Placement of Protective Grounds for Safety of Linemen

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The Safety Problem

INTRODUCTION

USE OF portable grounds for the protection of workmen engaged in maintaining high-voltage electric transmission lines is a subject that has not received the attention it deserves from electrical engineers. In general there are two working bases under which maintenance is performed on high-voltage transmission lines. One basis is energized and the other is de-energized. The first-named, which involves no direct contact with energized apparatus, is performed with the aid of specialized tools commonly referred to as "hot sticks." This is a method that is coming into more general practice but it is not universally applicable. The other basis is the one with which this paper is concerned, that is the de-energized or planned outage method.

Most electrical engineers know approximately what is involved in the outage method, but they may not have given much thought to the full implication of the protective measures which are instituted to safeguard the linemen who must come into direct contact with supposedly de-energized apparatus.

The de-energized working basis commonly starts with the isolation of the line section to be worked from all normal sources of supply including possible back feeds. This is usually accomplished by some sort of clearance procedure whereby a power dispatcher arranges for all of the switching which is necessary to assure full isolation of the line section in question from all normal sources of power supply. This procedure is generally based upon the recognition of manually operated air-break disconnects which can be locked open as the only permissible method of isolation by switch, ruling out all automatic mechanisms such as circuit breakers, etc. Also, it is more or less widespread practice to have associated and interlocked ground switches closed at all locations where line disconnects have been employed in the isolation process. As a final phase of the initial stage, the power dispatcher will cause "hold" tags to be placed on all disconnects upon which the isolation depends and issue to the linemen or their supervisors a clearance which purports to guarantee the integrity of the stated isolation until this clearance is released by the same individuals to whom it was issued.

It is not considered good practice for linemen to contact supposedly de-energized equipment merely with the guarantees just described. For one thing, accidental energization of the supposedly isolated section can occur without necessarily involving any violation of the clearance. Such energization can occur through accidental contact with energized "foreign" utility lines which cross over or under the lines being worked upon. The clearance process involves the possibility of human failures which, however infrequent, are usually of sufficient importance to warrant the application of further protective measures. Finally, additional protective measures are considered desirable by system engineers in the sole interest of equipment protection and without regard for human life. This additional protection consists of the attachment of portable grounds by the linemen in such a way as to protect them theoretically from not only the accidental energization of supposedly de-energized apparatus from outside sources but from violation of their clearance through error on the part of their associates. This is the point which electrical engineers have taken too much for granted.

In order to understand the problem, it seems useful to quote from some of the codes which various states and operating companies have used to govern the placement of portable grounds.

TYPICAL RULES

Form A

"All work on de-energized circuits rated above 4,000 volts shall be done between two sets of grounds. One set shall be placed on the first pole or structure towards the source of energy and the other on the first pole or structure towards the loads."

Form B

"Transmission line grounds shall be placed at towers or structures adjacent to those upon which work is to be done."

Form C

"Grounds should not be placed on the same pole or tower on which work is to be done, for in moving the conductor about, the ground might become detached. There may be an exception here if the foreman sees fit. The ground connections should be made at least one span away, usually, and never over a mile from the point of work."

Form D

"Grounds shall be placed on both sides of the section of line on which work is to be done."

Exception

"On steel tower lines it *may be* more desirable to install the ground at the tower to be worked on."

It seems clear that the philosophy which has surrounded the search for a measure of protection is to "work between grounds." A review of the operating practices of most companies confirms the fact that the principle of working between grounds governs the placing of all protective apparatus. It is a little difficult to account for the fact that so many electrical engineers have so long accepted as adequate the principle of working between grounds. In a substation, of course, where an adequate ground mat has been properly installed, the principle of working between grounds can be effectively implemented by the placing of portable ground sets, for example, on either side of the same bus section which is undergoing maintenance and always connected efficiently to the same ground mat. Contrariwise, with respect to transmission-line maintenance, the placing of portable grounds on towers adjacent to, or one or two towers removed from and on either side of, the tower being worked upon not only affords no protection whatsoever to the linemen but is an economic waste.

The exact nature of the fallacy which has crept into the problem almost unnoticed may be seen by an experimental rewording of code instructions. Suppose, for example, a given safety code were to be worded as follows:

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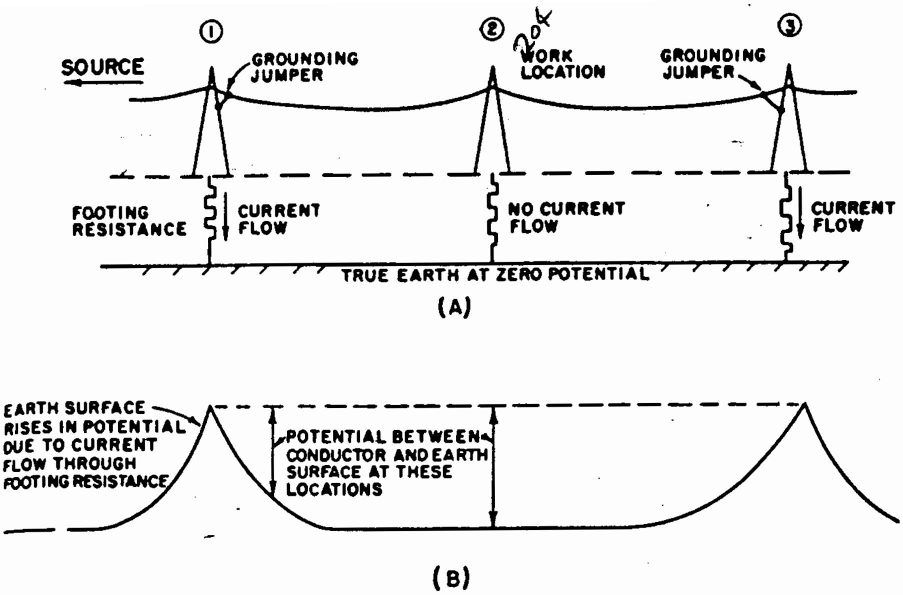


Fig. 1. A—Schematic representation of a steel tower line and the associated footing resistances. Conductors grounded to towers adjacent to the work location only. B—Approximation of potential gradients which may appear when the conductor in A is energized with respect to earth

Form E. Hypothetical

"After obtaining a proper clearance and before touching any of the conductors at a given structure where work is to be performed, it will be required that standard resistances be connected in the manner specified below at (a) the first structure toward the source of energy and (b) the first structure toward the load. At each of these locations all three phases of the transmission line will be connected together at a common point; and then, through a standard resistance of not less than 5 ohms nor more than 500 ohms, this common point will be connected to any available ground such as the tower steel or guy cable, etc." Electrical engineers would declare such a rule utterly without merit. What reasoning would condemn the process? Simply that a fault current of, say, 5,000 amperes would, through a resistance of even as little as 5 ohms, mean a current-resistance drop of 25 kv, which is far too much for a lineman working at the intermediate tower to intercept with immunity. Yet if a clearance is violated and an unauthorized energization takes place where a lineman is relying on grounds placed at locations removed from the structure at which he is working, the potential difference between the conductor and the tower he is working on, for example, will depend on the value of the fault current and the footing resistances of the adjoining towers. In most locations this will result in the conductor bouncing to nearly full line voltage whenever such faults occur.

Fig. 2. Potential transformers and driven probes used in the recording of earth gradients during fault

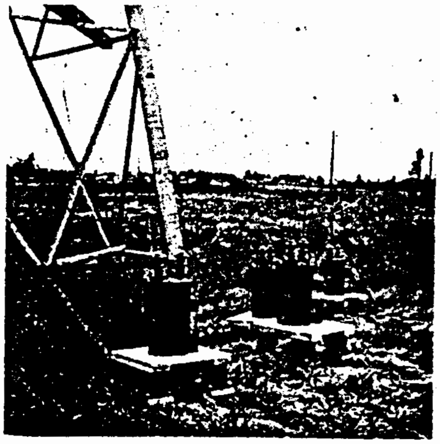


Fig. 3. Gradients were measured to a distance of 256 feet and transformer cases and secondary leads insulated as shown

The remedy for this situation requires a return to first principles. After all, what is so illusory about working between grounds is that it is a means and not an end. There is nothing *per se* desirable about working between grounds. What is desirable is that the workman be placed in a zone of constant potential, i.e., that the difference in potential between what he is standing on or otherwise embracing with his body and what he is touching with his hands is zero or nearly zero. If working between grounds achieves this end it is a proper means. If it does not it is valueless and should be abandoned.

The solution is to create by any practical means an equipotential zone for the man to work in. On steel towers this may be done by short-circuiting the conductors and connecting them securely to the tower steel. Naturally, there are some practical precautions. The method of grounding at the structure where work is progressing will have to be carefully applied to make sure that the grounds are not disturbed in the course of the work. A further precaution is to be sure that at deadend towers, or wherever the conductors are to be opened, both sides of the opened circuits are short-circuited and securely grounded.

The foregoing procedure takes care of steel towers. With regard to wood-pole transmission lines, some variations must be taken into account such as guyed and nonguyed poles and insulated and uninsulated guys. The authors have some suggestions which relate to possible methods of protecting linemen on wood poles. However different the problem of creating an equipotential zone on a

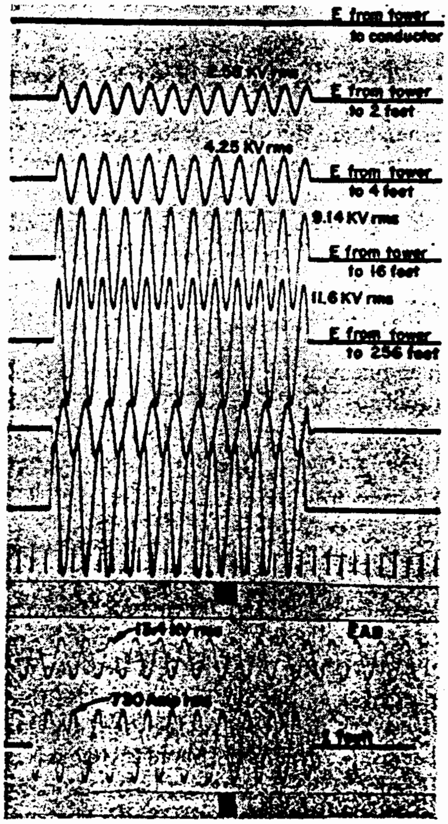


Fig. 4. Oscillograms for case I showing fault current and earth potentials as recorded

A—Potentials recorded at test site (conductor grounded at adjacent towers only)

B—Fault current and applied voltage recorded at the substation, or source, location

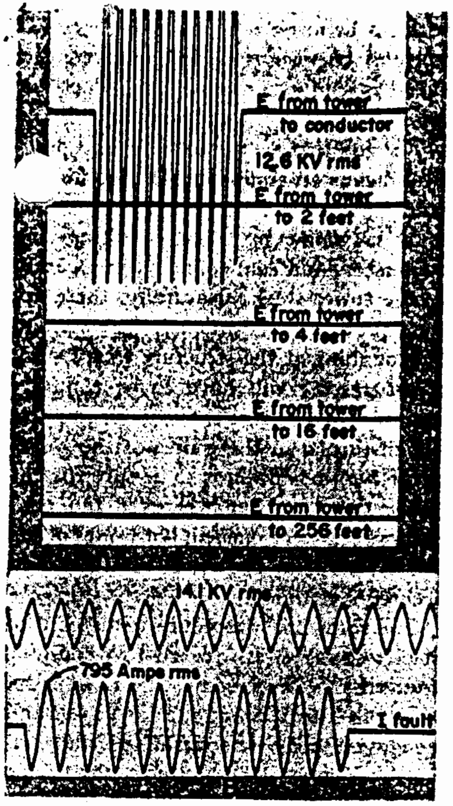


Fig. 5. A—Test site potentials recorded for case II (conductor grounded at test tower). B—Substation record of current and applied voltage for case II

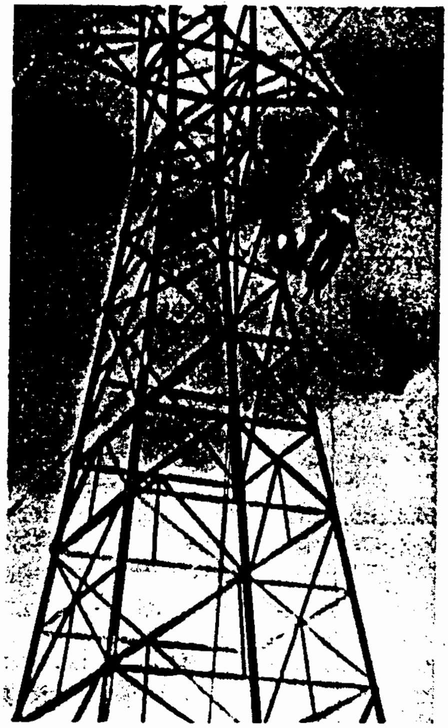


Fig. 6. Demonstration, using a dummy, that hazardous voltages may appear during energization of a conductor which has been solidly grounded at the adjacent towers

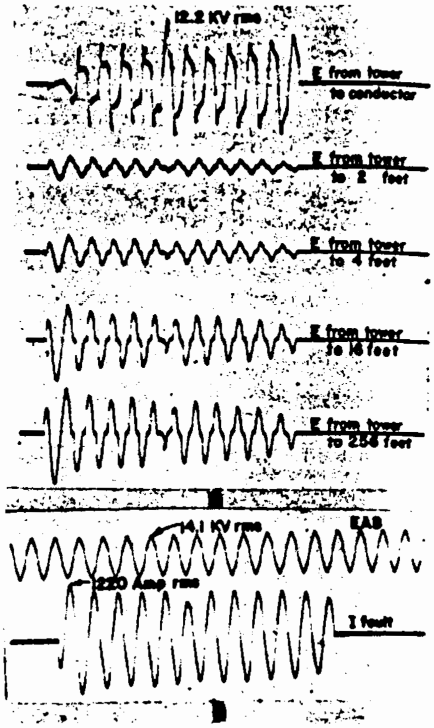


Fig. 7. A—Test site oscillograms for case III (conductor grounded at adjacent towers only and dummy at test tower). B—Substation oscillogram for case III

d pole, the general principles governing proper placement of protective grounds are the same as for steel towers.

Some explanation of the reason for field testing seems desirable. Most engineers will readily concede the theoretical correctness of the foregoing analysis and question the necessity of field demonstration. However, the authors, having been associated with a large class of journeymen linemen, are aware of some practical problems which face the professional electrical engineer who seeks to explain to these craftsmen why they should accept on faith assurance that the problem has now been accurately solved on paper. These journeymen can remember too many long, weary miles of lugging ground sets up and down rough terrain to reach adjacent structures. Whenever the placement of these sets became too burdensome, the answer always was that it was for their own protection—working between grounds. Should engineers blandly ask these men who actually climb the structures and touch the conductive materials to accept their apologies f slight mistake and put the grounds at the same place they are working rather than on structures to either side? At least something more than paper work seems to be required if such a radical change in methods is to be fully acceptable. Linemen, quite understandably, have expressed a desire to be shown by field demonstration that engineers have solved the problem correctly. They are less willing to believe that their lives are in danger by following previously prescribed methods than that the new methods are better. It would appear that most linemen are alive today because only rarely are clearances broken rather than because of their protective grounds. The second portion of this paper is devoted to a theoretical demonstration based on field tests of the correctness of the projected changes in grounding recommendations.

Field Tests

General Discussion

As mentioned previously, the fact that men are working between grounds does not insure safety. They may be subjected to potentials equal to the current-impedance drop at the grounding electrodes (tower footing, etc.) as may be readily appreciated by men of professional level. These facts may not be evident to the workmen in the field. Therefore, it was considered desirable to demonstrate by actual field tests that dangerous potentials may appear unless proper grounding procedures are followed.

Prior to the tests, a lecture was held using a sketch similar to Fig. 1 to illustrate the conditions which may exist when working between grounds but with no ground on the conductor at the work location. It was pointed out that all tower footings and other types of grounds are not truly grounds but incorporate a certain amount of resistance as shown schematically in Fig. 1(A). If one of the conductors should be energized, current will flow through the footing grounds. The points of grounding plus the conductor will then rise above zero potential by an amount equal to the current-impedance drop across the footing impedance. To all practical purposes, this is essentially the current-resistance drop, as very little reactance is associated therewith.

Because the tower at the work location is not connected to the conductors, no current passes through its footing resistance and it therefore remains at zero potential. A difference in potential will then exist between this tower and the conductor equal to the current-impedance drop across the footings at the grounding locations. Fig. 1(B) is an approximate representation of the potentials which may appear between the conductor and earth surface in this vicinity.

It was then pointed out that if grounds were placed between conductor and tower at the work location, such as would be the case if the work was to be performed at

I in Fig. 1(A), no appreciable potential could exist between conductor and tower.

This condition should provide complete safety to the linemen, but gradients may exist across the earth surface in the tower vicinity which constitute a hazard to groundmen. This appears to be unavoidable, and the best practice is for the groundmen to work as far away from the tower as feasible and to stand in such a manner as to intercept as small a potential as possible.

PROCEDURE

After the purpose and method of the demonstration had been explained, the series of tests were performed and the oscillographic data displayed and interpreted.

The tests were conducted at tower 204 on the Bonneville-Vancouver line no. 5. This line was opened at the North Bonneville end, while at the J. D. Ross Substation end *A* phase was connected to *A* phase of the 13.8-kv tertiary winding of transformer bank no. 2 via a circuit breaker. *B* phase of this delta-connected tertiary was grounded via this same circuit breaker.

During the tests, *A* phase of the transmission line was grounded at the test site, consequently, when the circuit breaker at J. D. Ross was closed, current flowed in the loop made by the transformer bank tertiary, *A* phase of the transmission line from J. D. Ross to the test site, and returned through the earth to the grounded point of the bank tertiary.

Voltages appearing between the conductor and tower and tower and ground rods driven at distances of 2, 4, 16, and 256 feet from the tower were recorded oscillographically through suitable potential transformers. Figs. 2 and 3 show how these potential transformers were set up. Note that at each location several short ground rods were driven along an estimated equipotential surface and connected in parallel. This was done in an effort to keep the resistance of the potential probe as low as possible and thereby produce minimum error due to transformer and oscillograph loading.

CASE I

A-phase conductor was grounded to the test tower using a standard 4/0 grounding lead and clamps. The circuit breaker at J. D. Ross was then closed for approximately 10 cycles. The oscillogram of Fig. 4(A) shows essentially no potential between conductor and tower. The voltages that existed between tower and various distances along the earth's surface are also shown. It will be noted that most of the potential drop appears across the first few feet of earth surface. The magnitude of the fault current and voltage applied at the source are shown on the oscillogram of Fig. 4(B). These data show that a fault current of 730 amperes produced a potential drop of approximately 12 kv across the footing impedance of this tower. The footing resistance as measured with a ground ohmer was 16.3 ohms.

CASE II

A-phase conductor was grounded at the towers adjacent to the test tower only. This test corresponds to Fig. 1(A) and was to demonstrate that hazardous voltages may appear when grounds are not present at the work location. The oscillograms in Fig. 5(A) and (B) indicate that a voltage between conductor and tower of over 12 kv appeared as the result of a total fault current of 755 amperes. The footing resistance of the towers serving as grounding points was 42.2 ohms for tower 203 and 24.3 ohms for tower 205. Note that because of the absence of current flow through tower-204 footings, no potentials appeared between tower and the probes located various distances out from the tower.

CASE III

This test was similar to case II except a dummy was suspended by a fuse wire to bridge the space from conductor to the

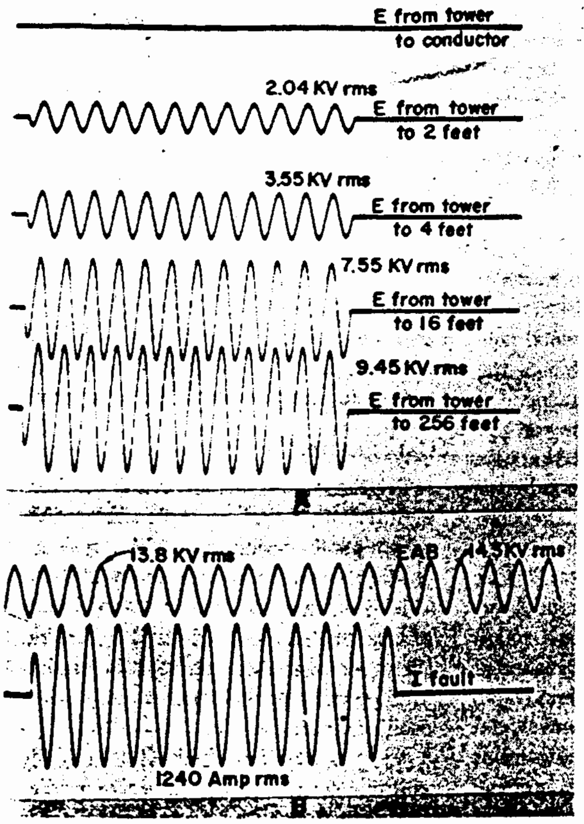


Fig. 8. A—Test site oscillograms for case IV (conductor grounded at both adjacent and test towers). B—Substation oscillogram for case IV

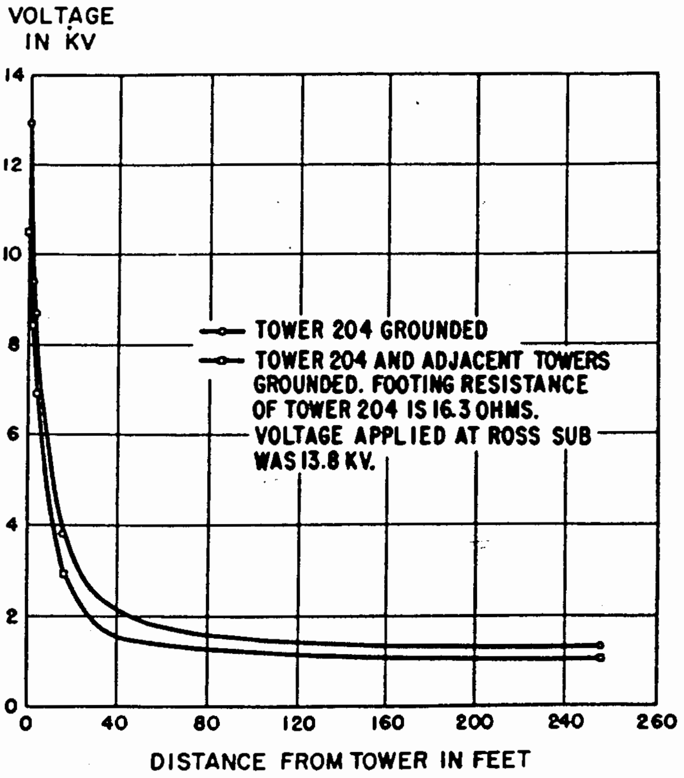
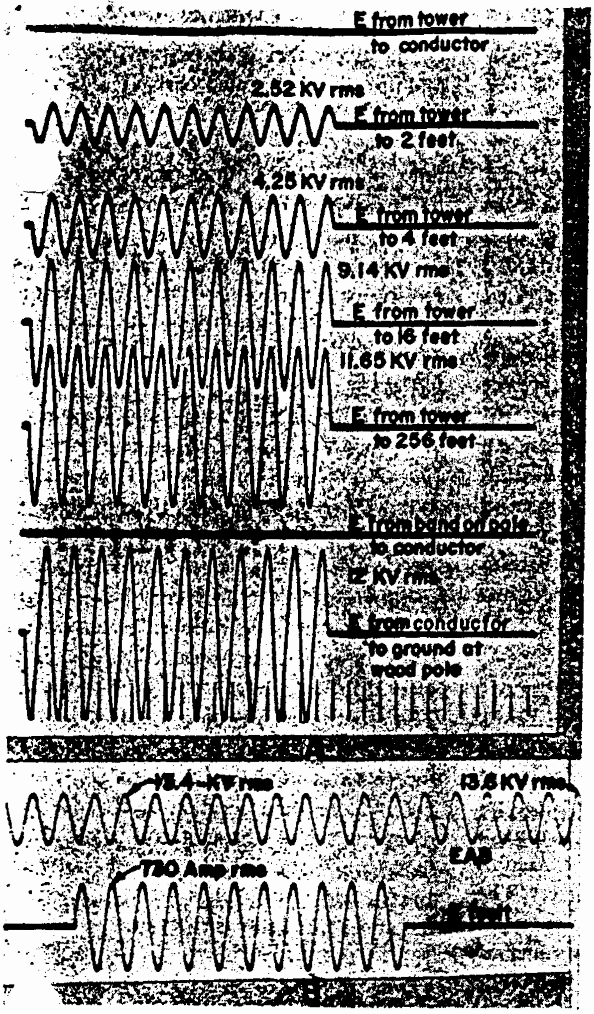


Fig. 9. Potential gradient curves showing reduction in gradient obtained by grounding conductor at three towers as compared to grounding at one tower only



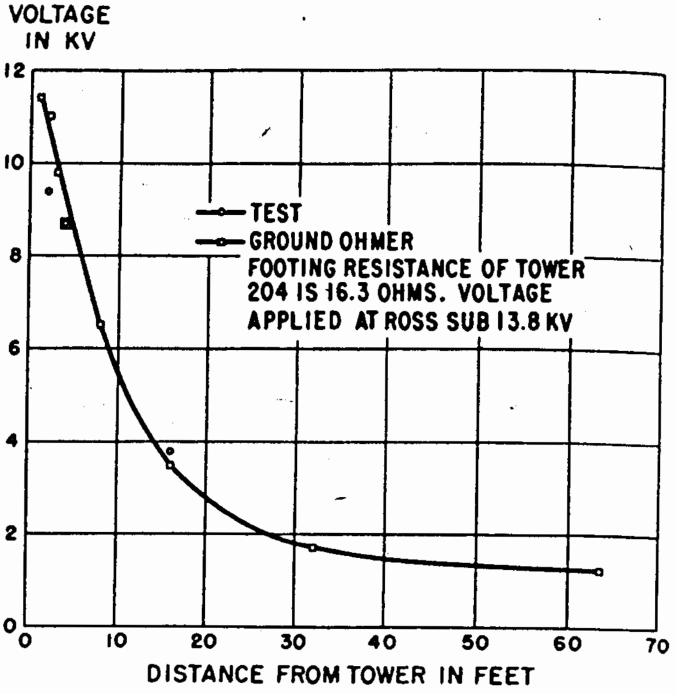


Fig. 10 (left). A—Test site oscillogram for case V (wood pole example). B—Substation oscillogram for case V

Fig. 11 (above). Comparison of potential gradient obtained by test with that predicted by resistance measurements

test tower. The conductor remained grounded at adjacent towers as fault current was established. This resulted in an arc across the dummy melting the fuse wire and dropping the dummy to earth in flames as shown in Fig. 6. This effectively demonstrated to the linemen that little protection had been afforded by the grounds at adjacent towers.

The oscillograms of Fig. 7(A) and (B) show potentials and current as modified by the established arc characteristics. Note that voltages up to 12 kv were recorded during the arcing period.

Case IV

This test was similar to case I except the conductor was grounded at the adjacent towers as well as at the test tower. The purpose was to demonstrate that the grounds additional to those at the work location produce little reduction in surface gradient when the fault current magnitude is principally determined by the footing or ground-rod resistance. F. (A) and (B) shows that the reduction in surface gradient was not enough to warrant the use of the additional grounds.

Fig. 9 is a plot of the potentials recorded on a radius from the test tower for cases I and IV. These curves illustrate the reduction in gradient obtained by the addition of grounds to the conductor at adjacent towers.

Case V

This test was performed to demonstrate one method of protecting linemen on a wood pole while eliminating the hazard to groundmen. For this test a wood pole was set approximately 300 feet from the test tower and a conductor suspended from the pole top to the test tower. A metal band was placed around the pole 10 feet below the point of conductor attachment and connected to the conductor with a standard grounding jumper. This placed the upper 10 feet of pole at the same potential as the conductor. This conductor was connected to *A* phase of the line at the test tower and grounded to the tower. This then corresponded to a condition where the conductors would not be grounded at the work location but at an adjacent structure. That portion of the pole below the metal band would be depended upon to act as insulation preventing fault current flow in the work area.

The oscillograms of Fig. 10(A) and (B) show that no voltage appeared between the conductor and metal band, which is the area that would be occupied by the linemen. A potential of 12 kv appeared between conductor and ground at the base of the pole indicating little, if any, potential gradient across the earth in this area.

This method of protecting the linemen without producing earth gradients in the work vicinity can only be achieved when sufficient insulation is present between the lineman's work area and ground to withstand the potential stress which may appear. Violation of this by guy wire attachment, etc., may make such procedure impractical on some structures.

Calculation of Earth Gradients

Prediction of surface gradients in the vicinity of grounds may be accomplished with good accuracy using resistance gradients measured with any of the available instruments designed to indicate ground resistances. Fig. 11 illustrates the agreement obtained between gradients predicted by ground ohmer readings and oscillographic test data.

Very heavy fault currents from high-voltage sources may produce gradients sufficient to cause arcing between earth particles or glow discharges. When this occurs, the effective resistance in these areas will change and agreement between predicted and actual conditions will not obtain

Conclusions

1. The present and apparently widespread practice of working between grounds with no ground at the work location does not insure adequate protection to linemen who may contact both conductor and structure during accidental energization of the conductor.

2. Short-circuiting and grounding of all conductors at the work location using leads and connectors of adequate current-carrying capacity will provide sufficient protection for the linemen.

3. Ground-fault currents at the work location may produce potentials across the earth of such magnitude as to constitute a hazard to groundmen. This hazard is generally present even though adequate grounds are not placed at the work location. This results from the common practice of using small diameter leads at these points to drain off induced charges. Many of the items of linemen's working gear employed at work locations such as hoists, etc., constitute inadvertent and, generally, inadequate grounds.

4. Additional grounds adjacent to the work location may reduce the earth potentials which could appear at the work location, but in general the reduction will not be sufficient to eliminate the hazard to groundmen. This is particularly true when the ground-fault current is principally limited by ground resistance rather than line and system impedance.

5. A method has been demonstrated whereby protection may be provided to both linemen and groundmen when working on certain types of wood structures.

6. Within limits, the potential gradients across the earth's surface resulting from the flow of current from a grounding electrode may be reliably predicted from resistance measurements.

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No Discussion