I. ABSTRACT

In joint-use corridors, AC electric power lines can induce objectionable voltages onto nearby railways. Excessive rail-to-rail voltages can interfere with the proper operation of grade crossing control equipment and track-connected signal equipment. The interference mechanism has been well known for many years and a sizeable body of literature exists on the subject. Nevertheless, the relationship between rail-to-rail voltages, track-connected equipment impedances, and ballast resistance has not been studied in a comprehensive manner. This study demonstrates that track-connected equipment impedances must be modeled in an electromagnetic compatibility study, in order not to overestimate rail-to-rail voltages. Furthermore, the maximum rail-to-rail voltage does not necessarily occur when the ballast resistance is extremely large, but rather at some intermediate value, which is a function of the impedances of the track-connected equipment. This paper provides a series of curves illustrating these points for a simple example, along with a case study showing what impact this can have in practice.

Keywords: AC interference, inductive coupling, electromagnetic compatibility, power line interference
II. INTRODUCTION

Communications and signal system engineers have known for many years that AC electric power lines can induce objectionable voltages onto parallel rails and signal conductors [1,2]. Excessive rail-to-ground voltages can represent a shock hazard for personnel and the public; excessive rail-to-rail voltages can interfere with the proper operation of grade crossing control equipment and other track-connected signal equipment. These voltage levels are a function of a number of well identified power line and railway parameters, many of which have been extensively studied [1-3].

In carrying out a recent study, the authors discovered an important gap in the published literature. It was found that track-connected equipment can constitute a primary influence not only on the maximum rail-to-rail voltage but also on the ballast resistance at which the maximum rail-to-rail voltage occurs.

This paper explains why this occurs and provides curves illustrating this phenomenon.

III. COMPUTER MODEL

Figure 1 depicts a simple system that exhibits the behavior described above. A railway consisting of 8 identical track circuits, each 7000 ft long and separated from adjacent circuits with an insulated joint, is modeled. An AC power line runs parallel to the two central track circuits, 100 ft away (center to center), with the equivalent of 100 A flowing in a single conductor. This is representative of any number of possible load current scenarios for power lines with different conductor spacings and different load unbalance levels. In any case, all results are directly proportional to this equivalent current, so the conclusions of this study are universally applicable.
A degraded insulated joint, modeled with a negligible resistance, is located on one rail at Insulated Joint IJ5 (see Figure 1), resulting in an electrical unbalance between the rails and, as will be seen, a large rail-to-rail voltage on the right-hand side of Insulated Joint IJ5. A train is located at Insulated Joint IJ4, effectively shunting the tracks and the insulated joints with a very small resistance. This represents the worst case location for all but the lowest ballast and equipment resistances studied. The rails are 133 lbs, the insulated joint resistance is 100 ohms, and the soil resistivity is 500 ohm-m. The ballast resistance (defined as the resistance measured between a pair of 1000 ft long rails, through the ballast) and the track-connected equipment impedances vary throughout the study, with the following values:

- Ballast resistance: 1 to 500 ohms-kft
- Track-connected equipment impedances: 1, 3, 9 ohms per track circuit

The ballast resistance and equipment impedances are uniformly distributed throughout each track circuit. The ballast resistances range from low (wet, contaminated ballast) to very high (hard freeze). The actual equivalent impedance from rail-to-rail, due to track-connected equipment, will depend on the type of equipment and number of devices. Impedances for representative electronic track signaling equipment, often with audio filters, can be on the order of 15 to 30 ohms, with an inductive component dominating at the higher end values. Representative track relays and relay feeds can be on the order of 15 ohms, primarily inductive. Representative grade crossing control equipment and associated narrow band shunts can each have impedances on the order of 15 to 20 ohms, ranging from slightly inductive to entirely capacitive. From the above, it can be seen that in an area with multiple pieces of equipment, as would be the case when grade crossing equipment is present, it is easy to obtain equivalent impedances on the order 1 - 9 ohms between insulated joints, when modeling a typical exposure. In this study, for each equipment impedance value indicated
above, three types of impedances have been examined: purely resistive, inductive (45 degrees) and capacitive (-45 degrees).

The computer simulations related to this simple example were made using the ROW Pro® software package [4], a tool designed to model complex corridors with multiple power line circuits, railways, pipelines, communications cables, etc., at variable separation distances, with variable grounding and interconnection impedances throughout the system.

IV. COMPUTER MODELING RESULTS

Figure 2 provides a plot of rail potentials as a function of distance along the railway, between Insulated Joints IJ1 and IJ7, in order to illustrate the fundamental electrical response of the system. The parameter values for this plot are as follows:

- Equipment impedance per track circuit: 3 ohm per track circuit
- Ballast resistance: 40 ohm-kft

As this plot shows, rail potentials are low from the left-hand side of the system to Insulated Joint IJ3, due to the absence of any source of induced voltages in this region and due to the electrical isolation from the rest of the railway provided by Insulated Joint IJ3. Similarly, rail potentials are low from Insulated Joint IJ6 to the right-hand side of the system.

Between Insulated Joints IJ3 and IJ5, voltages are induced in the rails by the power line. A potential peak occurs on both rails on the right-hand side of Insulated Joint IJ3, where induced voltages have built up to a maximum at the point at which the power line deviates from the railway. Another peak occurs at on the left-hand side of Insulated Joint IJ5, at the other power line deviation. Between the rail-to-ground voltage peaks at IJ3 and IJ5, the voltage curve drops to a minimum, roughly midway between the two, a characteristic shape for a long metallic structure exposed to
induction from a power line. On the rail with the degraded insulated joint, the potential remains high to the right of Insulated Joint IJ5, since there is no significant resistance blocking the passage of current. On the other rail, however, the potential drops considerably, due to the isolation provided by the intact insulated joint at IJ5 on that rail. The potential does not drop down to near-zero, though, because it is connected to the other rail through the equipment impedances, which allow current to flow from one rail to the other with relative ease. Indeed, it is this flow of current through the equipment impedance and the resulting voltage drop that produces the voltage between the two rails throughout the region between Insulated Joints IJ5 and IJ6. All equipment in this region will be subjected to this voltage.

The rail-to-rail voltage in the simulation shown in Figure 2 ranges from approximately 15 V to 17 V between Insulated Joints IJ5 and IJ6. To put this value into perspective, consider that the AREMA C&S Manual specifies that motion sensitive systems to control highway-rail grade crossing warning devices shall “operate properly on tracks having up to 5 volts ac rms at 60 Hz rail-to-rail voltage when used with the appropriate accessories,” whereas audio frequency track circuits must operate properly with up to 10 volts ac rms at 60 Hz [5]. For human safety, rail-to-ground voltages are recommended not to exceed 25 V [6,7].

Figures 3-7 present the results of the parametric analysis carried out to study the effects of simultaneous variations in equipment impedance and ballast resistance on rail-to-rail voltages, with a single degraded insulated joint at IJ5. Figure 3 presents results when equipment impedances are assumed to be purely resistive. Rail-to-rail voltages are plotted as a function of ballast resistance, for four different equipment impedances per 7,000 ft track circuit: 1 ohm, 3 ohms, 9 ohms, and infinity (i.e., no equipment). The latter value is provided for comparison purposes only. Figure 4 presents
rail-to-earth voltages immediately to the right of Insulated Joint IJ5, on the rail with the degraded insulated joint, for the same scenarios.

As can be seen in Figure 3, rail-to-rail voltages are minimal when the ballast resistance is low. In this case, the rails are well grounded, so the rail-to-earth voltages are low and therefore so are the rail-to-rail voltages. As the ballast resistance increases, the rail-to-earth voltages increase (see Figure 4) and the rail-to-rail voltages with them. There is a limit, however, to how high the rail-to-earth voltages can rise: this limited is imposed by the maximum induced electromagnetic force (emf) in the rails in the region exposed to the power line. As Figure 4 shows, the rail-to-earth voltage limit for the system studied appears to be approximately 55 V.

So far, we have explained why the curves in Figure 3 rise, initially. As the ballast resistance increases further, another important factor influences the rail-to-rail voltages. Figure 5 presents a simplified circuit diagram of the system under study, which can be used to understand why rail-to-rail voltages decrease as the ballast resistance becomes very large. In particular, Figure 5 represents the track circuit between Insulated Joints IJ5 and IJ6, along with the induced voltages provided by the system to the left of Insulated Joint IJ5 through the degraded insulated joint. Figure 5 shows a voltage source representing the induced rail-to-earth potential that would appear on the left-hand side of Insulated Joint IJ5 if the insulated joint were intact. The voltage source is in series with an equivalent circuit impedance representing the railway system to the left of Insulated Joint IJ5. Incidentally, this impedance is a function of the ballast resistance, but that has no bearing on the essence of this discussion. Each rail of the track circuit to the right of Insulated Joint IJ5 has a resistance to earth, Rballast, through the ballast. An impedance, Zequipment, represents the track-connected equipment located between Insulated Joints IJ5 and IJ6.
Consider what happens to the rail-to-earth potential at Point P2 in Figure 5, on the rail with the intact insulated joint, compared with the rail-to-earth potential at P1, on the rail with the degraded joint, as the ballast resistance increases. There are two ways to examine this. One is to observe that $R_{\text{ballast}}$ and $Z_{\text{equipment}}$ represent two series-connected impedances between P1 and remote earth, thus resulting in a voltage divider circuit. As a result, it is clear that as $R_{\text{ballast}}$ increases, the rail-to-earth potential at P2 will represent a correspondingly greater proportion of the rail-to-earth potential at P1, since $Z_{\text{equipment}}$ is a constant value. As $R_{\text{ballast}}$ becomes large, the rail potentials at P1 and P2 become very close and the rail-to-rail potential becomes very small. Another way to arrive at the same conclusion is to observe that the rail-to-rail voltage is equal to the product of $Z_{\text{equipment}}$ and the current flowing through this impedance. As $R_{\text{ballast}}$ becomes large, the current flow becomes small and so, therefore, does the rail-to-rail voltage.

As Figure 3 shows, the ballast resistance resulting in the maximum rail-to-rail voltage depends upon the impedance of the track-connected equipment. When this impedance is low, the peak occurs at relatively low ballast resistance values; as the equipment impedance increases, so does the ballast resistance value at which the peak rail-to-rail voltage occurs. The peak occurs at a ballast resistance of approximately 20 ohm-kft for a 1 ohm equipment impedance per track circuit, at approximately 40 ohm-kft for a 3 ohm equipment impedance, at approximately 50 ohm-kft for a 9 ohm equipment impedance, and at a value between 100 and 200 ohm-kft with all equipment disconnected from the rails.

It is also apparent from Figure 3 that the maximum achievable rail-to-rail voltage decreases with decreasing track-connected equipment impedance, as one would expect. Clearly, when studying induced rail-to-rail voltages on track circuits for equipment compatibility studies, it is important not
only to consider the mitigating effects of track-connected equipment, but also use the worst case ballast resistance value, which is not necessarily a high-end value!

Figure 6 shows what happens when the equipment in each track circuit has an overall inductive component (track relays and track relay feeds would tend to have these characteristics): the impedance phase angle is 45 degrees. The curves are similar to those obtained from the purely resistive equipment, but reach greater peak values: up to about 20% higher for the 1 ohm per track circuit curve.

Figure 7 shows similar results, but for track circuits with an overall capacitive component (narrow band shunts used for constant warning time train detection systems will tend to do this): the impedance phase angle is -45 degrees. In this case, the peak values are lesser than those obtained for the purely resistive equipment impedances: up to about 20% lower for the 1 ohm per track circuit curve.

V. CASE STUDY

Figure 8 presents a plan view of a case study that illustrates the importance of these findings. A 60 kV, single-circuit, vertically configured, transmission line runs more or less parallel to a railway for a distance of 17,000 ft, crossing the track at one location. The current flowing in the line during worst case load conditions is approximately 1.13 kA. The railway has a number of insulated joints, as shown in the figure. It was found that the worst case rail-to-rail voltages occurred in the region between IJ5 and IJ6 when one of the joints at IJ5 was degraded (to the point of offering no resistance at all), with a train present immediately to the left of IJ5.

A detailed computer model of this system was built, including the transmission line, the substation grounding systems at which it terminates, the railway (two tracks), and adjacent pipelines
Computer simulations were made with the HIFREQ® electromagnetic field analysis module of the CDEGS® software package [8-10], which analyzes a three-dimensional system of conductors based on electromagnetic field theory. Maxwell’s equations are solved directly, taking into account inductive, capacitive, and conductive (through-earth) coupling between all elements of the system.

It was initially believed that the maximum rail-to-rail voltages would occur for the maximum expected ballast resistance of 300 ohm-kft. Figure 9 plots the computed rail-to-ground voltages of both rails. As can be seen, the maximum rail-to-rail voltage obtained is approximately 2.5 V. Although this was initially believed to be the worst case, the system was modeled for other ballast resistances. Figure 10 shows the worst case rail-to-rail voltages obtained, corresponding to a ballast resistance of 30 ohm-kft. As can be seen, rail-to-ground voltages have decreased somewhat, but rail-to-rail voltages have more than doubled, to approximately 6 V. This can represent an important difference, when considering equipment susceptibility thresholds that can be 3V, 5V, 8V, 10 V, etc.

VI. CONCLUSIONS

From this study, it is seen that track-connected equipment impedances must be modeled in an electromagnetic compatibility study involving AC power lines and railways, in order not to overestimate rail-to-rail voltages. Furthermore, the maximum rail-to-rail voltage occurs for a specific value of the ballast resistance, which is a function of the impedances of the track-connected equipment; very high and very low ballast resistances result in lower rail-to-rail voltages. It is therefore necessary to study a range of ballast resistance values, in order to determine the worst case rail-to-rail voltage and implement suitable mitigation to prevent interference with grade crossing control and signaling equipment.
This paper provides a series of curves illustrating these points for a simple example, along with a case study showing what impact this can have in practice.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES


Figure 1. Plan view of simple system modeled.

Figure 2. Rail potentials as a function of position along railway for simple model.
Figure 3. *Rail-to-rail* voltages on right-hand side of IJ5 for *purely resistive* track-connected equipment.

Figure 4. *Rail-to-ground* voltages on right-hand side of IJ5 for *purely resistive* track-connected equipment.
Figure 5. Simple equivalent circuit for track between IJ5 and IJ6.

Figure 6. Rail-to-rail voltages on right-hand side of IJ5 for inductive (45 degree phase angle) track-connected equipment.
Figure 7. Rail-to-rail voltages on right-hand side of IJ5 for capacitive (-45 degree phase angle) track-connected equipment.

Figure 8. Plan view of system analyzed in case study.
Figure 9. Rail voltages from case study: 300 ohm-kft ballast resistance.

Figure 10. Rail voltages from case study: 30 ohm-kft ballast resistance.