Induced Voltage and Current in Parallel Transmission Lines: Causes and Concerns

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***Abstract*—Induced voltage and current in a deenergized transmission line caused by other lines nearby can be caused by electric-field and magnetic-field induction. These voltages and currents present a serious work hazard for line-crew personnel. Proper understanding of the phenomenon involved and identification of the associated hazards are necessary to safely perform deenergized line work. The purpose of this paper is to clarify some of the misconceptions that have been prevalent in the industry for many years as well as to expand on the test data available in literature. This paper discusses, in simple terms, the relevant parameters that affect the magnitude of the induced voltage and current as well as the work hazards they create.**

***Index Terms*—Electromagnetic induction, grounding, safety.**

I. Introduction

VOLTAGES and currents can be induced into deenergized transmission lines that are located close to other energized transmission lines by the electric and magnetic fields created by the energized line(s). While induced voltage is often thought to be the main culprit in accidents involving deenergized line work, the induced current and the subsequent current flowing through a worker's body is the primary reason for accidents. To counteract this potential problem, temporary protective grounds (TPGs) are required by the Occupational Safety and Health Administration (OSHA) whenever work is performed on deenergized transmission lines where there is an induction hazard [11]. However, the presence of grounds can provide opportunities for accidents to occur if the proper procedures are not followed. Caution should always be used when installing and removing TPGs. A worker can easily put themselves in a hazardous situation, such as being in series with a protective ground. The charging current associated with electric-field induction and the circulating currents associated with magnetic-field induction can be lethal.

This paper describes the parameters affecting induced voltages and currents in parallel transmission lines, and offers some examples showing what these values can be in a typical system. This paper also addresses potential work hazards as they exist when proper protective grounding installation methods are not followed.

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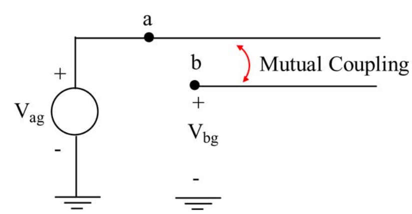

Fig. 1. Two-conductor electric-field induction example.

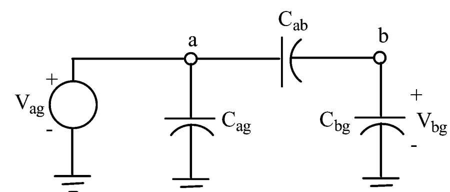

Fig. 2. Capacitively coupled circuit representation of two parallel circuits.

II. Electric-Field Induction

Whenever a deenergized transmission line is parallel to one or more energized transmission lines, voltages and currents will be induced in the deenergized line by a mechanism known as electric-field induction. To understand electric-field induction and the parameters that affect the resulting induced voltages and currents, it is convenient to look at the two-conductor case shown in Fig. 1.

In Fig. 1, conductor a is connected to a voltage source and conductor b is deenergized and ungrounded (i.e., floating). This configuration can be depicted by the capacitively coupled circuit shown in Fig. 2.

In any instance when two conductors are separated by a dielectric medium, such as air, a capacitor is created. The case shown in Fig. 1 is no different. Here, a capacitance is created between each conductor and ground, as well as a capacitance between the two conductors (i.e., mutual capacitance). The mutual capacitance C_{ab} is a function of the distance between the two conductors, their height above ground, and the length that they are paralleled. The closer the two conductors are to one another, the larger the mutual capacitance C_{ab} will be. The capacitances to ground of the two conductors C_{ag} and C_{bg} are primarily a function of that particular conductor's height above ground and its diameter.

The voltage induced into conductor b due to a voltage being applied to conductor a can be found by voltage division as shown

$$V_{bg} = \left(\frac{C_{ab}}{C_{ab} + C_{bg}}\right) V_{ag}. \tag{1}$$

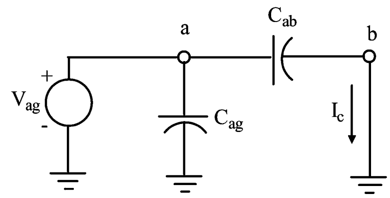

Fig. 3. Circuit configuration when conductor b is grounded.

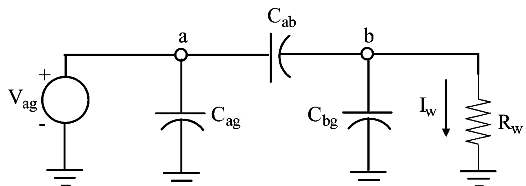

Fig. 4. Worker in series with protective ground.

The units of C_{ab} and C_{bg} are in farads per meter. From (1), it can be seen that the units of length cancel; thus, the distance the two lines are paralleled has no impact on the magnitude of the induced voltage. This is contrary to magnetic-field induction, where the distance the lines are parallel to has a dramatic impact on the induced voltage.

Once the deenergized conductor is grounded, a significant potential difference no longer exists between that conductor and ground. However, unlike the case of the floating conductor, there is now a path for charging current to flow. The circuit configuration for this situation is shown in Fig. 3. The magnitude of the current I_c, shown in Fig. 3, can be shown to be equal to (2), assuming a 60-Hz system

$$I_c = 377 C_{ab} V_{ag}. \tag{2}$$

As previously discussed, C_{ab} has units of farads per meter; therefore, its total value is a function of the length that the two lines are parallel as well as the distance between the lines. Thus, the amount of charging current induced into conductor b, when it is attached to ground, is also a function of these parameters. Also, (2) shows that the charging current is directly related to the operating voltage of the energized line.

The induced current caused by electric-field induction is arguably the most hazardous for line workers, because it is not impeded by the effective resistance of the worker [3]. This fact can be explained by the circuit diagram shown in Fig. 4.

Fig. 4 is an example of a worker becoming in series with a TPG and the local pole ground or earth. For all practical values of worker resistance, the parallel combination of $\mathrm{R_w}$ and $\mathrm{C_{bg}}$ is approximately equal to $\mathrm{R_w}$. Thus, the current flowing through the worker for this scenario is (for 60-Hz systems)

$$I_W = \frac{V_{ag}}{\sqrt{(R_W)^2 + \left(\frac{1}{377 C_{ab}}\right)^2}} \approx 377 C_{ab} V_{ag}. \tag{3}$$

Equation (3) is valid for typical values of worker resistance (e.g., 1000 Ω), and should be used only to explain the phenomenon of electric-field induction. Equation (3) tells us that under these simplistic conditions, the resistance of the worker will not impede the charging current of the line. Realistically, $\mathrm{R_w}$ would represent the complete impedance of the worker and his or her path to remote earth, including the local tower footing resistance and the shield wire network impedance. The total value of these variables would still allow (3) to be valid for this simplistic case. Although (3) is not valid for a realistic case, it can be shown through more complex analysis that the conclusion reached by the evaluation of (3) (i.e., that the charging current is impeded only slightly by the inclusion of the worker resistance) is also valid for three-phase transmission lines with and without shield wires. Furthermore, because there are no means to interrupt the flow of steady-state charging current, a worker who becomes in series with the current path might be subjected to this current indefinitely. These currents are generally well beyond the "let-go" threshold of 10 mA and, in many cases, are well beyond the 60 to 100 mA of current required to produce ventricular fibrillation [4].

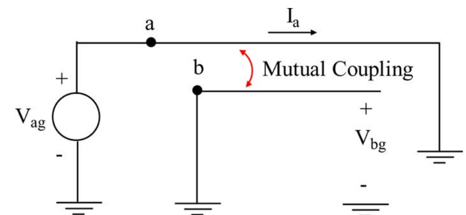

Fig. 5. Magnetic-field induction example circuit.

III. Magnetic-Field Induction

Transmission lines that share the same right of way or tower with other transmission line(s) will be magnetically coupled with one another. Current flowing in the energized circuit(s), due to loads or short circuits, will produce a magnetic field that links the conductors of the deenergized circuit. The changing magnetic field created by the energized line induces a voltage into the deenergized line. This phenomenon is referred to as magnetic-field induction.

As in the case with electric-field induction, it is convenient to look at the two-conductor case to understand the mechanics of magnetic-field induction. This situation is shown in Fig. 5.

As shown in Fig. 5, the current flowing in conductor a produces a magnetic field that couples conductor a to conductor b. This magnetic field induces a voltage that is longitudinal (i.e., distributed along the length of the deenergized conductor). If the conductor is grounded at a single location, as shown in Fig. 5, the voltage can be measured with respect to ground at any location remote from that point. This phase-to-ground voltage at the end of the line is indicated by $\mathrm{V_{bg}}$ in Fig. 5. The magnitude of this voltage is a function of the current flowing in conductor a, the distance between the lines, and the length that they are paralleled [2], [9]. This relationship is shown in (4)

$$\bar{V}_{bg} = \bar{I}_a \cdot \bar{Z}_{ab} \tag{4}$$

where V_{bg} is the phase-to-ground voltage at some distance from the attachment to ground (in volts per meter), I_a is the phase current flowing in conductor a (in amperes), and Z_{ab} is the mutual

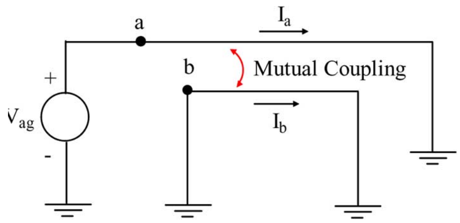

Fig. 6. Electromagnetically induced current.

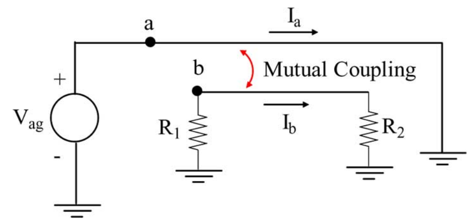

Fig. 7. Electromagnetically induced current including ground resistance.

impedance between conductors a and b (in ohms per meter). In the case of a three-phase transmission line, (4) can be expanded as shown in (5). Note that now the voltage induced is a function of all three-phase currents of the energized line and the mutual impedances between the deenergized line and the energized line. The prime terms in (5) represent the phase conductors of the energized line

$$\bar{V}_{bg} = \bar{I}_{a'}\bar{Z}_{a'b} + \bar{I}_{b'}\bar{Z}_{b'b} + \bar{I}_{c'}\bar{Z}_{c'b}. \quad (5)$$

Adding a second set of grounds to a deenergized line creates a path for magnetically induced currents to flow. Fig. 6 shows a simplistic case where conductor b is grounded at a second point remote from the first. Now a loop is formed and, consequently, current will be induced into conductor b by the magnetic field created by I_a.

The magnitude of the current flowing in the loop shown in Fig. 6 can be shown to be equal to (6)

$$\bar{I}_b = -\frac{\bar{Z}_{ab}}{\bar{Z}_{bb}} \cdot \bar{I}_a \quad (6)$$

where Z_{bb} is the self impedance of conductor b (in ohms per meter), Z_{ab} is the mutual impedance between conductors a and b (in ohms per meter), I_a is the current flowing in conductor a (in amperes), and I_b is the induced current flowing in conductor b (in amperes).

There are several interesting things to note about the induced current given in (6). First, just like the induced voltage caused by electric-field induction, the induced current caused by magnetic-field induction is independent of the length that the two lines are parallel. Note that the units of Z_{ab} and Z_{bb} in (6) cancel, leaving only a constant multiplied by the current flowing in phase a. Thus, the distance between the lines (Z_{ab} is a function of this distance), the series impedance of the deenergized line (Z_{bb}) and the current flowing in the energized line control the amount of current induced into phase b. Also, the direction of the induced current is opposite that of the current creating the magnetic field. As we will see later when the effects of electric-field induction and magnetic-field induction are evaluated simultaneously, this current will either add or subtract from the charging current that will be flowing in the ground connections at each location.

Fig. 6 and (6) can be expanded to include the resistance to remote earth. This expansion is shown in Fig. 7 and (7)

$$\bar{I}_b = -\left(\frac{\bar{Z}_{ab}}{(R_1 + R_2 + R_{bb}) + jX_{bb}}\right)\bar{I}_a \quad (7)$$

where X_{bb} is the self-inductive reactance of conductor b (in ohms), Z_{ab} is the mutual impedance between conductors a and b (in ohms), R_{bb} is the series resistance of conductor b (in ohms), R_1 is the resistance to remote earth at location 1 (in ohms), R_2 is the resistance to remote earth at location 2 (in ohms), I_a is the current flowing in conductor a (in amperes), and I_b is the induced current flowing in conductor b (in amperes). Equation (7) shows that the inclusion of the resistance to remote earth will tend to further reduce the current induced into conductor b by magnetic-field induction. However, it should be noted that (7) does not suggest that the potential work hazard is mitigated. The resulting induced current can still be lethal even with the inclusion of a large series impedance (e.g., a worker).

IV. Work Hazards

There are several hazards present when a worker installs or removes a set of TPGs on a deenergized line that is parallel to one or more energized lines. All of the hazards associated with the presence of parallel energized lines involve the worker becoming in series with a current path.

The first hazard associated with installing TPGs on a deenergized transmission line is the possibility of trapped charge being present on the line. It should be noted that, technically, this hazard is not associated with electric- or magnetic-field induction. However, it is the basis for much confusion associated with voltage and current induction phenomena.

By its very nature, an unloaded transmission line is capacitive. Thus, at the instant a circuit breaker (CB) deenergizes a transmission line by opening at a current zero, the line voltage is very close to its peak value on each phase. Since the line section is no longer connected to the system source, a voltage is left or "trapped" on the line. This results in a net amount of charge being left on the line, and is commonly referred to as "trapped charge." This trapped charge is dissipated over time by such means as line insulation losses, conductance of the line, as well as tapped load and transformers (if any) connected to the line. The amount of trapped charge left on the line at the instant when the first set of protective grounds is applied is a function of the operating voltage of the line prior to deenergization, the point on the current waveform where the line was interrupted, and the time that has elapsed since deenergization. The hazard that is presented by removing the trapped charge is the transient current associated with removing the charge from the line. Unlike the constant hazards of steady-state charging and loop currents, once this trapped charge is removed from the line through proper grounding, it does not return. Calculation of this trapped charge, the associated transient discharge current, and the effects of such current on humans is beyond the scope of this paper. However, its presence should be recognized, and it should be noted that the same methods used to protect the worker from the hazards of steady-state charging and loop currents will also protect the worker from the transient discharge current.

The second, and arguably, the most significant hazard associated with installing or removing TPGs in the presence of parallel energized lines is the charging current created by electric-field induction. The conditions that create this situation are not transient in nature, such as in the previous scenario, but are rather steady state. Thus, this hazard is present anytime a worker is near an ungrounded conductor or is in the process of installing or removing TPGs. The charging current is practically independent of the pole ground resistance, and all reasonable values of worker resistance (i.e., 1 kΩ or less). Beyond 1 kΩ, the charging current begins to decrease; however, lethal values of charging current can still be present with a series resistance values as high as 15 kΩ. It is believed that most fatalities and injuries attributed to induction are the result of a worker inadvertently becoming in series with this charging current. The physical and electrical characteristics of all the lines in the proximity of and in parallel with the deenergized line define these charging currents. The worker cannot do anything to reduce the charging current; it can only be avoided.

Adding a second set of TPGs to the deenergized line at some location remote from the first set of TPGs or contacting a phase conductor at a location remote from the first set of grounds provides the scenario required for the third hazard. Once a second set of TPGs is installed or a worker contacts a phase conductor and ground, current will flow in the resulting loop that is in addition to the charging current. This current is created by magnetic-field induction as depicted in Figs. 6 and 7. Unlike the charging current, this current will be reduced by the addition of the impedance of the worker as evidence by (7). However, due to the current magnitudes associated with magnetic-field induction (e.g., fault current), lethal currents are possible even when high resistance, such as a worker, is placed in series with the ground loop.

The removal of TPGs presents two basic hazards to the worker. One hazard is the possible arcing associated with the removal of the TPG while it is attempting to interrupt either capacitive or inductive current [9], and the other hazard is the possibility of a worker inadvertently getting in series with a current path.

V. Calculation and Field Test Results

To further show the mechanics of induction, a detailed case study was performed. The induced voltage and currents were calculated using WinIGS [10] and compared to field measurements for the system shown in Fig. 8. The line parameters for both lines are shown in Table I.

The loading of the energized line and its operating voltage were provided for several of the tests with the metering function of a protective relay. These values are provided in Tables VI–VIII. The location of Test 1–Test 3 was the second structure outside the generating facility switchyard. Test 4 was conducted at this same location as well as at a location three miles away.

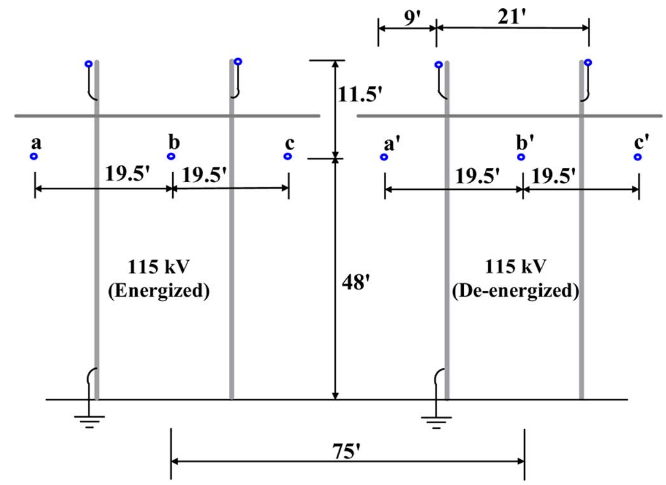

Fig. 8. Line configuration of the study line.

TABLE I
Line Parameter Data for 115-kV Study Line

Phase Conductors	(1) 397.5 26/7 ACSR per phase
Shield Wires	3/8" HSS
Earth Resistivity	1000 Ω-m
Nominal Voltage	115 kV ph-to-ph
Length	Paralleled for approx. 46 mi
Span length	0.25 mi
Average Tower footing resistance	100 Ω

TABLE II
Test 1 Measurement and Calculation Results

	Phase *a'* (kV)	Phase *b'* (kV)	Phase *c'* (kV)
Measured	3.57	1.66	0.80
Calculated	3.80	1.79	1.02

Test 1: The phase-to-ground voltage of each de-energized phase was measured with respect to the grounded shield wire, which for all practical purposes, is remote earth. No TPGs were attached for this test. The measured and calculated values are shown in Table II. Note that the prime notation (a', b', c') refers to the phases of the deenergized line shown in Fig. 8.

Test 2: A TPG was connected from the tower ground to phase a' and the charging current was measured with and without a 1000-Ω resistor in series with the protective ground (see Fig. 9). These measurements and calculated values are shown in Table III.

Test 3: Next, in addition to the TPG connected from the tower ground to phase a', TPGs were placed between phases a' and b' and between b' and c' and the total charging current was measured with and without a 1000-Ω resistor in series (see Fig. 10). These measurements are compared to calculated values in Table IV.

It should be noted that further simulations showed that a worker resistance of 15 000 Ω resulted in a current flow through the worker of approximately 175 mA.

Test 4: Finally, a second set of TPGs without a 1000-Ω resistor was installed three miles away from the first set of TPGs. The grounding configurations for Test 4 are shown in Figs. 11

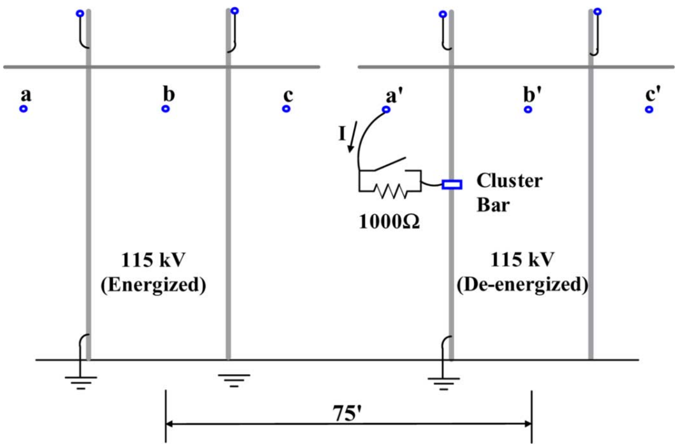

Fig. 9. Grounding configuration for Test 2.

TABLE III
TEST 2 MEASUREMENT AND CALCULATION RESULTS

Charging current (I)	Measured (mA)	Calculated (mA)
Through TPG only	765	792
Through TPG and resistor	741	774

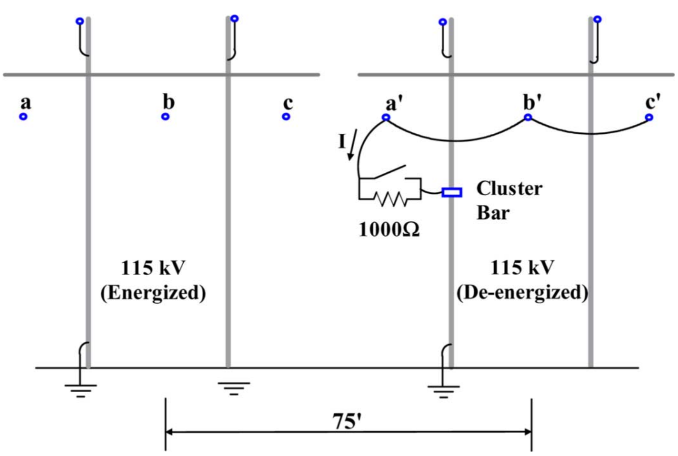

Fig. 10. Grounding configuration for Test 3.

TABLE IV
TEST 3 MEASUREMENT AND CALCULATION RESULTS

Charging current (I)	Measured (mA)	Calculated (mA)
Through TPG	1090	1142
Through TPG and resistor	918	1011

and 12. Note that the grounding arrangement near the switchyard (i.e., the source) is identical that used in Test 3.

The current was measured in the TPG connected from the cluster bar to phase a' at the source end of the deenergized line as shown in Fig. 11. This test was performed with and without a 1000-Ω resistor in series with the TPGs. Next, the current was measured at the site located three miles away as shown in Fig. 12. The measured and calculated results for both locations and scenarios are shown in Table V.

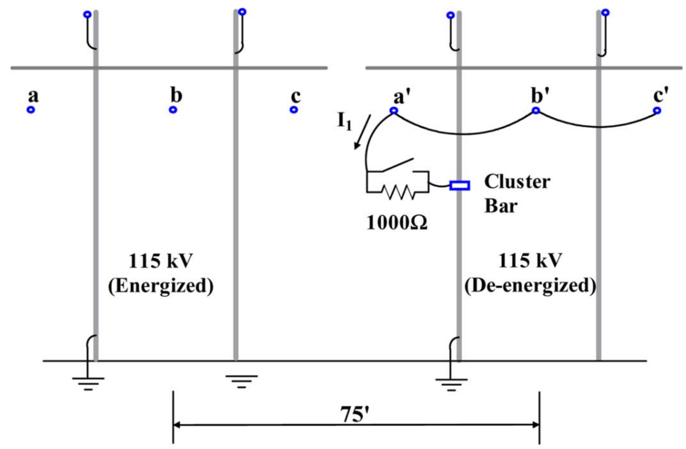

Fig. 11. Grounding configuration for Test 4 (located at the source).

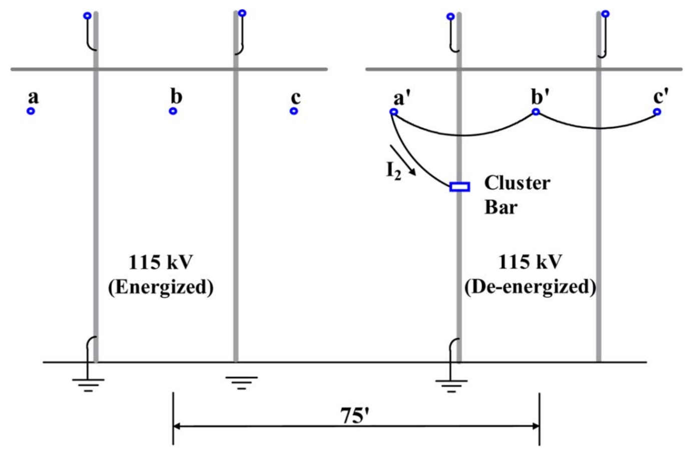

Fig. 12. Grounding configuration for Test 4 (located three miles from the source).

TABLE V
TEST 4 MEASUREMENT AND CALCULATION RESULTS

	Measured I_1 (mA)	Calculated I_1 (mA)	Measured I_2 (mA)	Calculated I_2 (mA)
w/ resistor	37	19	1049	1122
w/o resistor	2275	2315	1194	1248

VI. DISCUSSION

The tests showed that the theoretical conclusions reached by studying the two-conductor model are also valid for more complex systems, and can therefore be used as a means of accurately explaining a very complex subject.

Several field tests were conducted to point out several key elements of induction phenomenon related to work hazards as follows.

1) Although large voltages can be created by electric-field induction, the induced voltage (open-circuit voltage) does not drive current through a provided path (e.g., a worker). Once the line or conductor is grounded, the resulting charging current determines the resulting phase-to-ground voltage. The open-circuit voltage (voltage induced by electric-field induction) never determines the resulting charging current.

2) Once a path is established for the charging current, it is diminished only slightly when a large impedance (1000-Ω resistance) is placed in series with it. This simple fact is what makes charging current such an extreme hazard to line workers. Further simulations showed that lethal levels of charging current were available when 15 kΩ was placed in series with the charging path of the study line.
3) When a second set of TPGs is placed on a line, a loop is formed. The resulting current flowing in the TPGs is the phasor addition of the charging current due to electric-field induction and the circulating current, or loop current, caused by magnetic-field induction. If a large resistance is placed in series with the loop (e.g., a worker), the resulting loop current will be reduced. However, depending on the amount of current flowing in the energized line, the operating voltage of the energized line, the distance between the energized phases, the deenergized phases, and the distance between the TPGs, in many cases, the resulting current can still be lethal.

Test 1 and computer simulation results showed that the induced voltage due to the electric field ranged from 3.57 kV to 0.80 kV, as shown in Table II. These values compared rather closely to the calculated results.

The results of Test 2 can be used to dispel the myth that the induced current caused by electric-field induction can be computed simply using Ohm's law, where V in this case is the induced open-circuit voltage and R is the tower ground footing resistance to remote earth. Once a line has been grounded, the voltage created by electric-field induction is reduced considerably. For practical applications where multigrounded shield wires are utilized, the resulting voltage is generally negligible. However, in cases where insulated shield wires (grounded at a single location) are utilized, these voltages can be excessive. For cases where there is only one connection to ground, the magnitude of the resulting phase voltage is always the product of the charging current of the line and the total resistance to remote earth.

The subject line consisted of approximately 372 structures, and the shield wires were grounded at every structure. The average tower footing resistance was approximately 100 Ω. A current measurement was made in the TPG connecting the phase conductor to the cluster bar as shown in Fig. 9. Since the shield wire was grounded at every structure, the resulting resistance from the cluster bar to remote earth would be very small due to the parallel combination of all 372 structure grounds (see Fig. 13). Thus, using the measured induced voltage and Ohm's Law would result in the false assumption that the resulting charging current would be impeded only by the TPG and the resulting tower footing resistance. The theory presented in this paper, computer simulations, field measurements, and [3] show that this is not the case.

Fig. 13 shows the path that the charging current would take during Test 2 with and without the 1000-Ω resistor in series with the TPG. As shown in (3), the charging current is independent of the induced voltage of the deenergized line and the resistance to remote earth (assuming that the resistance to remote earth is not excessively large (e.g., greater than several kilo-ohms). Thus, the current I_c, shown in Fig. 13, will not be governed by

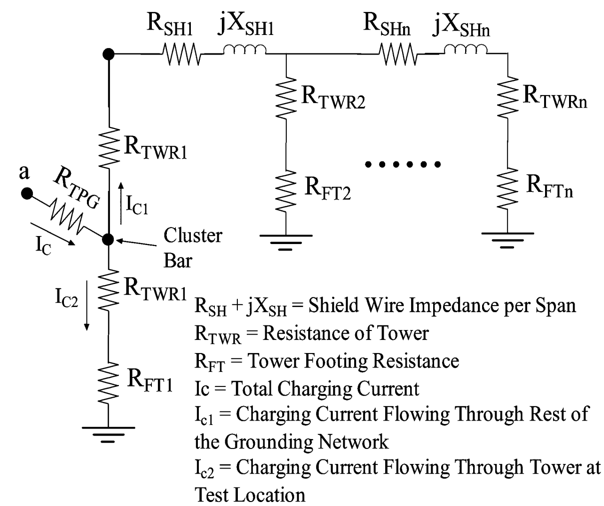

Fig. 13. Charging current path for Test 2.

any of the resistances shown. However, the resistances shown will dictate which path the charging current will take. Due to the low resistance of the multigrounded shield wire compared to the tower resistance and tower footing resistance at the test location, most of the charging current will take the path shown by I_{c1}; however, some portion of the current will take the path of I_{c2}. In most cases of multigrounded overhead shield wires, I_{c2} is below the threshold of measurement. The voltage that is developed as phase-to-ground (remote earth) as a result of the flow of charging current is the product of I_c and the equivalent impedance to remote earth (i.e., the Thevenin equivalent impedance "seen" by I_c). Using the induced voltage and Ohm's Law to compute the resulting charging current would lead one to believe that the charging current would differ greatly between the case with and without the 1000-Ω resistor in series with the TPG. Both test results and computer simulations show that this current only deviated by approximately 3% with the addition of the resistor. Again, this proves that the concepts learned from analyzing (3) are also valid and hold true for three-phase transmission lines. It should be noted, however, that the resulting voltage in both cases was different. Once the charging current is known, the resulting voltage can be found using Ohm's Law. The resulting voltage across the series resistor was found to be approximately 750 V. With the resistor having been removed from the circuit (protective ground only), the resulting voltage was found to be less than 50 V (below the measurement capability of the meter that was used).

Test 3 was simply an extension of Test 2. Here, a typical grounding arrangement was analyzed (see Fig. 10). In this case, the charging current increased from the values found in Test 2. This is due to the fact that all three-phase conductors were bonded together which, in effect, produced a larger conductor (i.e., better capacitor). Thus, more charging current was induced in the line. The same principles apply here, and again it was shown that the presence of a large series impedance did not substantially alter the magnitude of the charging current.

Test 4 was conducted to show the affects of magnetic-field induction. Both sets of TPGs were installed as shown in Figs. 11

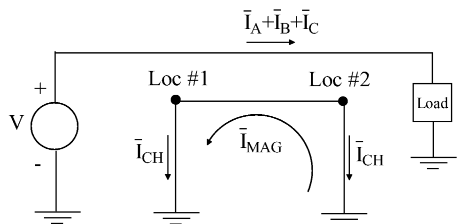

Fig. 14. Superposition of charging current and magnetically induced current.

and 12. Once the second set of TPGs was installed approximately three miles away, a loop was formed and at that point, a second path for charging current and a path for magnetically induced current were created. Measurements were made at both locations in order to compare values. Prior simulations indicated that although a current loop was formed and the TPG installations were identical at both locations (i.e., with the resistor bypass switched shown in Fig. 11 closed), there would be a difference in the amount of current flowing through each set of TPGs. Further analysis showed that the difference in current was attributed to the phasor addition of the charging current (electric-field induction) and the loop current (magnetic-field induction) at each TPG location as shown in Fig. 14.

The addition of a second TPG simply means that there is a second path for the charging current to flow. In theory, if the resistance to remote earth was the same for both paths, the charging current would be split equally between the two paths. The current induced in the loop by magnetic-field induction, on the other hand, will flow in the opposite direction of the phasor sum of the three load currents flowing in the energized line (i.e., $3I_0$), assuming that the mutual impedances between the deenergized line and the energized line are approximately equal. The resulting current flowing in the two sets of TPGs will be the superposition of these two currents (i.e., charging current and loop current). Therefore, one set of TPGs will experience higher current flow than the other set. The addition of a series resistance into the circuit greatly reduces the magnetically induced current, but will not impede the total charging current. However, since there are still two possible paths for the charging current to flow, the charging current will divide according to the differences in resistance of the two paths. Therefore, the end of the line that does not have the resistor installed will experience the highest current flow when the series resistor is in the circuit. As shown in Table V, this was found to be exactly the case. Location #1 was a generating facility; therefore, it can be assumed that the load current in the energized line is flowing from Location #1 towards Location #2 (the location three miles away). Thus, the direction of the induced current caused by magnetic-field induction (i.e., the loop current) will be from Location #2 toward Location #1. The direction of the charging current will be from the bonded conductors toward the tower as shown in Figs. 13 and 14. The current flowing in the TPGs at Location #1 will tend to be increased by the magnetically induced current; whereas the current flowing at location #2 will tend to be decreased by this same current. The result is that the currents at both ends of the line will be different from one another. In practice, this difference will be a function of line geometry, line loading, and the series impedance of the loop. With the 1000-Ω resistor in the circuit, the magnetically induced current is diminished, and the resulting current is, for all practical purpose, the charging current of the line. However, with the resistor in the circuit, most of the charging current flows through the TPGs located three miles away.

Further analysis of the field tests and simulation results showed that differences between the two are caused by the assumed modeling parameters (e.g., tower footing resistance, tower height, distance between lines, etc. and measurement error). In most cases, the difference between the measured and calculated values was negligible; however, the percentage difference in one of the measurements associated with Test 4 (current flowing in source TPG with the resistor in the circuit) suggested that further studies be done to determine the source of the error. Further analysis showed that the tower footing resistance plays an important role in determining the charging current flowing through the resistor and TPG combination when two sets of TPGs are installed. Lowering the footing resistance of the tower where the TPGs are installed affectively reduces the Thevenin equivalent resistance to remote, resulting in an increase in the charging current at this location and, thus, the total current flowing through the TPG. The location of the transmission tower where the "source" measurements were made was only a few hundred feet from a large substation ground grid, thus reducing the effective tower footing resistance of the subject tower.

VII. Conclusion

The primary electrical hazard for workers involved in the construction or maintenance of deenergized lines in proximity to energized lines is current. There has been much emphasis placed on determining the induced voltage caused by electric-field induction [1]–[3], [8]. However, as shown through computer simulations and field tests, this voltage does not drive current through a worker's body. The induced current due to the electric field is a function of the line parameters and the operating voltage of the energized line(s), and is not mitigated by the resistance of the worker's body. Once a second set of TPGs is installed on a line or if a worker comes in contact with a phase conductor and ground at a location remote to the TPGs, a current loop is formed. The resulting induced current is produced by magnetic- and electric-field induction. The current produced by magnetic-field induction will be reduced by the presence of additional series impedance (i.e., a worker's body); however, the resulting current can still be lethal.

The tragic thing about injuries and fatalities associated with induced voltages and currents is that most, if not all, incidents could have been prevented if proper work rules had been strictly followed. Avoiding contact with floating conductors and maintaining the proper order of installation and removal of TPGs is essential to maintaining a safe work environment. Also, as we saw with the induced current caused by magnetic-field induction, care must be taken when working remotely from TPGs.

Individuals who work on deenergized lines must be taught two simple concepts as follows.

1) Avoid getting in series with the path for charging current or loop current. A worker is most at risk when TPGs are being installed or removed.

TABLE VI
LINE LOADING OF ENERGIZED LINE DURING TEST 1

	Phase A	Phase B	Phase C
Current Mag (A)	248	266	256
Current Ang (deg)	6.8	-114	122
Voltage Mag (kV)	66	67	66.8
Voltage Ang (deg)	0	-120	119.6

TABLE VII
LINE LOADING OF ENERGIZED LINE DURING TESTS 2 AND 3

	Phase A	Phase B	Phase C
Current Mag (A)	244.8	261.7	251.3
Current Ang (deg)	8.3	-113	123
Voltage Mag (kV)	66.8	67.2	66.8
Voltage Ang (deg)	0	-120	119.6

TABLE VIII
LINE LOADING OF ENERGIZED LINE DURING TEST 4

	Phase A	Phase B	Phase C
Current Mag (A)	220.5	236.7	226.7
Current Ang (deg)	10.3	-111	125
Voltage Mag (kV)	66.8	67.2	67
Voltage Ang (deg)	0	-120	119.7

2) Strictly follow the rules of "order of connection" and "order of removal." According to OSHA 1910.269, the order of connection is as follows: When a ground is to be attached to a line or to equipment, the ground-end connection shall be attached first, and then the other end shall be attached by means of a live-line tool. Likewise, the order of removal is as follows: When a ground is to be removed, the grounding device shall be removed from the line or equipment using a live-line tool before the ground-end connection is removed.

It should also be pointed out that parallel lines that are out of sight of the work location can still produce lethal currents and voltages. Lines running parallel to the line in question induce the most voltage and current. Lines running perpendicular to the line in question will induce negligible voltages and currents [3].

There are many misconceptions prevalent in the industry about electromagnetic induction and its effects on worker safety at the work site. As a result, it is imperative for personnel who are involved in the construction and/or maintenance of transmission lines be properly trained on the subject so that work hazards can be properly avoided. Simple work rules and/or guidelines should be provided to remove the hazards that workers recognize and those that they do not. The information presented in this paper can be used to present this very complex phenomenon in a simple and accurate manner.

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