, and also depends on physiological characteristics of the individual. About 10 mA is assumed for adult males in IEC Standard 60479 [12]; about 5 mA is the common design limit for the entire population [12]–[15]. Fig. 7 shows the let-go current plot based on the lab test [12].

In case of railway, the track system is semi-insulated from the ground through the ballast. The resistivity of local ballast varies with the weather and contamination. Therefore, the electric induction and 5 mA let-go limit is generally not applicable to railway tracks [11].

When the railway is located near power lines under steady state conditions, inductive coupling is always the governing interference type. The safety limit under magnetic induction varies among various standards based on different assumptions. Two common safety limits under magnetic are 50 V rms and 15 V rms. The basic idea of 50 V rms safety limit assumes that a body impedance value is 2000 Ω , and it follows the c-1 current curve (Fig. 8) in IEC Standard 60479 [12]. For the current above c1 curve, it will cause strong involuntary muscular contractions, difficulty

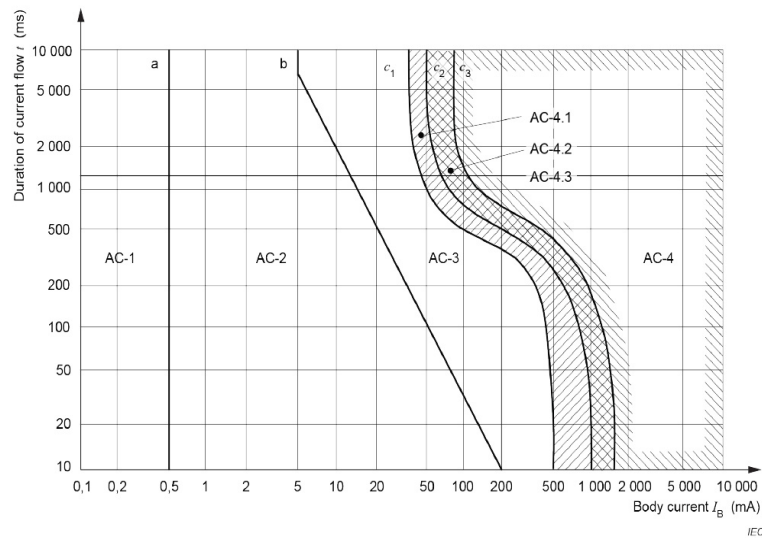


FIGURE 8. The zones of effects of AC currents (15 Hz To 100 Hz) on persons for a current path corresponding to left hand to feet [12].

in breathing, reversible disturbances of heart function, and immobilization may occur. The effects increase with the current magnitude. Usually no organic damage to be expected. Industry Standards citing 50 V rms limit includes OSHA [14], NESC [15], IEEE Standard 80 [16] and NEC [17].

In Canada, the standard CSA C22.3 No.3 has been adopted by all railway companies. For adjacent track sections of equal length separated by a pair of insulated joints, the ac voltage developed across each insulated rail joint is twice the maximum voltage of each rail with respect to the remote earth. To limit the voltage across insulated rail joints to 50 V, the maximum rail-to-remote earth voltage should not exceed 25 V [7].

B. SAFETY LIMITS UNDER POWER LINE FAULT CONDITIONS

In Canada, CSA C22.3 No.3 is a unique standard by providing the safety limit under fault conditions. The acceptable level for the longitudinal induced voltage in railway signaling and communication circuits is 430 V rms under power line fault conditions. This level applies to usual power line equipment and maintenance. Higher voltages may be acceptable under special conditions, such as high reliability power lines with high-speed relaying and fault clearing [7]. On top of it, all railway companies adopt additional safety standard for detailed analysis. When an individual is exposed to AC current under power line fault conditions, ventricular fibrillation is the primary concern. In this case, the consideration shall be given to any metallic parts of a railway system where public or railway personnel can make contact (touch potential) or near the fault location (step potential). The safety limits under fault condition are well documented in IEC standard 60479 [12] and IEEE standard 80 [16]. In North America, IEEE standard 80 is the only recognized standard for the short duration current to the human body by almost all electric utilities and railway companies.

C. SAFETY RAILWAY COMMUNICATION EQUIPMENT OPERATION LIMITS

According to the AREMA C&S (communication and signaling) Manual Part 8.2.1 [18], audio frequency track circuits shall operate properly on tracks having up to 10 V AC rms at 60 Hz to 180 Hz sinusoidal rail-to-rail voltage when used with operating frequency and appropriate accessories specified by manufacturers.

Surge arrestors have been widely used to protect the railway communication system. According to EPRI report [11], typical current limit ranges from 190 – 470 A rms was used for designing of Safetran air-gap arrestors based on up to 0.23 second fault. Additionally, a few arrestor limits are documented in [19], typical destructive rms current limit for arrestor is 500 A for a 0.2 s energy fault.

V. SYSTEM MODELING

To evaluate the AC interference between power lines and railway systems, the system modeling and simulation is essential. The modeling allows us to analyze the worst-case scenario, which is nearly impossible to acquire actual measurements in the field due to costs and restrictions on railway operation. Therefore, an accurate model representing real-world scenarios is extremely important to properly determine the actual AC interference level on railway systems from both safety and operation perspectives.

In 1985, EPRI and The Association of American Railroads (AAR) funded a research project, which focused on electromagnetic interference to railroad facilities [6], [24] and the creation of a computer program called CORRIDOR. This software package was one of the first that can predict the steady state induced voltage on various configurations of railway facilities. However, it cannot handle the conductive coupling under power line fault conditions. Despite decades of efforts, there is limited commercial software available for AC interference studies. Nowadays, there are two standard

approaches to study the AC interference between power lines and railway. The first approach is the circuit model, where line parameters, such as self and mutual impedance of various metallic paths are determined to create the circuit model. The second approach is the electromagnetic field model, which usually requires the finite element analysis.

The simulation of the electromagnetic coupling between power lines and the railway is complex. One of the major challenges is to determine the equivalent railway characteristics. To properly create the railway system in the software, several researches were conducted to focus on different components of railway systems.

Reference [25], [26] focus on determining the railway conductor's characteristics, where a methodology is presented to model the railway conductor by subdividing it into many smaller cylindrical conductors. The major drawback of this approach is the subconductors are not connected with each other so the magnetic circuit within the railway conductor are discontinued. Another challenge of this approach is how to determine boundary conditions to achieve acceptable accuracy [27]. In [28], a new methodology is discussed by modeling the railway conductor as an equivalent cylindrical conductor, whose impedance as a function of the frequency and the current approximates that of a rail.

In [29], a simplified effective method is presented for computing the equivalent parameters for the rail ballast resistance. In the model, the measured ballast resistance can be replaced with an insulated coating with proper resistivity to provide the same leakage current as the railway ballast.

Refs [30], [31] investigate the importance of modeling track-connected equipment for some scenarios. Properly modeling the track-connected equipment can impact the maximum rail-to-rail induced voltage. In [19], [32], [33], sensitivity and case studies are presented to show the step-by-step model building.

VI. COMMON MITIGATION OPTIONS

When AC interference level on the railway system exceeds the design or safety limits, the proper mitigation is required to reduce the level of the interference to allow a railway system to operate normally, reliably and safely. As always, there might be more than one mitigation options available to solve the interference issue, so it is very important to have the full system model representing the power line and the railway system to identify the type of interference. Each type of interference requires a different mitigation option. In this section, we discuss the most common mitigation methods, which have been successfully utilized in the past projects. All mitigation options discussed in this section focus on the design perspective instead of introducing any new operation or maintenance procedures.

A. COUNTERPOISE WIRE

The counterpoise wire is a multigrounded conductor, which is buried between power lines and the railway to reduce the magnetic induction through passive cancellation, and it

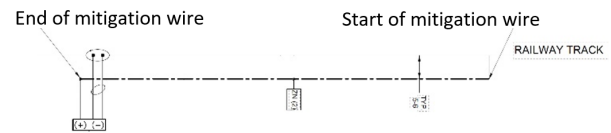


FIGURE 9. An example of counterpoise wire.



FIGURE 10. An example of overhead cancellation wire [20].

can also provide the protection against conductive coupling under power line fault conditions by reducing the amount of currents flowing into the rail system. Fig. 9 shows an example of counterpoise wire.

The location of the counterpoise is very critical in providing sufficient cancelling effect on inductive coupling. The optimization work is usually done in a software programming model to determine the optimum location, size and grounding method for the counterpoise wire [11].

The counterpoise wire along with overhead cancellation wire had been successfully used in ComEd's service territory to mitigate the power line and railway interference issue [20].

B. OVERHEAD CANCELLATION WIRE

The overhead cancellation wire has been used around the world to reduce the EMF emission from power lines. In some cases, utilities build underbuilt overhead ground wire below the bottom phase conductor to reduce the EMF level and backflashover rate caused by lightning.

The overhead cancellation wire only offers cancellation effect on the inductive coupling. Typically, this migration option is not effective enough on its own and needs to be combined with other mitigation options to solve interference issues. An example of an overhead cancellation wire is shown in Fig. 10. In this example, multiple cancellation wires are installed to provide cancellation magnetic field by coupling with nearby power lines, which results in a lower magnetic field at the railway track location.

C. POWER SYSTEM STRUCTURAL DESIGN AND PHASING CONFIGURATION

If the power line is a new design, the electric utility company has the opportunity to make the structural design and phasing arrangement to have less impact on the inductive coupling on the adjacent railway. Reducing the spacing between phase conductors increases the effectiveness of magnetic field cancellation for balanced phase currents. Many electric utility

companies have already done it to make a compact tower design due to the limited right of way width and the public opinion.

When there are more than one circuit on the power system structure, the phase of the circuits can be arranged so that steady-state magnetic fields at the ground are minimized. This is a common design practice in most electric utility companies.

The magnetic field decays with the distance between the power lines and railway tracks. Therefore, increasing the distance between power lines and railway tracks is usually an effective way to reduce the inductive coupling. A taller structure can be useful to reduce the inductive coupling. However, the taller structure is usually not preferred by utilities or the public.

D. SEPARATION DISTANCE

The magnetic field created by power line varies along the separation distance from the centerline. The induced voltage is proportional to the magnetic field and magnetic field will be reduced significantly with a larger separation distance from the power line. Therefore, the separation distance between a power line and a railway track plays an important role on the inductive coupling. For a new transmission line, increasing separation distance is always an effective way to reduce AC interference. Note, this option would only work on a new power line with undefined corridor.

E. SHORTEN TRACK LENGTH

The amount of voltage induced into railway track rails with respect to remote earth depends heavily on the length of the exposure. The longer the track circuit, the greater induced voltage that can be developed on the track.

By limiting or reducing the length of electrically continuous sections of track, the induced voltage and energy can be limited. Longer sections minimize the number of signaling circuits required, but also reduce the operating efficiency of the railroad by increasing the amount of time that each train spends in each “block”. As no other train may enter a block of track that is already occupied, longer blocks mean longer waits for other trains [11].

The length of track section may be reduced by adding sets of insulated joints to partition a section of track into a greater number of smaller pieces, or by removing bypass couplers used to carry signaling frequencies around insulated joints. Often this requires the installation of additional track circuit hardware. In the long term, partitioning the tracks covered by railroad signaling circuits into smaller pieces can contribute to higher maintenance costs and increased signal system complexity, but these may be slightly offset by increases in operating efficiencies and greater individual track circuit reliability [11], [21].

F. IMPEDANCE BOND

An effective mitigation method is presented in [3] to mitigate the inductive interference on the railway. This mitigation

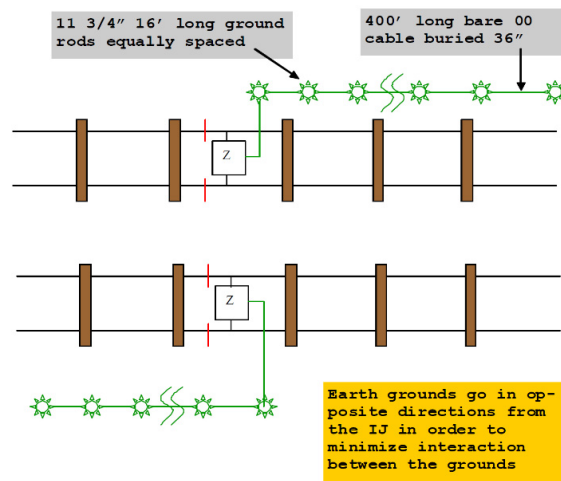


FIGURE 11. An example of impedance bonds installation [3].

method is to use impedance bonds across the track circuit insulated joints. The impedance bond provides a short circuit path, bypassing the insulated joint for the common model induced current. Meanwhile, it still allows the signal system to operate in differential modes. An example of the application of impedance bonds is shown in Fig. 11.

G. GROUND GRID

It is a common practice to install the copper wire around the signal equipment enclosures by railway companies to provide grounding to the signal equipment and also to reduce the touch potential risk. Ground loop conductor or simple ground grid is very effective mitigation option if human safety is a concern.

VII. CONCLUSION

In this paper, a literature review is conducted on the railway electromagnetic interference issue due to nearby power lines. The different types of interferences has been reviewed. The present design, equipment and safety limits used by railway industry are summarized along with existing state of art mitigation options to tackle this issue.

The future research directions are recommended as follows:

1. Due to complexity of this issue, advanced finite element method is required to accurately evaluate the AC interference issue on railway. However, a rule-of-thumb is required during the project planning stage to allow utility companies to briefly assess the potential AC interference issue with some typical information. Therefore, it is important to develop a best practice or rule-of-thumb to be used by the power industry as the starting point of this assessment.
2. Determining the minimal separation distance to avoid the AC interference issue between railway and different configurations of power lines. Such information can be used to update CAN/CSA 22.3 No.3 to provide a similar guideline as the pipeline standard.

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