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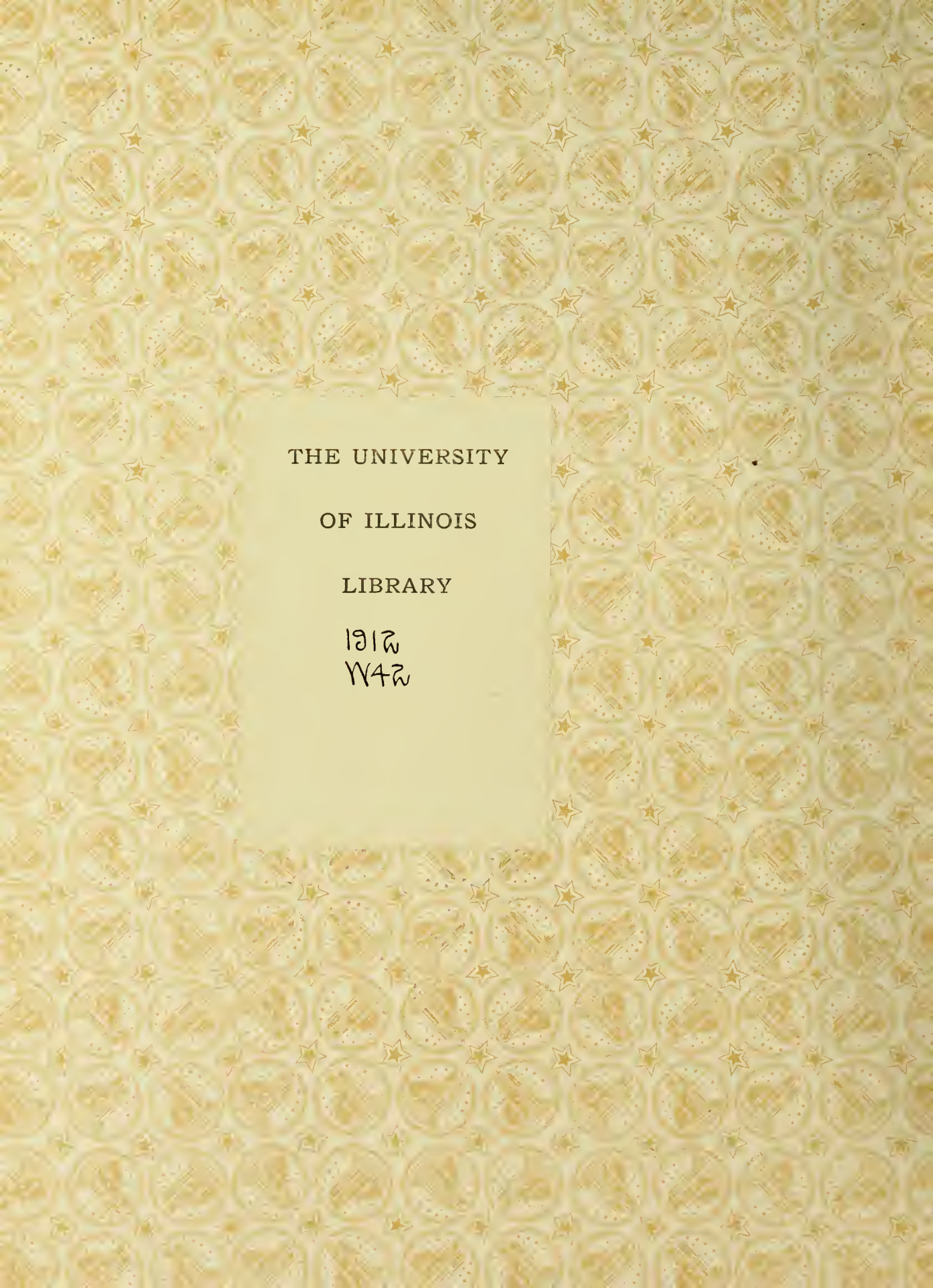
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The Grounding of Electrical Systems

Electrical Engineering

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THE GROUNDING OF ELECTRICAL SYSTEMS

BY

MELVIN EICHBERG WEIL

T H E S I S

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

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May 28, 1902

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

MELVIN EICHBERG WEIL

ENTITLED THE GROUNDING OF ELECTRICAL SYSTEMS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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THE GROUNDING OF ELECTRICAL SYSTEMS.

Introduction.

The grounding of the neutral of electrical systems has come into extensive usage in the last few years, and, although the concensus of opinion is that it is good practice, yet, considering the possibilities for the extension of this practice, there is comparatively little definitely known about it. Many engineers argue in favor of low resistance grounding while others urge the use of moderate resistance. Because of this difference of opinion among authorities, it will be the object of this thesis to cite and describe methods now in use and to draw conclusions from the results which have been obtained.

Before the installation of the grounded neutral on some high voltage systems, serious burnouts were common, and whole systems were sometimes put out of commission for considerable lengths of time. The Interborough Rapid Transit Company, of New York, offers a good example of the beneficial results derived from grounding the neutral of high tension cable transmission lines. Before this company adopted the use of the ground, several serious burnouts were experienced. Five to thirty minutes sometimes elapsed from the time the detectors gave indication of ground until the circuit-breakers opened. The original scheme for grounding was as follows:- The neutral of each generator was connected to a common neutral bus-bar through a disconnecting switch and a current transformer. The neutral bus-bar was grounded through about six ohms resistance in each of the two power stations, making about three ohms between the neutral of the combined system and the ground. The original system had 11,000 volts between lines, and the voltage between line and ground, after grounding the neutral, was thus 6350 volts. In case one of the transmission cables became grounded, thus causing a short circuit, the maximum current possible was 2117 amperes or 1059 amperes per rheostat, all of which was generated by the grounded alternator. Time-limit relays on the feeder switches were set to open instantaneously at 300 amperes and the generator relays were set to open at 900 amperes in five seconds. The neutral resistances were of the iron grid type, and had a carrying capacity of 1000 amperes for two minutes. The engineers who designed this system believed that it would prove entirely satisfactory, but after it was installed, serious trouble was experienced with triple frequency cross-currents in the neutral connections. These cross - currents fluctuated in magnitude from zero ^{to} one-half full load current, and a large synchronizing current flowed. These troubles were so serious that the original ungrounded system was again installed, and the use of a grounded neutral was delayed to allow time to make more extensive experiments.

After considerable experimenting and other research, it was found that the insertion of a resistance in the neutral connections between the generators and the neutral bus-bar would reduce ~~ee~~ the cross-currents to a safe value, but a further difficulty

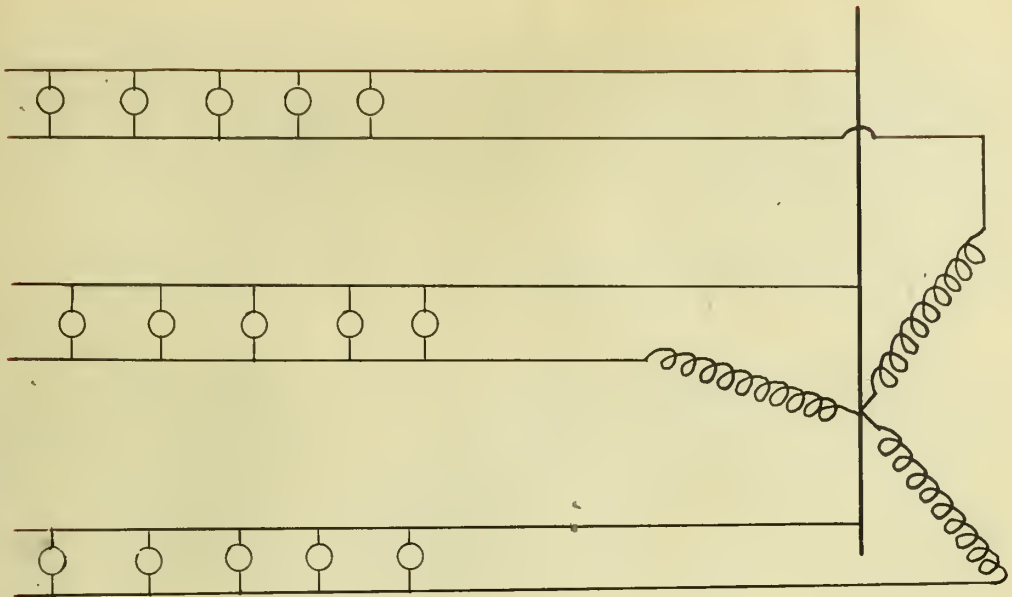


arose when it was found that this was undesirable on account of the varying resistance in the ground circuit, depending on the number of generators in parallel, the resistance to the ground decreasing as the number of generators increased. Even had this trouble not arisen, the plan would not have been feasible, since the calculations showed that resistance grids of large enough capacity would have ^{occupied} more space than the generating stations could have spared. It was finally decided to connect but one live generator to the neutral bus-bar in each power station. Even this was not entirely satisfactory, since considerable current still flowed in the neutral rheostats. The system was adopted, however, and has proved that the trouble and expense were well worth while, as will be seen in the comparison below, of conditions before and after the adoption of the ground.

Previous to the grounding of the neutral, there had been twelve burn-outs, and since, there have been sixteen. Of the former twelve, however, four had shut down the power station, one had shut down two substations, and four others had shut down one substation; while of the latter sixteen, not one has shut down either power station, eight have shut down the substation fed by the grounded cable, two have caused one other feeder to open, and the remaining six have done nothing more than to open the switches.

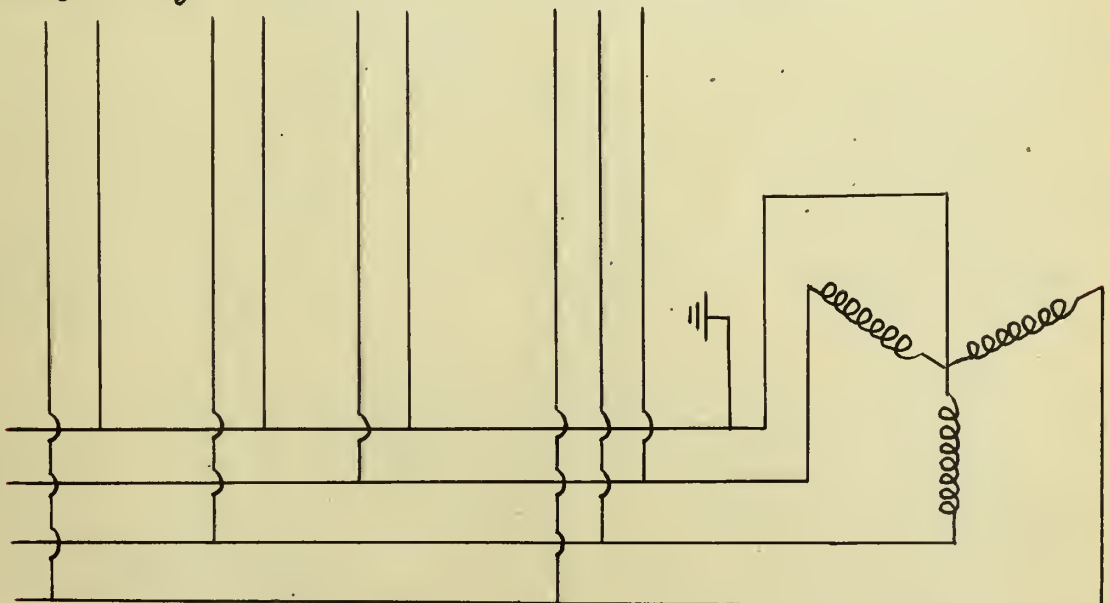
It appears to the writer that a better solution of the matter could have been obtained by operating each power station as a separate unit instead of connecting them together in parallel and operating them as one station. If this were done, and the neutrals grounded as they now are, there would have been no circuit for the ground currents through the rheostats, and the cross-currents between the stations would have been eliminated. Interconnections could be made between the stations through switches which would normally be open, but which could be closed in case one station should be shut down and it was necessary that the other station carry the total load.

The troubles arising in ungrounded transmission lines and which are remedied by grounding the neutral, are many, and have various causes. Static conditions in an ungrounded system are easily unbalanced, while, by using the three-phase transmission line with earthed neutral, conditions of stable equilibrium can be obtained. Previous to grounding, most of the distribution of the Commonwealth Electric Company, of Chicago, and of the Chicago Edison Company, was single phase. The generating station was three phase, star wound, sixty cycle, with 3980 volts between lines. The lines were arranged somewhat as is shown in the diagram on the next page. As can readily be seen, this involved considerable complication in the switching apparatus at the generating stations, and, after the business of these companies became extensive, the system was very unsatisfactory. The grounded neutral was adopted as a solution of the difficulties, and the entire system of distribution was rearranged. The final method of dis-



Before the Adoption of the Grounded Neutral.

Lighting Circuits Power Circuit.



After the Adoption of the Grounded Neutral.

 Diagrams Showing the Distribution Systems of the Chicago Edison Company and the Commonwealth Electric Company.

tribution consisted of single phase lighting circuits and three phase three wire power circuits, with three phase four wire transmission lines. This final arrangement is shown in the diagram on the preceding page. From this latter diagram it may be seen that the phases are almost perfectly balanced and thus unstable static conditions are obviated. The ground was not used as a current carrier, but merely served as a device for holding the potential between line and ground at a constant value, and to keep the neutral permanently at ground potential.

In a three phase three wire star connected system, no triple harmonics can flow, since the circuits are all open. If the neutral is connected to the ground at two points, as the neutral of two synchronized alternators, these triple frequency currents have a closed path, and will flow. If an ammeter is connected in the ground circuit, it will be found that these triple frequency currents sometimes attain to a considerable ^{value}, as has been shown in the example of the Interborough Rapid Transit Company.

As has been stated in the introduction to this thesis, there has been much discussion in regard to the resistance to be connected in ground connections, many engineers arguing in favor of low resistance and others in favor of appreciable resistance. Resistance grids of the ordinary type having large current carrying capacity occupy considerable space, and for this reason are inconvenient, especially when the stations are in small buildings where every foot of floor space is utilized. In such cases it would be necessary to build an addition to the power house in order to accommodate them. For this reason experiments have been conducted to determine the resistance of the connections between the ground and the ground plate, in order to ascertain whether or not there is a possibility of eliminating the grid resistances and utilizing the resistance of the contact with the ground. Whether or not this is practicable, remains to be seen.

A very striking difference between short circuits occurring on grounded systems and those on ungrounded systems is, that circuit breakers, time limit relays and oil switches respond readily to the former, but do not act at all readily in the latter case. When a conductor of a grounded system breaks, a short circuit immediately ensues, since the ground acts as a fourth current carrier. In most cases of this kind, the switches open quietly, and no damage is done. With an ungrounded neutral, the opening of one line does not immediately cause a short circuit, but, strange as it appears, shortly after one line breaks, a second line is almost sure to open, and thus a short circuit is caused. Under these conditions, the protective apparatus does not act readily, as has already been stated, and serious damage is often done. If the switches do open, they usually make a violent disturbance, sometimes making a loud noise and spattering oil. Various reasons have been assigned to these phenomena, but as far as the writer's knowledge extends,

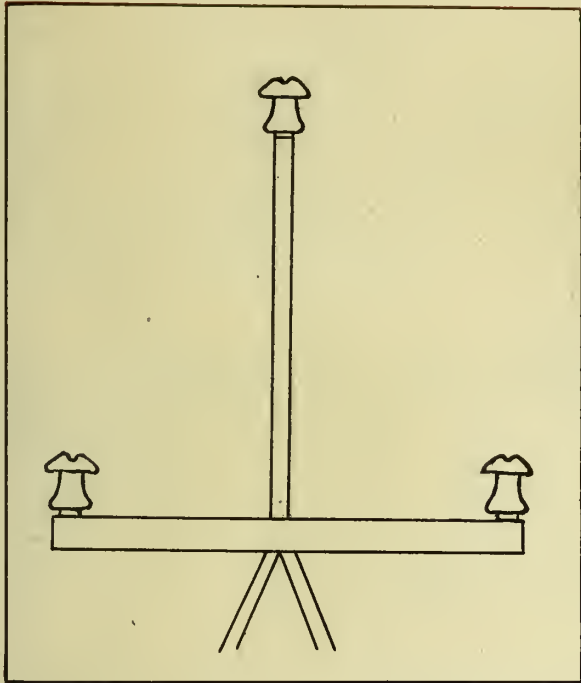
no definite agreement has been reached among engineers to fully explain them.

There are two plausible reasons which account for the fact that, in an ungrounded system, the opening of one transmission conductor is almost sure to open a second. When all the conductors are in place, and the load is balanced on all three phases, the static stresses between each conductor and the ground are practically the same. If one conductor breaks, the static stress on that conductor is removed, and the system becomes decidedly unbalanced, statically. The stresses between the remaining conductors and the ground are enormously increased and a second conductor becomes connected to ground by breaking down the insulators. Another explanation might be the following. In a star connected system, with ungrounded neutral, the triple frequency currents cannot flow. When a line becomes grounded, a completed path is formed for these triple harmonics. In some way these currents may affect the voltage of the system, and thus break down the insulators.

In certain climates where violent electrical storms are prevalent, it has been found that the grounded neutral is an effectual preventative against damage to the line by lightning discharges. A notable example of this application of the grounded neutral is cited by Mr. Norman Rowe, in the Transactions of the American Institute of Electrical Engineers, issue of June, 1907.

In the year 1903 a steel-tower long-span transmission line was built in the states of Michoacan and Guanajuato, in Mexico. The line was originally without the grounded neutral, and was designed for 60,000 volts at the generating end and 51,000 volts at the receiving end. The three wires were strung on the towers at the vertices of an equilateral triangle, and the upper end was supported upon a three-inch extra heavy pipe, which formed the continuation of the tower, the other two being placed at the ends of a double channel-iron cross-arm, approximately seven feet in length, the sides of the triangle being six feet. The insulators were connected directly to the cross-arms on cast-iron pins. For protection against line voltage, as well as against any high voltages due to lightning discharges, dependence was placed entirely on the insulators. The length of the line was approximately 101 miles. The original construction if the tops of the towers is shown in the sketch on the next page.

The line is tapped at Irapuato, which is about seventy-five miles from the generating station. At this point there is a sub-station where lightning arresters of the usual station type are installed to protect the step-down transformers. Thus there was a chance for the line to discharge at this point as well as over the arresters at either end of the line. In the part of Mexico where the line is situated, heavy thunder storms come up nearly every day during the months of July and August, and considerable ^{trouble} was experienced with lightning. The rainy season of 1904 came on with great severity in April and lasted until October. The injury to the transmission line from light-

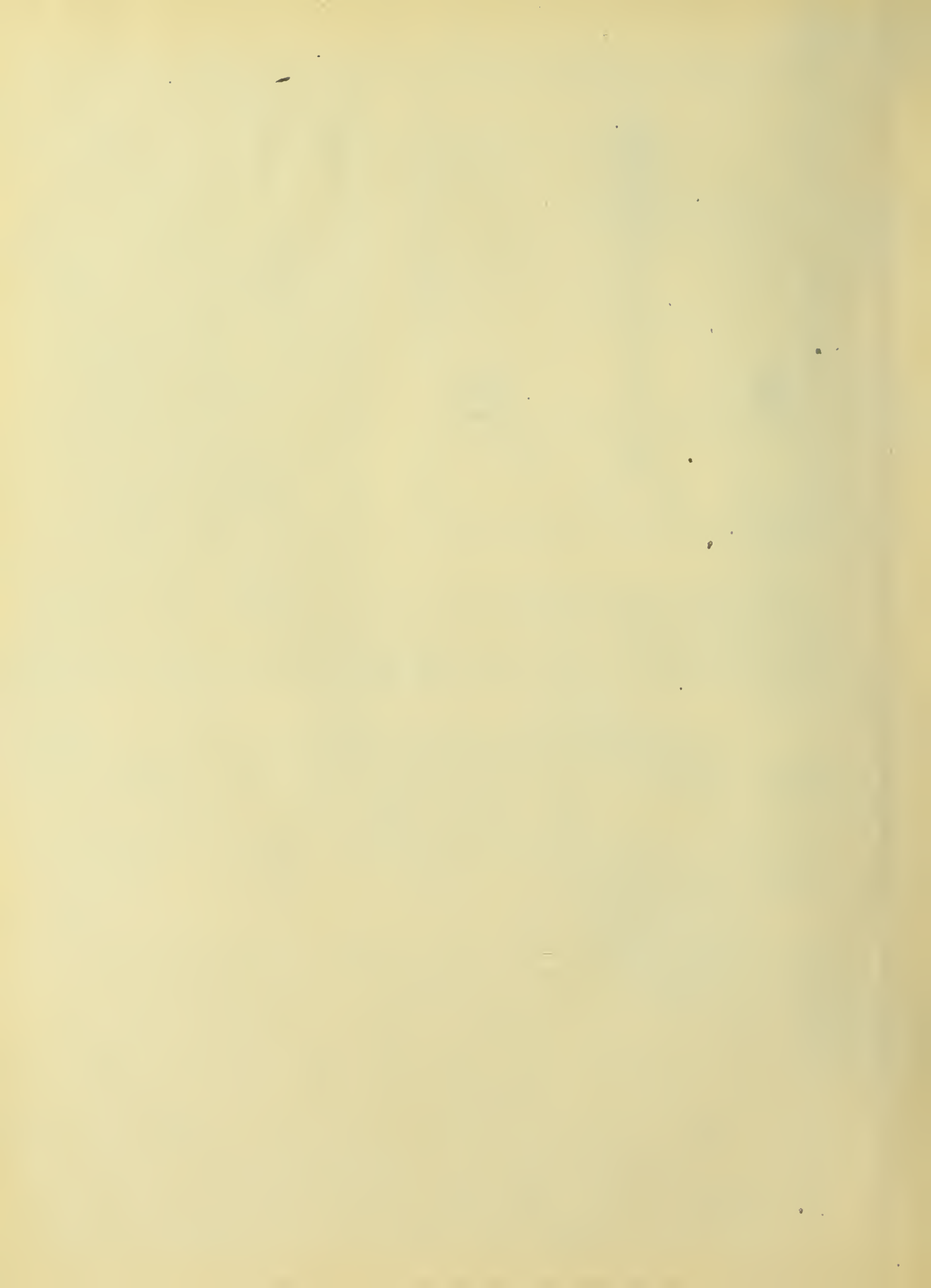


ning was mostly confined to the puncturing of the top insulators by direct bolts of lightning, and in most cases a hole was bored through the top of the insulator in a line nearly vertical to the pin. The holes were about one inch in diameter and the sides were glazed. Usually the insulators were badly shattered, but on putting the parts together one could generally find the glazed hole referred to. Some few side insulators were lost, but they were almost invariably injured at the same time that the top insulators on the same or adjacent towers were destroyed. The side insulators were never punctured vertically from the top, but in some cases they showed

a small puncture in a horizontal direction from the tie-wire to the pin. In nine cases out of ten, however, they were not punctured at all, but half of the top and portions of one or both petticoats on the same side were broken, presumably by the power current following the lightning discharge over their surfaces.

As the greatest trouble came from direct bolts of lightning striking the top insulators, it was thought advisable to erect lightning rods on the section of the line where the most trouble had been experienced. Other means of protection were discussed at this time, the grounding of the neutral among others, but it was finally decided to put up these lightning rods immediately, on order to gain experience from the rainy season then in progress.

The lightning rods were erected in pairs starting from the point where the cross-arm was attached, and projecting up on either side of the three-inch pipe to a distance of six feet above the top insulator at an angle of about thirty degrees from the vertical. By the middle of August one-half of that part of the line giving the most trouble was equipped with lightning rods, and there had been quite a few rods erected on towers that were considered as being particularly exposed to lightning. After the erection of these rods the difficulties were very greatly lessened, but there was still considerable trouble experienced. In no case ^{were} top insulators punctured through from the top as were those on towers where there were no rods in place. During one very severe storm, eight insulators were broken on seven towers spread out over a distance of more than a mile. On account of the distance between the towers, it is improbable that the



same discharge of lightning could have caused all this trouble, unless it was transmitted over the power lines. These eight insulators were broken in such a manner as to make it entirely probable that the current had gone over their sides. Several other cases occurred similar to this one, until at last the engineers of the line came to the conclusion that the lightning-rods merely prevented the lightning from striking the insulators, and really increased the tendency of the discharge to travel along the power lines.

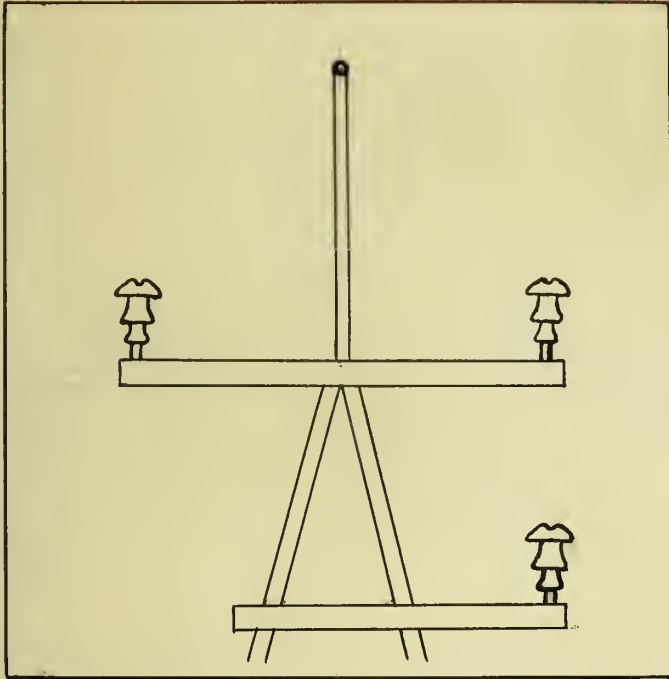
After finding that that the lightning-rods were not an adequate protection, it was decided to try the experiment of lowering the top conductor to a place below the side conductors, and putting a grounded cable in its place. On the highest point of the tower a quarter-inch seven-strand cable was strung, and was grounded at each tower. At the time that this change was made, larger insulators were also installed. This change was only partially completed when the rainy season of 1906 set in, and the work was suspended until the following year.

During the rainy season of 1906 the transformers were connected in star on the high tension side, the center of the star being grounded. In order to detect instantly when a ground was on the line, a current transformer was put into this ground connection and the secondary leads were brought out to an ammeter on the switch-board. By this means, when an insulator broke down, or the power current followed the lightning over the insulator, the station operator was able to tell it instantly, and could shut down at once, if necessary.

There was no apparent trouble from lightning during the rainy season of 1906 where the grounded cable was in place. On several occasions grounds came on the system during lightning storms, and the power was immediately cut off to clear them. In general, the grounds did no permanent injury to either the line or the insulators, for it was seldom that the ground could be located. Thus it is probable that the discharge did go over the insulators on the section where the grounded cable was in place.

The experience derived from this experiment indicated that the grounded cable itself was the best possible protection against lightning discharges, so the lightning rods were dispensed with entirely. With the lowered top conductor, and the grounded cable in its place, the present appearance of the line is as is shown in the sketch on the next page. It will be noticed that the top cable is fastened directly to the pipe extension of the tower and is thus grounded through the tower itself.

The conclusions which may be drawn from the example just cited can be summed up in a few words. A grounded cable, strung above the transmission wires at the highest point of the tower, is certainly much more effective than lightning rods as a protection for the insulators and conductors against the direct



bolts of lightning. If this grounded cable is combined with a grounded neutral, a very effective means of detecting grounds on the system is obtained. The importance of this means of protecting the line against lightning is rapidly becoming less, since, with the new lines which are transmitting extremely high voltages, the corona limit is placed so low that lightning discharges are taken care of by corona discharge.

In order to reduce the space covered by citing examples of lines which use, or do not use the grounded neutral, the remainder of this

thesis will be devoted to a general summary of conclusions drawn from numerous papers and articles written by electrical engineers. These papers and articles are listed at the end of this thesis.

In discussing the advisability of grounding electrical systems, several questions naturally present themselves, among which are these:-

1. Why should the neutral be grounded? What advantages and disadvantages would be entailed if the neutral is grounded?
2. If a ground is used, shall it be at one point of the system, or at several?
3. Should a resistance be used in series with the ground connection, and if so, how much?

The advantages of grounding the neutral may be summarized briefly as follows:-

- a. Grounding the neutral fixes the value of electromotive force between line and ground. In case the insulation between line and ground is broken, the potential is only .58 as much as the voltage between lines. With an ungrounded neutral, the breaking of one conductor causes full line voltage to exist between the remaining two conductors and the ground.
- b. By keeping static conditions balanced, the grounded neutral minimizes the static induction on neighboring circuits. Since it is the static induction of transmission lines which causes the trouble on telephone circuits, this point is an important one.
- c. The grounding of the neutral makes possible the use

of the earth as a return current carrier. It is perfectly possible to continue to transmit power over a three-phase system with one line out of commission, if the neutral is grounded at both the sending and receiving ends. Some companies, in fact, transmit power to some customers over a single line and depend entirely on the ground as a return circuit. In a modified form, this is what has been previously explained in the discussion of the Chicago Edison and Commonwealth Electric Companies' lines. As soon as it is attempted to transmit power over a three-phase line with one conductor out of commission, the electrostatic balance is destroyed, and the static induction on adjacent telephone lines is as great or greater than the induction of a three wire line without the grounded neutral.

- d. The grounded neutral makes possible the detection and removal of any grounded portion of the system. This has been explained in the discussion of the use of the grounded neutral as a protection against lightning discharges.
- e. The grounded neutral insures equality in the condenser current drawn from each phase. All alternating current transmission lines take a certain amount of condenser current from the generators, this current depending upon certain constants of the system. These currents may be considered as flowing over two paths, namely:-
 - I. Through the condensers formed by the conductors as opposite plates, and
 - II. Through the condensers formed by the conductor as one plate and the ground as the other.

The currents flowing between the conductors are evidently independent of grounded neutral conditions. Those flowing from the conductor to the ground, however, depend entirely upon the position of the neutral. If the neutral is grounded, the condenser currents from each phase are equal. Should one of the three conductors become grounded, with an ungrounded neutral, the condenser currents between the remaining conductors and the ground will be increased to the same value as the current between conductors.

The disadvantages of the grounded neutral are obvious, the most important one lying in the fact that, with the grounded neutral, the grounding of one conductor causes a short circuit on the line, and in the fact, now generally conceded, that a satisfactory ground connection is hard to obtain. The first is unavoidable, but may be partially converted into an advantage by using the short circuit current to cut out the broken conductor automatically. The second is rapidly losing its importance, since, with the present day high voltages, slight variations in the resistance of the ground connections, due to climactic conditions, are rarely the cause of much trouble.

The questions which arise in regard to the number of places

to ground the system, and the resistance to be connected in series with the ground connections, are subjects which must be dealt with separately in every system. Increasing the resistance of the ground connection decreases the current which can flow on short circuit, but it also produces an undesirable drop in voltage. The correct plan to follow is to employ such resistance as will produce the smallest voltage drop in combination with safety under short circuit.

High voltage alternating current systems only have been treated with in this discussion. In low voltage systems, both alternating and direct current, the ground has been used as a return current carrier, and has proved eminently satisfactory in most cases. Telephone and telegraph circuits also use the ground as a current carrier, and thereby save a considerable amount of copper. In using the ground as a current carrier for direct current, care must be taken to ground the negative terminal, in order to prevent the wearing away of water and gas pipes.

Summing up briefly, it may be seen that the disadvantages of grounding the neutral of electrical systems are rapidly decreasing, while the advantages, on the other hand, are even more rapidly increasing, so that it is safe to conjecture that it will not be long before every three phase transmission line of any appreciable length and of more than moderate voltage will be equipped with device. It is probable that, before long, even low voltage systems will be fitted with some modification of the grounded neutral, since possibilities for the extended use of this contrivance are becoming greater every day.

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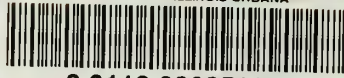
The Investigation of Ground Connections.

Of the many other publications which were read, but a very small percentage of the subject matter was available for the particular needs of the writer.





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