De-energized Lines Can Still Start Fires. Understanding the Risks and the Effects of Grounding

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***Abstract*-- The fire risk associated with energized transmission and distribution lines is well known, and protection tripping to de-energize a line is commonly viewed as the method that eliminates the electrical energy that can cause combustion. In recent years some utilities have been proactively de-energizing lines during extreme wind events to prevent the possibility of sparking catastrophic wildfires. This is often referred to as Public Safety Power Shutoff (PSPS). It is common to refer to a line as de-energized once the voltage sources have been removed by opening their respective breakers, but due to the proximity of adjacent energized lines these "de-energized" lines can carry appreciable voltages that can present both a shock hazard and a fire hazard.**

The risk associated with catastrophic wildfires caused by utility infrastructure is of paramount importance to many utilities, and the purpose of this paper is to bring an awareness of the wildfire risk associated with de-energized lines. At the author's utility many cases of broken hardware, downed conductors, and vegetation contact have been documented on lines during these high wind related PSPS events. Due to the concern over possible ignitions caused by de-energized lines a proposal was made to intentionally ground lines cleared for PSPS events or long duration clearances. Studies were conducted and field measurements made on cleared lines to quantify the relative risks of intentionally grounding a line versus leaving it ungrounded in the event that hardware failure or vegetation contact results in a path of current flow to ground that can spark a fire. Studies have shown that as little as 10 mA of current can ignite a fire.

The unique electrical properties of the two distinct mechanisms by which de-energized lines can carry voltage will be discussed. The first is the voltage developed by the electric field dropped across the mutual capacitance between the energized line, de-energized line, and earth, and its magnitude is related to the voltage level of the energized line. The second is the voltage induced in the de-energized line by the magnetic field associated with the current flowing in the energized line. The risks associated with grounding a de-energized line versus leaving it ungrounded will be discussed, along with the results of actual field testing on de-energized lines and EMTP simulations. The often unappreciated paradox between Faraday's Law, which states that the voltage around a closed loop is equal to the time changing magnetic flux inside the loop, and Kirchoff's Voltage Law, which states that the voltage around a closed loop sums to zero, will be discussed, with the analysis of induced voltages on de-energized lines serving as an excellent example to reconcile this paradox.

***Index Terms*—Electromagnetic induction, EMTP, grounding, wildfires.**

I. Introduction

THERE has been an enormous effort in recent years by utilities in regions that are plagued by wildfires to address the risk of electrical equipment sparking fires by developing faster protection schemes that de-energize faulted lines as quickly as possible, even exploring non-traditional schemes that purport to identify precursors to faults such that a line can be de-energized before the fault develops. Additionally, Pacific Gas and Electric Company (PG&E) has a Public Safety Power Shutoff (PSPS) program that involves de-energizing distribution and transmission lines in high wildfire threat areas during extreme wind events in order to prevent catastrophic wildfires. Though it is easy to become complacent with the idea that galvanically isolating (i.e. clearing) a line removes the risk of sparking a fire, we've long been aware of the risk of electrocution posed to linemen when working on de-energized lines, and extending this understanding to the risk of a de-energized line igniting a fire only requires us to imagine the right fuel source and weather conditions. Furthermore, fires started in recent years when grounding de-energized lines have removed any doubt of the capacity of de-energized lines to start fires.

One example in the PG&E system involved a grounded 500kV line, where sparking and burnt grass were observed at the base of a transmission tower, and boiling water was observed in a small puddle near the base. Another incident involved removing a temporary protective ground (TPG) from a 500kV line which drew an arc that ejected hot metal particles from the surface of the conductor or ground clamp which fell to the dry grass below, starting a small grass fire. Although both of these incidents involved voltages induced on de-energized 500kV lines, studies [1] have shown that as little as 10mA of current can ignite a fire if the condition is allowed to persist long enough, and the example in section IV below will demonstrate that currents well above this level are easily met on much lower voltage lines.

During high wind events when PSPS is initiated there is an increased risk of fault conditions on a de-energized line (debris, vegetation contact, failed equipment, etc. due to high winds) which can cause sparks and fires just like these events that occurred during the process of grounding 500kV lines. If the risk of starting a fire at the location that grounds are applied is addressed, electrical energy can be reduced for subsequent faults by applying grounds on a de-energized line. While applying grounds on de-energized lines might not be possible during the accelerated timeframe of a PSPS event, lines that are de-energized for extended clearances offer an opportunity to study the effect of grounding on reducing the electrical energy present on a de-energized line, thereby reducing the fire risk. Furthermore, idle lines are a subclass of de-energized lines that are either permanently abandoned or temporarily out of service, and they present the unique opportunity of dividing the line into many smaller segments as a fire mitigation strategy, either by opening up jumpers or creating insulated open points.

II. Basic Physics of Induced Voltages and Currents

There are two distinct mechanisms which create induced voltages and currents on lines that are de-energized but mutually coupled with energized lines. The first, shown in Fig. 1, is a result of the electric field that originates from the energized conductor, dropping across the mutual capacitance of the two lines to ground. The second, shown in Fig. 2, is a result of the magnetic field that circulates around the energized conductor, coupling with the mutual inductance of the two lines.

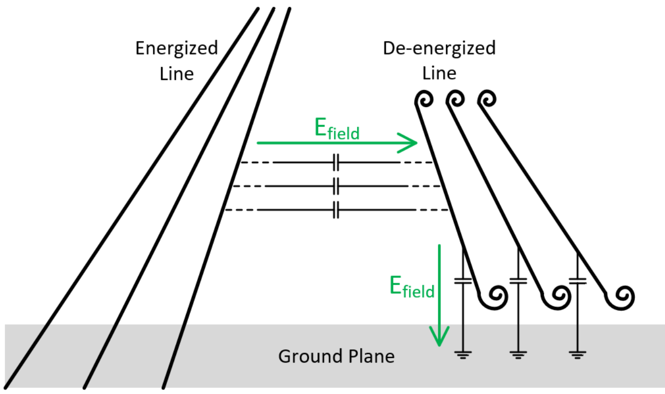

Fig. 1. Electric field dropped across mutual capacitance of lines creating induced voltage on the de-energized line.

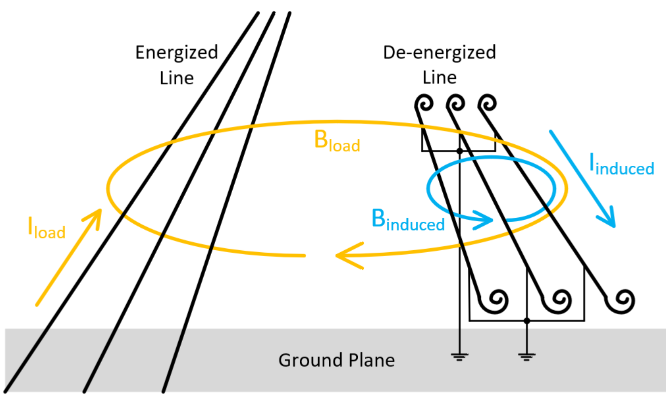

Fig. 2. Magnetic field from load current inducing current on the de-energized line that is grounded on both ends.

A. Electric Field and Mutual Capacitance

The electric fields produced by the individual phases of the energized line permeate the surrounding space, with the net sum of these individual fields resulting in a net electric field shown dropped across the mutual capacitance of the two lines shown in Fig. 1. If we could conceptualize the energized conductors as occupying the exact same space, and if the voltages were perfectly balanced positive-sequence, then the net electric field in Fig. 1 would sum to zero, but of course neither of these assertions are true, and the net electric field will depend on the geometry of the conductors and will be directly proportional to the voltage of the energized line.

As the distance between the two circuits is increased the difference between the phase angles of the voltages induced on the individual phases of the de-energized line will decrease due to their relatively close proximity to each other when compared with the distance between the energized and de-energized lines. For simplicity it will be useful going forward to deal only with single-phase circuits, with the understanding that the same basic principles apply to three-phase circuits. Three-phase circuit analysis can be left to an electromagnetic transient program (EMTP) which can handle these complex calculations with alacrity.

The single-phase circuit in Fig. 3 shows the electric field produced by the energized line which drops across the mutual capacitance of the energized line and de-energized line to ground. The voltage to ground is constant along the length of both the energized and de-energized lines assuming constant geometry is maintained, a point worth noting when contrasted with the less intuitive voltage profile caused by magnetic induction that will be detailed later. If the de-energized line in Fig. 3 was grounded (either intentionally or by a fault condition), then the resultant current flow to ground would lead the induced voltage by 90 degrees. It can be understood that the induced voltage does not depend on the length of the line by noting that electric field at any point on the line is unaffected by what's going on at a distant location down the line. The capacitance, however, will increase in proportion to the length of the line.

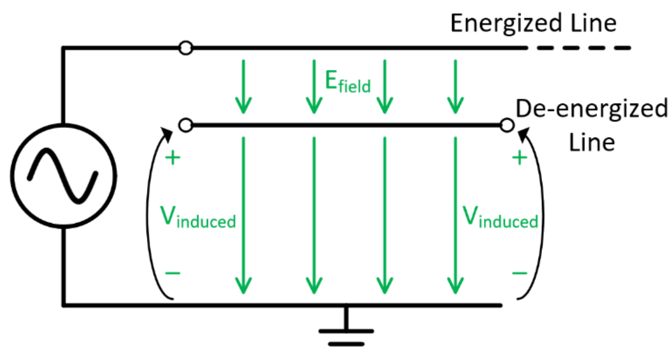

Fig. 3. Single-phase circuit representation of electric field induction on de-energized line.

Because the voltage of the energized line is unaffected by the electrical connections of the de-energized line (i.e. whether it is grounded or left ungrounded), this circuit can be reduced to the Thevenin equivalent shown in Fig. 4, with a voltage source that is directly proportional to the voltage of the energized line, and with a capacitance that is directly proportional to the length of the line. Once the de-energized line is shorted to ground (either by intentionally applying grounds or if a fault occurs) the current flow will be proportional to the length of the line, with the impedance 1/jωC of the capacitor in Fig. 4 being inversely proportional to the line length.

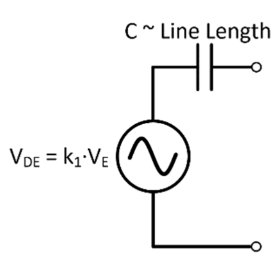

Fig. 4. Thevenin equivalent of the effect of electric field induction. Voltage of de-energized line (V_{DE}) is proportional to energized line voltage (V_E), and capacitance is proportional to line length.

B. Magnetic Field and Mutual Inductance

The net sum of the magnetic fields circling the current flowing in the individual phases of the energized line results in a single magnetic field coupled with the mutual inductance of the two lines shown in Fig. 2. If we could conceptualize the current carrying conductors as occupying the exact same space, and if the currents were perfectly balanced positive-sequence, then the net magnetic field in Fig. 2 would sum to zero, but since neither of these assertions are true, the net magnetic field will depend on the geometry of the conductors and will be directly proportional to the current flowing on the line. Additionally, a fault on the energized system, particularly a ground fault, would create a significant magnetic field up to many orders of magnitude larger than that caused by load flow.

The single-phase circuit in Fig. 5 shows the magnetic field produced by the energized line which permeates the area in between the de-energized line and ground. The voltage induced in the de-energized line by this mutual inductance follows Faraday's law which states that the voltage in a circuit is proportional to the rate of change of the magnetic flux in the circuit, with half of the voltage appearing at each end of the open de-energized line and of opposite polarity such that the sum total of the circuit voltage equals the negative of the time rate of change of the magnetic flux in the circuit. Unlike the current flow through the mutual capacitance, once an initial ground is applied the current induced by the magnetic field only flows when subsequent grounds are made after the initial ground connection (grounding switch, TPG, or fault). Shown in Fig. 6, the voltage at the ungrounded end of the line follows Faraday's law, and if the open end was grounded as in Fig. 7 (grounding switch, TPG, or fault), then the resultant current flow to ground would lag the induced voltage by 90 degrees. The induced current would flow as required to cancel the flux produced by the energized line. It can be understood that the induced current does not depend on the length of the line by noting that flux created by the energized line increases linearly with the length of the line, but so does the cancelation flux produced by the induced current, and therefore the induced current varies proportionally with the energized line current, and does not depend on the line length. The induced voltage in Fig. 6 on the other hand does increase proportionally with the length of the line.

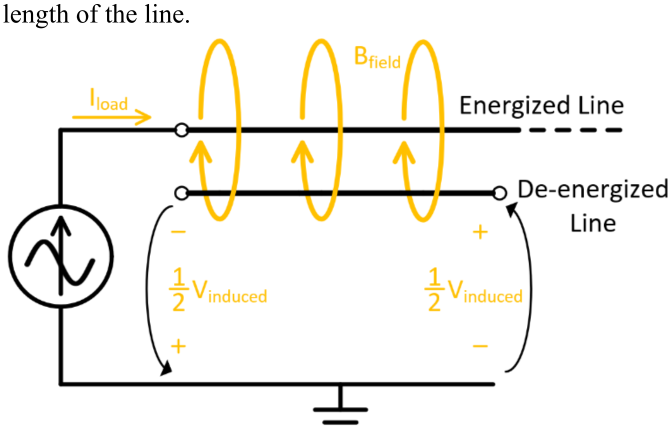

Fig. 5. Single-phase circuit representation of magnetic field induction on de-energized line, both ends open.

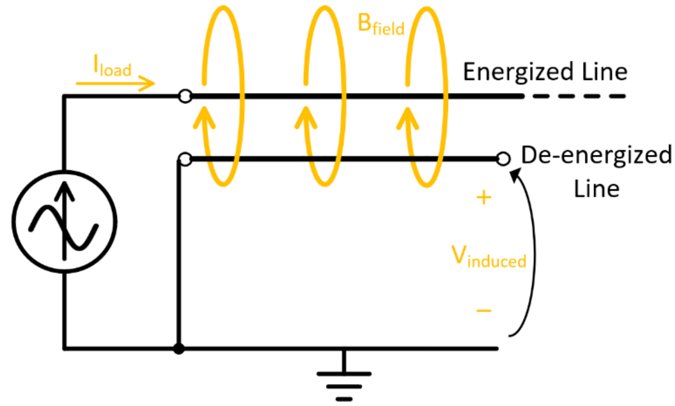

Fig. 6. Single-phase circuit representation of magnetic field induction on de-energized line, one end grounded.

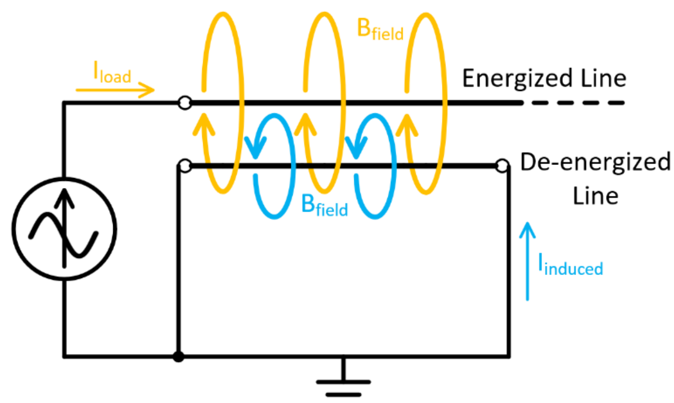

Fig. 7. Single-phase circuit representation of magnetic field induction on de-energized line, both ends grounded.

Because the current of the energized line is unaffected by the electrical connections of the de-energized line (i.e. whether it is grounded at both ends or left ungrounded), the circuit of Fig. 6 can be reduced to the Norton equivalent shown in Fig. 8, with a current source that is directly proportional to the current flowing on the energized line, and with an inductance that is directly proportional to the length of the line. The current flow on the energized line is converted into flux via the inductor L in Fig. 8 which manifests as a voltage across the open terminals that will increase with increasing line length, but a subsequent short across these terminals will result in fixed current that is independent of the line length and proportional to the current flow on the energized line.

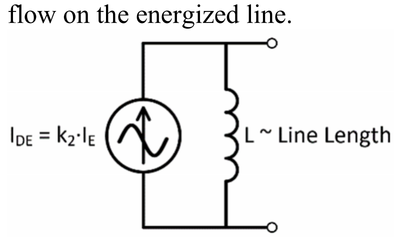

Fig. 8. Norton equivalent of the effect of magnetic field induction. Current flow on shorted down de-energized line (I_{DE}) is proportional to current flow on energized line (I_E), and inductance is proportional to line length.

C. Shortcomings of KVL

There is a paradox at the heart of two of the basic equations used by electrical engineers. The first is Kirchoff's voltage law (KVL) which states that the sum of the voltages around any closed loop is zero.

$$V_{closed\ loop} = \sum_i V_i = 0$$

The second is Faraday's law of induction, which states that the sum of the voltages around any closed loop equals the negative of the time rate of change of the magnetic flux in that loop.

$$V_{closed\ loop} = \oint \boldsymbol{E} \cdot d\boldsymbol{l} = -\int \frac{\partial \boldsymbol{B}}{\partial t} \cdot d\boldsymbol{A}$$

Since we're dealing with 60Hz sinusoids, we can restate this by saying that the voltage around a closed loop is proportional to the flux, a direct contradiction to KVL which states that it is zero. It is easy to forget that the derivation of KVL, as Richard Feynman put it, relies on the assumption that "there is no magnetic field in the region outside the individual circuit elements" [2]. Most electrical engineers rarely use Faraday's law and are perfectly content applying KVL without ever confronting this paradox, and this works as long as we stay within the bounds of lumped circuit analysis, but Faraday's law is essential to understanding the internal workings of the most enigmatic of these lumped circuit components: the inductor.

To demonstrate how easy it is to unnerve our KVL wired brains we need only to look at a simple two resistor circuit which has voltage induced by an external source (Fig. 9) providing a 60Hz sinusoidal magnetic (B) field.

If the B field that is applied by the external source is coming out of the page (Fig. 9), then this will induce current in the circuit to flow such that the resultant induced B field (into the page) will tend to cancel the externally applied B field. If the resistors were removed and you just had a shorted loop, then by Faraday's law the total magnetic flux (Φ) in the circuit would be zero since the voltage along a short must be zero, the induced current being the source of this induced B field which accomplishes the requisite flux cancellation.

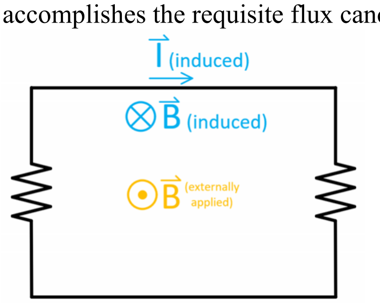

Fig. 9. Current and magnetic field induced by externally applied magnetic field.

Returning back to the case of two resistors (Fig. 10), if the induced current was equal to 1A, and we had two different resistance values of 1Ω and 5Ω, then I would read -1V if I placed a voltmeter on the left side of the circuit, and 5V if I placed a voltmeter on the right side of the circuit.

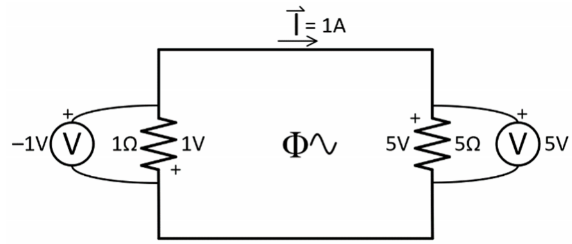

Fig. 10. Two resistor circuit with different voltages on the left and right sides of the circuit.

The assiduous observer might resolve this conundrum by inserting one of their favorite lumped components into the circuit, the mutual inductor, drawing a 6V drop across the mutual inductor in order to satisfy the KVL requirement that the total voltage drop around the circuit equals zero. When used in this way KVL always holds true, but what is good for computational analysis is not always the best approach for an intuitive understanding of the underlying physics [3]. The reality is that there is no such 6V drop across the wire that extends from the 1Ω resistor to the 5Ω resistor—there can be no such voltage drop across a piece of conductor.

If I set aside KVL for the time being and instead turn to Faraday's law, I can break apart the lumped component and better understand what goes on inside inductors. For example, in Fig. 11, when I slide the voltmeter to the middle of the circuit, I now effectively have two circuits, divided by the high impedance voltmeter. Each half will contain half of the original flux, assuming the flux is evenly distributed. If the original flux created 6V, then the voltage in each half should sum to 3V, which will hold true if there is a 2V drop across the voltmeter.

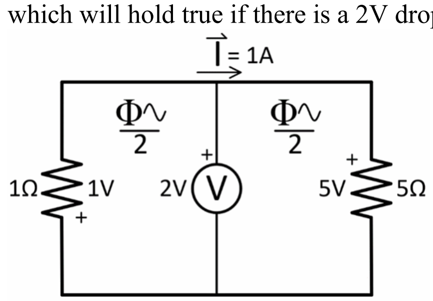

Fig. 11. Two resistor circuit with voltmeter in the middle of the circuit.

If we now uniformly distribute this 6Ω total resistance along the length of the circuit (Fig. 12), and assume that the flux is uniformly distributed along the length of the circuit, we have something that looks more like a transmission line that is grounded on both ends. With 1A of induced current, then the total flux in the circuit per Faraday's law is proportional to the 6V dropped across the 6Ω resistor.

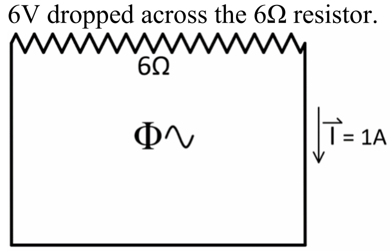

Fig. 12. Uniformly distributed 6Ω resistance.

If we connect a voltmeter at, for example, a location 1/3 of the way down the circuit (Fig. 13), then the new left circuit will contain 1/3 of the original flux which is equivalent to 2V, and the right circuit will contain 2/3 of the original flux which is equivalent to 4V. Since these voltages exactly match the voltages dropped across the 2Ω and 4Ω resistances respectively, there is no remaining potential to be dropped across the voltmeter, which therefore yields a reading of 0V.

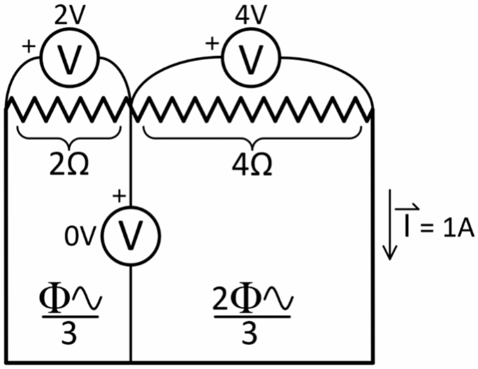

Fig. 13. Uniformly distributed 6Ω resistance with voltmeter one third of the way down the circuit.

If we shorted the circuit at this same 1/3 location (Fig. 14), then we would get 0A of current flow through the short (the 1A flowing through the 2Ω resistor due to the 2V drop is matched by the 1A flowing through the 4Ω resistor due to the 4V drop, with no remaining current to flow down the short).

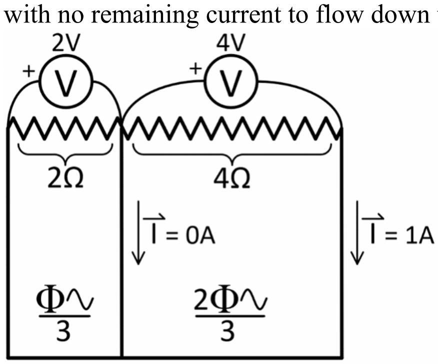

Fig. 14. Uniformly distributed 6Ω resistance with short one third of the way down the circuit.

If the magnetic field is not uniformly distributed along the line (Fig. 15), then we can get an uneven distribution of flux, where the left third of the circuit contains half of the total flux, and the right two thirds of the circuit contains the other half of the total flux.

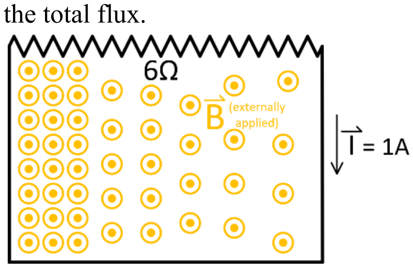

Fig. 15. Non-uniformly distributed magnetic field.

With the voltmeter connected at the 1/3 point in Fig. 16, the left circuit loop contains half of the flux just as the right circuit loop does, and so the total voltage around each of those loops must sum to 3V (corresponding to Φ/2). A 1V drop across the voltmeter accomplishes this (KVL around the right loop for example is -1V+4V), and we now have a potential difference from line to ground.

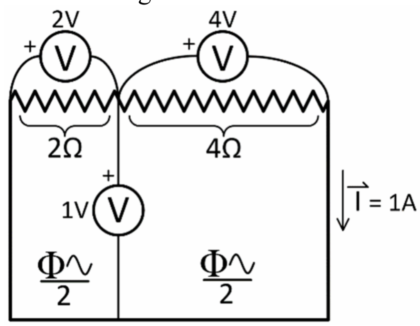

Fig. 16. Uneven distribution of flux due to non-uniformly distributed magnetic field.

If we shorted the circuit at this same 1/3 location (Fig. 17), and assuming that the left 1/3 of the circuit and the right 1/3 of the circuit still each contain half of the flux respectively (which is equivalent to 3V), then we now have the current distribution through the resistors as shown in Fig. 17, with current flow through the short equal to 0.75A due to this uneven distribution of flux, and we now have the equivalent of current flow from line to ground. Note that for simplicity I'm assuming that the net flux is unchanged once the short is applied, but for this to be accomplished the external source applying the flux would have to be increased to compensate for the cancellation flux produced by the induced current flow.

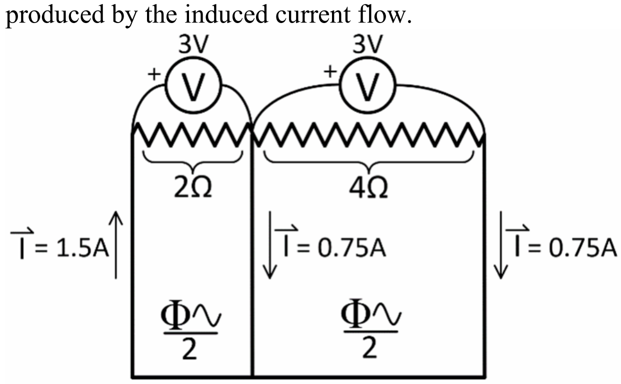

Fig. 17. Non-uniformly distributed magnetic field with short one third of the way down the circuit

This analysis suggests that the voltage due to magnetic induction, and subsequent short circuit current, can be driven down to zero if the grounds on both ends of a transmission line have negligible resistance, and if the conductor resistance is constant and the magnetic flux induced by the energized line is uniformly distributed along the length of the line. Low grounding resistance can be achieved through substation grounding switches, TPGs applied at substations or well grounded structures with low soil resistivity, or on lines with static wire where the parallel ground connections of the towers achieve a net low resistance to ground. Non-uniformity in magnetic flux distribution can be due to either a change in the proximity of the energized and de-energized lines, or a change in the configuration of either the energized or de-energized line, for example a change in transmission tower configuration (e.g. vertical to horizontal conductor configuration) or due to transpositions on the line, a topic we will revisit in more detail following.

III. Transmission Line Grounding

Now that we've reviewed electric field induction through mutual capacitance and magnetic field induction through mutual inductance, we will apply this knowledge to various transmission line grounding configurations and discuss the effect with regard to the risk of starting a fire if a conductor on the de-energized line makes contact with a fuel source (e.g. vegetation), or causes sparks which subsequently reach a fuel source (e.g. conductor arcing to another conductor or tower), which I'll refer to as faults on the de-energized line.

Although the following sections demonstrate how fault current can be limited, further study into the complex topic of electrical fire ignition is needed for comprehensive understanding of how to mitigate fire risk. The lines modeled in the following sections manifest a relatively high voltage and high source impedance characteristic for the effect of mutual capacitance, and a relatively low voltage and low source impedance characteristic for the effect of mutual inductance. Although it appears that appreciable voltages are required to ignite the dry vegetation that would be considered a wildfire risk (favoring electric field induction as the higher risk factor), the lower voltage and higher current characteristic typically resulting from magnetic field induction could pose a higher ignition risk if there's excessive heating of the earth floor as in the example of the TPG applied to a 500kV line given earlier, or if clashing conductors or a conductor contacting a tower results in current induced sparks which fall to dry vegetation on the ground. These unknown factors make it much more difficult to decide whether or not to apply grounds on a line during an emergency situation like PSPS, where time is of the essence, and both the ability to physically place grounds as well as determine the effectiveness of those grounds (due to changes in soil resistivity by geography) is extremely limited.

A. Ungrounded Line

The most straightforward way to handle de-energized transmission lines is to leave them ungrounded. This is a particularly appealing option for emergency switching such as PSPS which requires quickly de-energizing multiple lines, with the goal to return these lines to service as quickly as possible once the extreme fire risk subsides. This is also an appealing option for idle lines which can be broken up into small sections, thereby reducing the capacitive current flow during a fault on those sections.

Since current flow due to magnetic field induction only occurs with two or more ground connections, a fault on the ungrounded line would result in current flow by the effect of electric field induction alone, which for typical lines has the relatively high voltage and high impedance characteristic shown in the Thevenin equivalent of Fig. 4. This situation poses a unique fire risk due to the fact that fault current flow will remain relatively constant throughout a range of resistance values. Field tests [4] confirm that inserting a 1000 Ω resistor in series to ground changes this capacitive current flow by only a negligible amount. Factors that increase fire risk include operating voltage of the energized line and the length of the line which affects the capacitive current flow. Line configuration and the proximity between the cleared line and energized line are additional factors that increase fire risk that are common to this section and the following sections.

B. Single Ground

In the case of a single ground applied on a de-energized transmission line as shown in Fig. 18, we now have to consider the effect of both electric field induction and magnetic field induction.

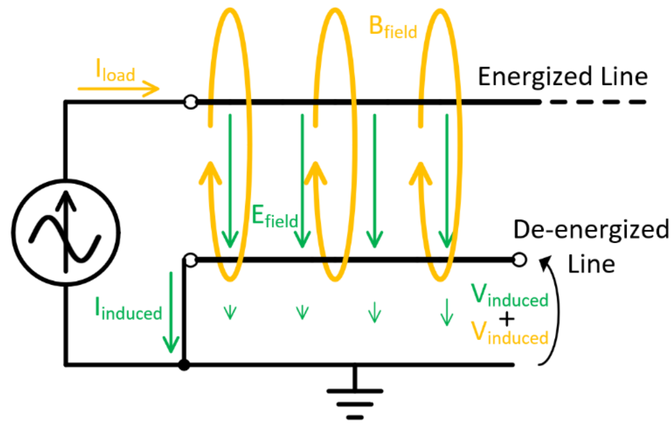

Fig. 18. De-energized line with single intentional ground.

At the location of the single ground, current will flow due to the electric field induction through the mutual capacitance of the lines. Unlike the case of a grounding switch inside of a substation, the risk of starting a fire at the location of a TPG needs to be considered since constant current will be supplied over a range of ground resistance values, and there is a possibility of catching ground vegetation growth on fire if an adequately low ground resistance cannot be accomplished. Factors that increase fire risk at a TPG location include operating voltage of the energized line and the length of the line which affects the capacitive current flow.

A fault on this line will experience both the effect of electric field and magnetic field induction. The current flow through the mutual capacitance will be split through the established single ground and the fault location depending on the impedance of the ground, the fault, and the line. The current flow due to magnetic field induction will circulate in the loop established by the single ground and the fault.

When compared with the ungrounded line, both electric and magnetic field induction affect the fire risk at the fault location on a line with a single ground. There is a decrease in fire risk associated with electric field induction as the induced voltage has been clamped down by the applied ground, and the current flow has two paths, one through the applied ground and the other through the fault, with the majority of current flowing through the typically much lower resistance path of the applied ground. But there is an increase in fire risk associated with, and due to the introduction of, magnetic field induction, and factors that increase this risk include current flow on the energized line and length of the line which affects the magnetically induced voltage. Single-point grounding at the middle of the line can decrease the induced voltage at the open end since the length from the ground to the open end is now cut in half, but the effectiveness of the grounds at that location (e.g. tower footing resistance) and fire risk at that location would have to be carefully considered.

C. Grounded at Both Ends

If we grounded the open end of the de-energized line in Fig. 18 such that it is grounded at both ends of the line, then the resulting current flow will be due to both electric field induction and magnetic field induction. Unlike the case of a grounding switch inside of a substation, the risk of starting a fire at the location of a TPG needs to be considered since it is in a field environment with potentially significant ground resistance, and significant current flow can result from the combination of electric and magnetic field induction (enough to boil ground water as in the case of the 500kV line mentioned in the introduction), and even much larger currents if there is a ground fault on the energized system.

A fault on this line that is grounded at both ends will see current flow that is reduced when compared to the fault on a line with a single ground. Current flow due to electric field induction now has multiple ground paths to take as opposed to the path through the fault, and as we saw in the circuit analysis of section II, the fault current flow due to magnetic induction will be a fraction of the current flow that results when only a single ground is applied, with this value approaching zero if the grounds have low resistance and if the conductor resistance is constant and the magnetic flux is uniformly distributed over the length of the line.

When compared with the ungrounded line, there is a decrease in fire risk associated with electric field induction as the induced voltage has been clamped down by the two applied grounds, and the current flow has multiple paths, with the majority of current flowing through the typically much lower resistance path of the two applied grounds. There is an increase in fire risk associated with magnetic field induction, and factors that increase this risk include current flow on the energized line, the length of the line which affects the magnetically induced voltage, the non-uniformity of the magnetic field distributed along the length of the line, a change in conductor resistivity, and the resistance of the two applied grounds. If the conductor resistance is constant and the magnetic field is uniformly distributed along the length of the line (conductors maintain the same configuration, the distance between the energized and de-energized lines is constant, there are no transpositions), and the resistance to earth of the applied grounds if reduced to zero, then the fire risk associated with magnetic field induction for faults along the line can be significantly reduced. Such a configuration shifts the fire risk to the locations of the grounds themselves, which might be acceptable if the fire risk at those locations can be mitigated.

D. Multiple Grounds

Multiple grounds further reduce fault current flow due to electric field induction due to the increased paths through ground for the current to take. Furthermore, one can judiciously choose the location of these multiple grounds such that the magnetic flux between grounds is uniform, driving the fault current due to magnetic induction down to zero, as demonstrated in the following example.

E. Example: Double Circuit Line

Shown in Fig. 19 is an example of two mutually coupled lines which illustrates the grounding methods previously discussed in this section. Between Station A and the junction (5 miles from Station C) runs a double circuit line of the vertical configuration and dimensions shown in Fig. 20. After the junction, going to Station B and Station C, the lines run with the same vertical configuration, but they are no longer mutually coupled as they run in separate corridors. Also shown is a single transposition which introduces a change in the magnetic flux profile along the line (a transposition on either circuit in the mutually coupled section would cause this non-uniformity in the magnetic flux profile). These lines were modeled using an EMTP, with a SLG A-phase fault placed on the de-energized line 5 miles from Station A as shown in Fig. 19 for a variety of grounding configurations, with the pre-fault voltage and fault current recorded in Table I for 0 Ω faults and Table II for 100 Ω faults.

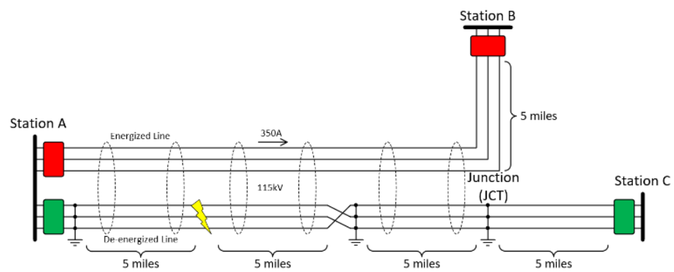

Fig. 19. Example of two lines mutually coupled between Station A and the Junction (JCT).

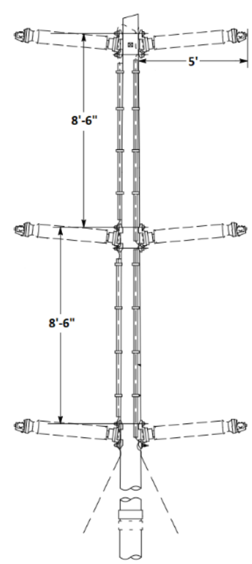

Fig. 20. Double circuit, vertical configuration.

TABLE I

Prefault Voltage and Fault Current for 0 Ω Fault in Fig. 19

Grounding Applied	**V_A (prefault, V)**	**I_A (fault, A)**
None	2060	0.188
Station A	102	14.4
Station A and JCT	37.7	7.85
Station A and Transposition	0.176	0.048

TABLE II
Prefault Voltage and Fault Current for 100 Ω Fault in Fig. 19

Grounding Applied	**V_A (prefault, V)**	**I_A (fault, A)**
None	2060	0.188
Station A	102	1.01
Station A and JCT	37.7	0.373
Station A and Transposition	0.176	0.002

For the case of an ungrounded de-energized line, the pre-fault voltage was significantly higher than any of the situations where grounds were applied. The fault current was comparatively small, but at 188 mA is within a range that studies have suggested is enough to start a fire. It is noteworthy that the fault current led the pre-fault voltage by approximately 90 degrees, consistent with capacitive coupling charging current, that both the pre-fault voltage and fault current scale linearly with the voltage of the energized line, and that the fault current level is maintained through a range of fault resistance values (undiminished at 100Ω).

With a single ground applied to the de-energized line at Station A, the capacitively coupled voltage is shunted to ground, and the overwhelming driver of prefault voltage and fault current is now due to mutual inductance, with these voltages and currents now scaling linearly with the current flow on the energized line. The prefault voltage is a fraction of what it was for the ungrounded line, but the current is two orders of magnitude greater, though it quickly diminishes as fault resistance is increased (compare Table I with Table II). Complex testing would need to be performed to attempt to understand the fire ignition risk associated with this setup, but it is not convincing that this low voltage source has the capacity to ignite the highly resistive dry foliage. On the other hand, the large currents that result from a clashing conductor fault or conductor contacting a tower could create significant sparking, particularly if this fault on the de-energized line coincided with a fault on the energized system. It is noteworthy that the fault current lagged the pre-fault voltage by approximately 90 degrees, consistent with magnetic induction, and that both the pre-fault voltage and fault current scale linearly with the current flow on the energized line, confirming the idea that the effect of magnetic induction due to current flow on the energized line is the dominating factor once the de-energized line has been grounded.

When a subsequent ground is applied at the junction (JCT) in Fig. 19, the pre-fault voltage and fault current is further reduced, but not driven to zero due to the non-uniform distribution of magnetic flux between Station A and the junction due to the presence of a transposition.

If we instead apply a ground at the transposition (with or without the ground still applied at the junction), we now establish a uniform distribution of magnetic flux and drive the pre-fault voltage and fault current toward zero. In practice the resistance of TPG connections to earth will limit our ability to drive the fault current of mutually coupled de-energized lines to zero, but substation ground switches, substation TPGs, or lines with static wire will more closely approach this ideal, and on lines without static wire it might be necessary to apply TPGs at multiple adjacent pole/tower locations to achieve the desired results, assuming that the fire risk at those ground locations can be mitigated. The purpose of this example is to demonstrate the importance of the location of the grounds, creating inductive loops that have a uniform magnetic flux distribution between the ground locations.

A final observation can be made that once a ground is applied at the junction, fault current along the section between the junction and Station C is driven to zero since there is no magnetic field coupling between the two lines along this section.

IV. Field Testing and EMTP Simulations

Field tests were performed to confirm the relatively high voltage and low current characteristic of an ungrounded de-energized line that is subsequently grounded (either intentionally or by fault condition), and the relatively low voltage and high current characteristic of a de-energized line that is already grounded at one end and then is subsequently grounded at the other end. It is possible for a de-energized line to exhibit higher current flow due to electric field induction than due to magnetic field induction (e.g. if the energized line is very high voltage and lightly loaded, and the two lines are very long), and likewise it is possible for the magnetic field induced voltage to exceed the electric field induced voltage (e.g. if the energized line is very low voltage and heavily loaded, and the two lines are very long), but the opposite characteristic as captured in the following example is more typical. The lines were modeled in an EMTP to determine how effective software simulations are at capturing the unbalanced voltages and currents that result from electric and magnetic field induction. There are many factors that will contribute towards discrepancies between the field measurements and EMTP simulations including accuracy of the measurement equipment, accuracy of ground resistance measurements, assumptions of earth resistivity, and accuracy of the line model developed in the EMTP, but because the ultimate goal is to reduce fire risk (a topic which is incredibly complex and difficult to quantify in its own right), we are not looking for precisely accurate numbers, but instead general trends.

Two lines along a four line corridor (Fig. 21) were de-energized and tested, the Moraga-Oakland #1 115kV line and Moraga-Oakland #2 115kV line, which were induced by the energized Moraga-Oakland #3 115kV line and Moraga-Oakland #4 115kV line.

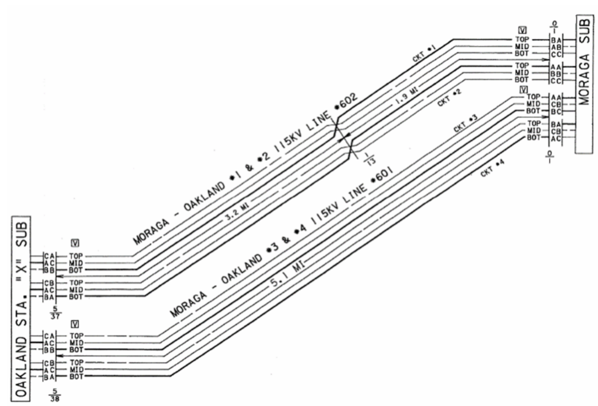

Fig. 21. Four 115kV line corridor.

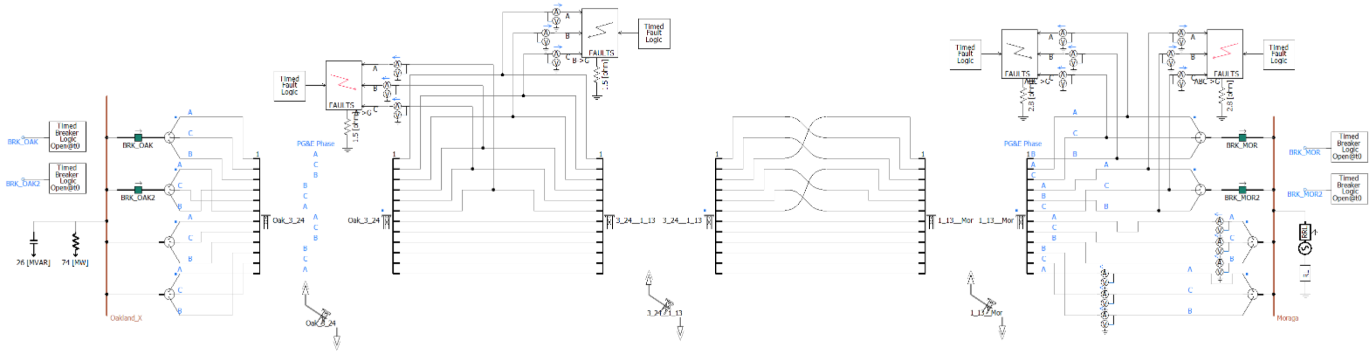

Fig. 22. Four 115kV line corridor modeled in an EMTP.

The four lines were modeled in an EMTP (**Error! Reference source not found.**), with a variety of factors that can affect the accuracy of the simulation results taken into consideration, including the ground resistance of the towers in question, the load current on the energized lines, and the order that the phases are arranged on the tower from top to bottom. The line model for this EMTP study includes a default option to create an ideal transposition of the circuit, an option which needs to be disabled in simulations such as this which critically rely on the unbalance created by the fact that these lines are not ideally transposed.

The two test locations chosen were Tower 0/1 which is the first tower outside of Moraga Substation, and Tower 3/24 which is about 1.7 miles from Oakland Substation. Both the #1 and #2 lines were de-energized throughout the testing, and measurements were taken for a given circuit on a given tower under the following two scenarios: a tower location was tested with the de-energized line ungrounded, and re-tested with the same circuit at the other tower location grounded (3-phase to ground). Voltage measurements were taken on each phase, and then each phase was subsequently grounded one at a time, with current flow to ground measurements taken. Table III shows the voltage and current measurements taken on the Moraga-Oakland #2 115kV line compared with the values obtained from EMTP simulations for the case of an ungrounded line, and Table IV shows the results with the opposing tower location grounded (e.g. the measurements at Tower 0/1 were taken with Tower 3/24 grounded).

TABLE III
Ungrounded Line: Test and Simulation Values

	Voltage (V)			Current (mA)		
Circuit 2	Top Phase	Middle Phase	Bottom Phase	Top Phase	Middle Phase	Bottom Phase
Tower 0/1 Test	722	825	400	16.7	18.6	9.9
Tower 0/1 Simulation	951.3	1275.1	544.9	19.9	26.5	19
Tower 3/24 Test	828	401	715	19	12	16
Tower 3/24 Simulation	1267.7	547.2	956.6	26.3	19.1	20

TABLE IV
Grounded at Opposite Location: Test and Simulation Values

	Voltage (V)			Current (mA)		
Circuit 2	Top Phase	Middle Phase	Bottom Phase	Top Phase	Middle Phase	Bottom Phase
Tower 0/1 Test	29	33	13	800	1000	800
Tower 0/1 Simulation	6.2	7.6	8.6	821	1003.4	1133.5
Tower 3/24 Test	10	9	11.5	900	700	800
Tower 3/24 Simulation	7.8	8.7	6.3	1024.6	1152.6	833

The relatively high voltage and low current characteristic captured in Table III is overwhelmingly due to the effect of electric field induction on this ungrounded line, and the relatively low voltage and high current characteristic captured in Table IV is overwhelmingly due to the effect of magnetic field induction with the opposite location grounded. The magnetic field induced voltages in Table IV are also present in Table III, either adding or subtracting from the electric field induced voltages depending on the location of measurement and direction of current flow on the adjacent circuits, but because the magnetic field induced voltages are 1 to 2 orders of magnitude lower than the electric field induced voltages, we can effectively ignore their contribution to Table III.

The electric field induced currents in Table III are also present in Table IV, either adding or subtracting from the magnetic field induced voltages depending on the location of measurement and direction of current flow on the adjacent circuits, but because the electric field induced currents are 1 to 2 orders of magnitude lower than the magnetic field induced currents, we can effectively ignore their contribution to Table IV.

Although there are discrepancies between the measured and simulated values, the EMTP simulations produce reasonably accurate results for the purpose of determining the effectiveness of grounds in removing the source of electrical energy on a de-energized line. Once the line model is built, the user can quickly simulate any combination of ground locations. This software additionally serves as an excellent educational tool: by adjusting voltages and currents on adjacent line the user can convince themselves of the effect of the voltage level of the adjacent line on the Thevenin equivalent of Fig. 4, and the effect of the current flow on the adjacent line on the Norton equivalent of Fig. 8.

V. Conclusion

There are documented cases of de-energized 500kV lines causing fires due to ground current flow through a TPG or due to falling hot metal particles produced by arcing at the overhead conductor when removing a TPG. It has been demonstrated that significant voltages and currents can also be induced on de-energized lines at lower operating voltage levels.

Grounding de-energized lines can be an effective method to reduce electrical energy and thereby reduce fire ignition risk, but many factors must be understood and considered including the fire risk at the location of the grounds themselves, the separate effects of electric field induction and magnetic field induction, consideration of the magnetic field profile along the line when choosing ground locations, and the effectiveness of the grounds (resistance to ground). If the line can be grounded in segments such that each segment has conductor resistance which is constant, a magnetic field that is uniformly distributed along the length of the line (conductors maintain the same configuration, the distance between the energized and de-energized lines is constant, there are no transpositions), and the resistance to earth of the applied grounds if reduced to zero, then the fire risk at a subsequent fault location will be significantly reduced. Though this shifts the fire risk to the locations of the grounds themselves, this might be acceptable if the fire risk at these known locations can be mitigated.

An EMTP simulation can be used to provide a reasonable approximation of the voltages and currents induced on a de-energized line, and can be a valuable tool to study the effect of the location where grounds are connected. Finally, although KVL applies without failure to lumped circuit analysis, Faraday's law requires that the non-conservative electric fields that are induced by time changing magnetic fields result in voltages around closed loop paths that do not sum to zero, and grappling with this unnerving feature of magnetic inductance is an essential part of un-lumping the inductor, revealing the internal mechanics not only of magnetically induced transmission lines, but of any wire wound component including generators, transformers, and CTs.

VI. References

[1] P. M. Ross, "Burning of Wood Structures by Leakage Currents," *IEEE Trans. of the American Inst. Of Electrical Engineers,* vol. 66, issue 1, pp. 279–287, Jan. 1947.

[2] R. C. Feynman, "AC Circuits", in *The Feynman Lectures on Physics, Volume II*, the New Millennium Edition, New York, Basic Books, 2011, ch. 22, sec. 3, pp. 22-7.

[3] W. Lewin, "8.02x - Lect 16 - Electromagnetic Induction, Faraday's Law, Lenz Law, SUPER DEMO", *8.02x – MIT Physics II: Electricity and Magnetism*, Lecture 16. Available: https://www.youtube.com/watch?v=nGQbA2jwkWI&list=PLyQSN7X0ro2314mKyUiOILaOC2hk6Pc3j&index=17

[4] R. Horton, "Induced Voltage and Current in Parallel Transmission Lines: Causes and Concerns," *IEEE Trans. On Power Delivery,* vol. 23, no. 4, pp. 2339–2346, Oct. 2008.

VII. Biographies

Robert James received his BS in Electrical Engineering and Computer Science from University of California, Berkeley in 2005, and graduated with distinction with an MS in Electrical Engineering from California State University, Fresno in 2009. He started his career with Pacific Gas and Electric Company in 2008 as an intern in Distribution Engineering and has been in System Protection since 2010 where he currently holds a position as Senior Consulting Protection Engineer. Robert has previously co-authored papers for the Western Protective Relay Conference, Texas A&M and Georgia Tech relay conferences covering topics such as traveling wave fault locating, fused transformer failures and wildfire risk due to overhead arcing faults. He is a registered Professional Engineer in the state of California.

Scott Hayes received his BSEEE from California State University, Sacramento in 1985. He started his career with Pacific Gas and Electric Company in 1984 as an intern. Since then he has held multiple positions in System Protection including supervisor, as well as Distribution Engineer, Transmission Operations Engineer, Supervising Electrical Technician, Supervising Engineer in Power Generation and is currently a Principal Protection Engineer focusing on standards, procedures, and quality. Scott has previously co-authored papers for the Western Protective Relay Conference, Georgia Tech Protective Relaying Conference, Texas A&M Conference for Protective Relay Engineers, CIGRE, TechCon Asia Pacific, CEATI Protection and Control Conference, North American Transmission Forum and Transmission and Distribution World Magazine. Topics include many aspects of protective relaying including Thermal Overload Relaying, Data Mining Relay Event Files, Effects of CCVT Ferroresonance on protective relays, PG&E's Wires Down Program and Ground Fault Neutralizers. Scott is a registered Professional Engineer in the state of California and has served as Chairman of the Sacramento Section of the IEEE Power Engineering Society, chairman of the CEATI Protection and Control committee and Chairman of the North American Transmission Forum System Protection Practices Group. He has served as a member of a NERC Standard Drafting Team and is currently the Vice Chair of the IEEE PSRC D45 group looking at Protection Methods to Reduce Wildfire Risks due to Transmission and Distribution Line. He is also a member of the IEEE PSRC D subcommittee.