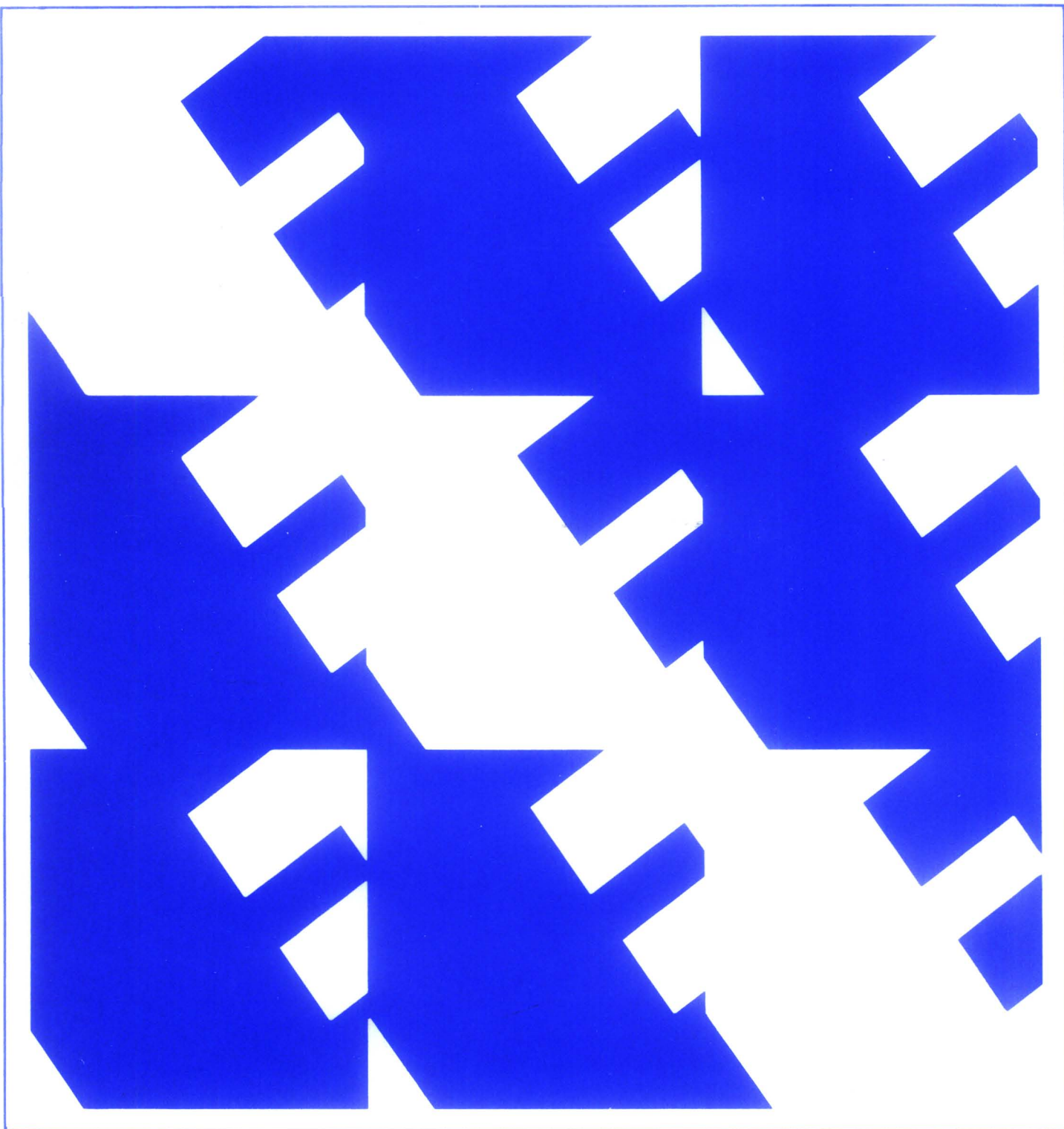


IEEE Guide for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding of Transmission Systems

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IEEE Guide for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding of Transmission Systems

Sponsor

Working Groups of the Fault Limiting Devices
Subcommittee of the AIEE Committee on Protective Devices

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Application Guide for GROUND-FAULT NEUTRALIZERS

Improvement in service reliability is a factor in power transmission and distribution which has received considerable emphasis in recent years. Several means for obtaining improvement in service reliability are in general use. These include ground-fault neutralizers, immediate reclosing of circuit breakers, overhead and buried ground wires, arresters and expulsion protector tubes. All have demonstrated an ability to limit outages on transmission and distribution systems. None of these means considered, however, has shown a perfect record in all cases of application.

Ground-fault neutralizers have been applied principally in the range of medium transmission voltages. The effectiveness of ground-fault neutralizers on a system depends on the ratio of single line-to-ground faults in the total number of non-persisting faults. This ratio is influenced by the transmission line configuration, the line insulation employed, and the structure-footing resistance if structure down-leads are used. Where this ratio has been high, ground-fault neutralizers have provided an excellent record in reducing line outages 80 to 90 percent.

Immediate reclosing of circuit breakers has been effectively applied in many applications mainly to radial feeders and tie lines in the medium transmission voltage range.

Overhead ground wires have shown an almost perfect record when they are installed properly to shield the conductors from direct strokes and when accompanied by low structure-footing resistance* and adequate insulation. These applications have been most effective mainly at the higher transmission voltages on steel towers. On wood structures, where the design utilizes the impulse insulation strength of the wood, they have been effective at all transmission voltages.

Expulsion protective gaps have demonstrated good performance mainly in the range of medium transmission voltages and especially on wood-pole H-frame lines.

It should be recognized, however, that the use of one of the above methods does not preclude the use of one of the other methods applied in combination. Combining two methods may be justified economically when sufficient stress is placed on service continuity.

The intent of this application guide is to present the various criteria which may effect a proper application of ground-fault neutralizers to a system. Included are the factors which determine the ground-fault neutralizer ratings required.

The Ground-Fault Neutralizer

The ground-fault neutralizer, which may be installed at one or more locations on a system, is a protective device which responds to single line-to-ground faults on any three-phase system which otherwise is not grounded. It

* The buried ground wire (counterpoise) has been an efficacious, and usually economical means of securing suitable structure-footing resistance.

is a grounding device which provides an inductive component of current in a ground fault that is substantially equal to and therefore neutralizes the rated-frequency capacitive component of the ground-fault current. The device is essentially an adjustable reactor with special characteristics, connected between one or several transformer neutrals and ground. Although the theory of operation has been described in the literature,¹ any consideration of the application of the ground-fault neutralizer justifies a review of the basic principles.

A single line-to-ground fault on a three-phase power system operated without grounded neutrals causes the two unfaulted phases to rise to line-to-line voltage above ground, or higher in some circumstances. Line-to-ground charging currents which lead their respective voltages by 90 degrees flow in each of the unfaulted phases. The vectorial sum of these currents returns through the fault to the system. This summation current will lead the phase-to-neutral voltage of the faulted phase by 90 degrees. Hence, the current in a line-to-ground fault on an ungrounded system consists solely of the charging current to ground of the other two conductors except for a slight loss current.

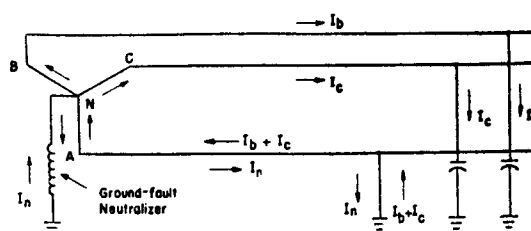


FIGURE 1A
Idealized ground-fault currents on neutralizer grounded systems.

The principle of operation when a ground-fault neutralizer is applied to such a system is illustrated in Figure 1. This considers a single line-to-ground fault on phase A. The voltage on the two unfaulted phases rises to line-to-line voltage above ground, and line-to-ground capacitive, or charging, current flows in these phases. The line-to-ground capacitive reactance of the faulted phase is effectively shorted out by the fault.

Since the system voltages to ground are displaced at the time of fault, phase-to-neutral voltage is applied across the ground-fault neutralizer connected between the transformer neutral and ground. An inductive current tends to flow through the fault. This current lags the voltage by nearly 90 degrees, and is limited primarily by the neutralizer reactance. This current is also nearly 180 degrees out of phase with the resultant line-to-ground charging, or capacitive, current. With the neutralizer properly adjusted, the magnitude of the inductive current

¹ For numbered references see bibliography.

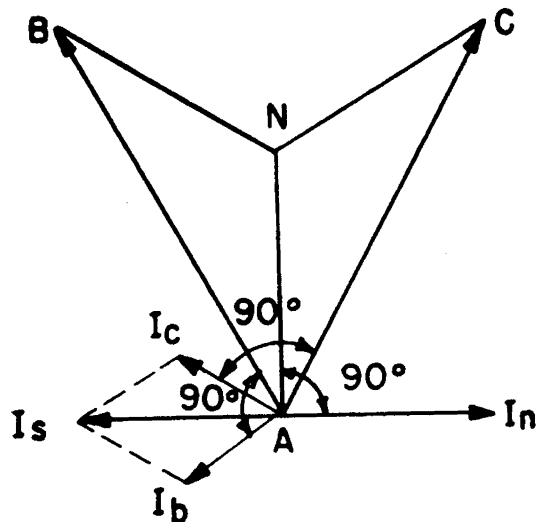


FIGURE 1B

Idealized vector relationships of voltages and currents in Figure 1(A).

through the neutralizer will be approximately equal to the capacitive ground-fault current so that the reactive component (quadrature component) of the current in the fault will be substantially zero. In other words, the capacitive current in the fault will be "neutralized."

In practice, complete neutralization of the fault current is not essential. A small in-phase component of fundamental frequency is always present due to resistance, leakage, and corona loss. This residual current component, however, is practically in phase with the voltage and will not sustain an arc since the current and voltage pass through zero at approximately the same time. If harmonic components exist in the system voltage, harmonic components of fault current will be present. In addition to the limitation of the fault current to a low value, the rate of rise of the recovery voltage of the faulted phase is kept so low that the arc path will have time to de-ionize before the arc can restrike.

When the neutral of the delta-wye supply transformer or grounding transformer is solidly grounded; i.e., a ground-fault neutralizer is not used, a line-to-ground fault causes current to flow in the fault which lags the phase-to-neutral voltage of the faulted phase. This current is usually so much greater than the charging current to ground of the unfaulted phase that the effect of the latter is negligible. There is, therefore, a high current flowing through the arc, which is favorable to the maintenance of the arc, as contrasted with the low, and easily self-extinguished, current in the arc when a ground-fault neutralizer is used.

From this brief outline of the principle of operation, it is evident that the ground-fault neutralizer is effective only in the case of single line-to-ground faults on the system. Furthermore, in the majority of ground-fault neutralizer applications to utility systems in this country, it is only in the case of non-persisting line-to-ground

faults (i.e. a fault that persists for not more than a few seconds under the arc-quenching action of the neutralizer), that an outage is prevented. However, there are some applications of ground-fault neutralizers to utility systems and all applications of neutralizers to industrial type systems, where the fault may be allowed to persist until it can be located and arrangements made for repairs. Experience has indicated that non-persistent faults represent approximately 50 to 80 percent of the faults on most systems. This percentage is a function of the type of system, whether overhead or cable, of the type of line construction, and of the maintenance of the transmission system. Furthermore, many faults which are "relayed off" as line-to-line or three-phase faults start as single line-to-ground faults and spread with time to involve additional phases. This spread is prevented in most cases by the arc-quenching action of the ground-fault neutralizer. Further, it is noteworthy that the neutralizer is effective not only in the case of lightning but in other causes of disturbances as well; small animals, birds, tree limbs, wind, sleet or any other cause of single line-to-ground fault.

Ground-fault neutralizers have been applied on overhead line systems, mixed overhead line and underground cable systems and on underground cable systems. Operating experience on all of these types of systems has been satisfactory. However, experience to date in this country on cable systems has not been sufficient to establish a reliable statistical analysis of the operating results.

On cable systems, non-persisting ground faults are rare. The application of a ground-fault neutralizer to a cable system is predicated on the following:

- Minimize the damage to the cable at the fault location through the limiting of the fault current to a few amperes.
- Materially reduce or eliminate the damage to the cable sheath in the ducts.
- Take advantage of the slow rate of rise of the recovery voltage during faults.
- Limit the amplitude of transient overvoltages which exist during line-to-ground faults on systems operated with neutrals isolated.

The application of ground-fault neutralizers to cable systems in this country has been to those previously operated as isolated-neutral systems. These applications have been made to accomplish the above benefits. However, the location of persisting ground faults has been by the "cut-and-try" methods common to location of faults on isolated-neutral systems. It might be pointed out in passing that in Europe an additional reason for the application of ground-fault neutralizers to underground cable systems is to keep ground-faulted cables in service until they can be de-energized to locate the fault and repair the cable at a more convenient time. However, operation can cause interference on communication circuits and false operation of signal circuits, and is usually disapproved in this country when these disadvantages are encountered.

In underground cable systems a reduction of the residual ground-fault current to its minimum value is desirable on permanent faults to gain maximum benefit from the neutralizer. This necessitates operation of the neutralizer near the correct tuning point to the system.

Ratings of Ground-Fault Neutralizers

Neutralizers are rated on the basis of voltage, current, frequency, and time in accordance with AIEE Standard No. 32-1947. A consideration of these ratings is essential to the problem of application.

Voltage Rating

The nominal voltage rating of a neutralizer is the same as the system nominal line-to-line voltage. However, the insulation class is determined by the line-to-neutral voltage and is selected from the standard voltage class equal to or next higher than the system line-to-neutral voltage.

Examples

1. Ground-fault neutralizer for a 57 kv system. The line-to-neutral voltage is 33 kv so that the neutralizer would normally be placed in the 34.5 kv insulation class.
2. Ground-fault neutralizer for a 69 kv system. The line-to-neutral voltage is 39.9 kv so that the neutralizer would normally be placed in the 46 kv insulation class.

A lightning arrester is normally applied across the

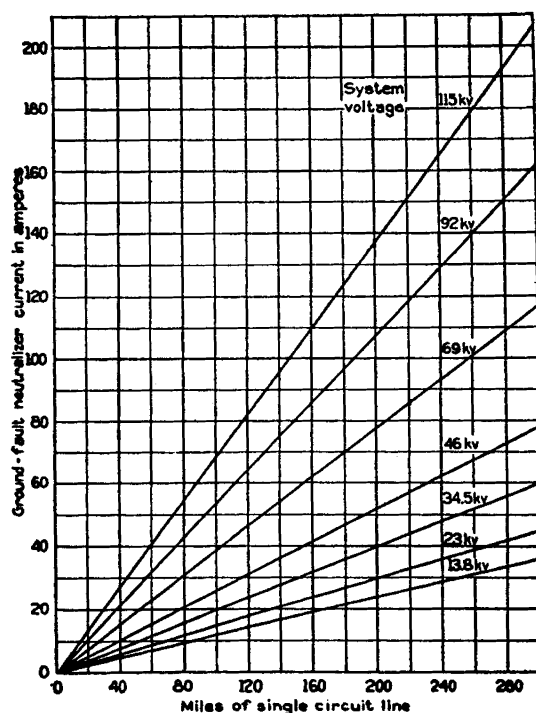


FIGURE 2

Curves, based on average data, indicating approximately the current rating a neutralizer should have for protection of single-circuit, open-wire lines of various lengths and voltages.

neutralizer as an integral part of the equipment to protect this insulation level. The lightning arrester should have a rating of at least 120 percent of the line-to-neutral voltage of the system. In the above Example No. 1, a 40 kv rating of lightning arrester would be the minimum rating.

Current Rating

The nominal current rating of a neutralizer is specified as a range of currents. The theory of neutralizer operation demonstrates that, in order to accomplish neutralization of the fault current, the neutralizer current must be equal to the charging current in the line-to-ground fault. The charging current is essentially proportional to the length of transmission lines (overhead line and/or underground cables) in the system. This charging current can be calculated by various analytical methods. However, experience has demonstrated that the methods available invariably give lower values than actual test determinations.

The curves of Figure 2, based on average values, indicate the approximate current rating of a ground-fault neutralizer as a function of the number of miles of single-circuit overhead line in service for various nominal voltages. For double-circuit lines on the same tower or poles, the particular line sections can be reduced to approximate equivalent single-circuit miles of overhead line by increasing the single-circuit mileage by a factor indicated in Figure 3. For lines having overhead ground wires, the line section can be converted to approximate single-circuit miles of overhead lines by using multiplying factors, such as 1.08 for one ground wire and 1.15 for two ground wires. For cables, the particular sections can be converted to approximate equivalent sections of single-circuit overhead line by the following factors: 1 mile of 3-conductor cable = 25 miles; 1 mile of 1-conductor cable = 50 miles.

For those systems where the length of cable or the length of double-circuit lines may materially affect the ampere rating of the ground-fault neutralizer, tests to determine the actual charging current should be made. An adequate test would be to measure the fault current

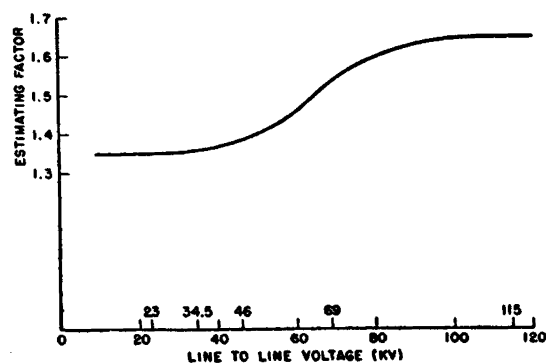


FIGURE 3

Estimating factors for converting miles of double-circuit line to equivalent miles of single-circuit line.

in a single line-to-ground fault with all neutrals isolated from ground. This test would measure the charging current of the faulted system. In making this test, caution should be exercised to insure measuring equipment and connections are adequately protected against effects of the occurrence of a simultaneous ground fault on another phase.

If it is desired to estimate the ampere rating for a ground-fault neutralizer at a voltage other than indicated in Figure 2, the rating can be approximated by interpolating between the two appropriate curves.

The maximum current rating is dictated by interconnections and future system growth at the same voltage. In cases where such factors cannot be readily determined, experience has proved that it is good practice to allow a margin of approximately 20 percent in excess of the existing maximum requirements. The minimum current rating is generally established by the minimum length of line that operating experience indicates may be connected to the system and for which retuning of the neutralizer is desirable. Therefore, it is necessary that the neutralizer be capable of supplying a range of currents depending on the total mileage of the transmission lines in service.

The ratio of maximum to minimum current found most applicable in this country is generally 2 to 1 or 4 to 1; e.g., 60 amperes to 30 amperes, or 60 amperes to 15 amperes.

Frequency Rating

The frequency rating of the neutralizer is the same as the system frequency.

Time Rating

Ground-fault neutralizers are designed for either a 10 minute rating or an extended-time rating, in accordance with AIEEE Standard No. 32-1947, paragraph 32-4.08. The 10 minute time-rated neutralizers are required to be capable of carrying 30 percent of rated current continuously. Experience has demonstrated that these ratings will meet adequately the requirements of application. As generally applied in this country, the 10 minute rated units are applied to systems having protective relays and circuit breakers for locating and immediately isolating any line section which has a permanent ground fault. These units carry full-rated current for only short-time intervals, as they include equipment for automatically by-passing the neutralizer on the occurrence of permanent faults. During the by-passed period the system neutral is grounded, permitting fault currents to flow which in turn allow selective relaying to isolate the faulted-line section.

The extended-time rated units are applied to systems on which permanent ground faults must be located by "cut-and-try" methods, so that considerable time may elapse before the fault can be isolated. Extended-time rated units, therefore, are based on systems where the fault is allowed to persist until it is convenient to locate and repair the faulted circuit. This form of operation may be undesirable on systems involved in inductive

exposures since excessive noise in communication circuits and false operation of signal circuits may occur during the period that one phase is grounded.

APPLICATION

Number and Location of Units

It is impossible to state any general rule on the number of neutralizers to use in a given application. However, a neutralizer in each section of the system which may become sectionalized during disturbances is necessary to provide the utmost in protection and simplicity of operation. Theoretically, one large neutralizer is sufficient to protect all parts of a metallicallly-connected system. However, if the system is extensive it is usually advisable to install several smaller neutralizers. These can be used either individually or in combination as system operating requirements may dictate. The total of the neutralizer currents will be the same, whether one or several neutralizers are required.

The individual neutralizer current ratings are chosen so that the neutralizers will then tune the portion of the system to which they are assigned. System sectionalizing by switching should be arranged so that it will not affect the tuning of the neutralizer appreciably. Furthermore, each neutralizer should be centrally located, preferably at a location from which several lines radiate.

System Insulation Levels

During a single line-to-ground fault, the two unfaulted lines are raised to line-to-line voltages above ground. Hence, all conductors and apparatus connected between line and ground must have sufficient insulation to operate at least temporarily at line-to-line voltage. This necessitates selection of system lightning arresters on the basis of line-to-line voltage and precludes the use of lightning arresters of a lower voltage rating. Neutral insulation and neutral bushings on power and grounding transformers must be suitable for the normal line-to-neutral voltage.

Balanced Voltages to Ground

Few systems have their lines completely transposed, but experience has shown that, in general, for the system as a whole, the three phases of a system are well transposed, the capacitance-to-ground of the three phases are nearly equal. Hence, the line-to-ground voltages are satisfactorily balanced when a ground-fault neutralizer is installed. This is explained from the fact that most systems are composed of several types of construction in which the position occupied by the phases varies in the different configurations, or in different sections of the same configuration.

The electrostatic balance can be checked in advance of the neutralizer installation by measurement of the voltage between neutral and ground, with the system neutral isolated from ground at all points. (Caution: For safety reasons, the measuring device should have an insulation level of at least the line-to-neutral voltage class.) If this voltage does not exceed approximately one percent of

the system line-to-neutral voltage, the balance is reasonable, and no steps need to be taken to improve the balance.²

A reasonable electrostatic balance can be obtained by having each section of the system completely transposed or by balancing the system as a whole. The former offers the greatest flexibility in system operation but is generally not required for satisfactory system operation.

Why is a reasonable voltage balance required for a neutralizer application? The unbalanced, or residual voltage, which can be measured as above, can be considered as impressed in series with the circuit consisting of the neutralizer and the capacitance-to-ground of the transmission system. When the neutralizer is in tune and the system is without a fault, a series resonant circuit exists which permits a circulating current to flow through the neutralizer and the system distributed capacitance-to-ground. This current is caused by the residual voltage referred to above and is limited by the equivalent zero-sequence resistance only. The current flowing through the neutralizer causes a voltage drop across it with resultant unequal voltages between phase conductors and ground and a consequent displacement of the system neutral. Practice has indicated that this current should not exceed approximately 25 percent of rated tap current. This arbitrary limit of 25 percent has been chosen as the maximum for values noted in tuning tests. System voltage fluctuations in operation may cause the neutralizer current to approach the 30 percent limit permitted

by AIEE Standard No. 32-1947. Although the 30 percent limitation is applied to the 10 minute time-rated units, this limit has proven a practical one for system operation with neutralizers of all time ratings. The variation of this current near the tuning point of the system is illustrated in Figure 4 and is discussed under "Tuning of Ground-Fault Neutralizers."

The capacitive balance can often be corrected by properly interchanging the phases in one or two line sections. In some cases the neutralizer has been slightly detuned so as to reduce the circulating current.

Single-phase disconnecting equipment, such as line sectionalizing fuses or single-pole disconnecting switches, may create a serious unbalance on an otherwise well-balanced system. In general, single-phase disconnecting devices should not be used at any location where the operation of one will isolate more than approximately 8 percent of the total conductor length of the entire system. To express the value in terms of a percentage in this manner is a good approximation since system recovery voltage is influenced in this way. If a greater percent is isolated by fuses, dangerous overvoltages can result. This permits the use of fuses at tap-off substations to protect transformers.

System Interconnections

Systems at the same voltage which are independently protected by ground-fault neutralizers may be metallically connected without retuning the neutralizers. When metallic interconnection with an unprotected system is made, successful operation of a neutralizer is obtained only when the neutralizer is retuned to compensate for the added line mileage. Obviously, no neutral can be grounded through low impedance on the interconnected system as this would effectively short circuit the neutralizer. In cases where metallic interconnection cannot be made, a two-winding transformer connected either delta-delta or wye-delta of one-to-one ratio will serve as an isolating barrier as far as neutralizer operation is concerned.

Transformer Consideration

The neutralizer imposes an additional load on the transformer bank to whose neutral it is connected. For 10 minute rated units, this is usually of small consequence. Where operation may continue for an extended time with a sustained ground fault, it is necessary that the loading of each phase of the transformer be checked. For this condition on an extensive system where more than one neutralizer is used, the transformer loading problem is simplified because of the smaller rating of the neutralizers.

Where there is no neutral available for connection of a neutralizer, a grounding transformer can be applied. The grounding transformer of low zero-sequence impedance may be connected either zig-zag or wye-delta.

The use of three-winding transformers connected wye-wye-delta requires special consideration for operation with ground-fault neutralizers. If the neutral of one wye winding is isolated from ground, a neutralizer can be con-

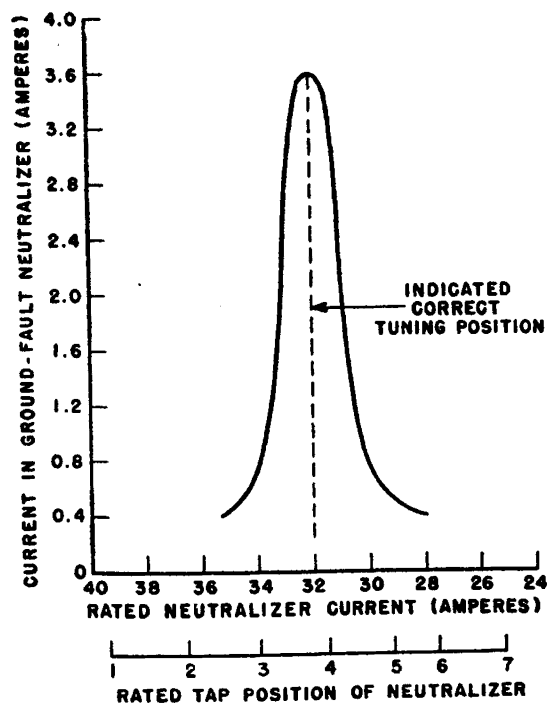


FIGURE 4
Sample tuning curve for ground-fault neutralizer with no fault on a 69 kv system.

nected to the neutral of the second wye winding. Caution is required if it is desired to connect neutralizers to the neutrals of both wye windings or to connect a neutralizer to the neutral of one wye winding with the second wye grounded. This caution is occasioned by the fact that faults on one system would inject a zero-sequence voltage into the series resonant circuit of the unfaulted neutralizer-grounded system, and thus would provide the possibility of overvoltages in the latter system. Special consideration can be given to the transformer impedance to preclude the occurrence of overvoltage. If this is not feasible, the use of special compensating transformers connected to the transformer neutrals will permit the application of neutralizers under these conditions.

The use of an autotransformer precludes the application of ground-fault neutralizers unless the rated voltages of the autotransformer are within approximately 10 percent of each other. When the voltage ratio requirement is fulfilled permitting application of a neutralizer it must be capable of compensating for the line-to-ground charging current of both systems connected to the autotransformer since the autotransformer effectively constitutes a metallic interconnection.

Ground-Fault Neutralizer Auxiliaries

The ground-fault neutralizers, as generally furnished in this country, are supplied with a fault indication source in addition to the lightning arrester heretofore mentioned. The fault indication source may be a potential transformer connected in shunt relation to the neutralizer or may be a current transformer connected in series with the neutralizer. Either arrangement will show the existence of a fault on the protected system when neutralizer current of sufficient magnitude is flowing.

On extended-time rated neutralizers, as generally applied in this country, the above fault indication is used to sound an alarm. In addition, a record of the neutralizer operation is obtained through use of a recording ammeter or voltmeter.

On 10-minute time rated neutralizers, the fault indication is generally used to initiate the start of a timing device which, after a predetermined interval, causes closure of the ground-fault neutralizer by-pass switch. The by-pass switch is usually a spring operated air insulated switch arranged for automatic closing. It was previously noted that the ground-fault neutralizer can be of the insulation class of the line-to-neutral voltage. Accordingly, the by-pass switch can be of the line-to-neutral voltage class. However, for systems 69 kv and below, the desirability of bus supports and switch components being of the same class as the other substation apparatus outweighs the economics of the reduced insulation. Hence, it has been general practice to use the insulation class of the line-to-line voltage for the by-pass switch in the voltage range of 69 kv and below, and to use the insulation class of the line-to-neutral voltage for applications above 69 kv.

The time interval before closure is determined by the period felt by the system operator as sufficient for the

non-persisting faults to be cleared without resorting to a service interruption through relay action. Primarily, tree conditions dictate the length chosen. The period chosen by most system operators is from 5 to 10 seconds. It is evident that it is essential for the timing relay and its auxiliaries to be incorporated in a scheme which insures co-ordination of the closure of all neutralizer by-pass switches on the system as well as those used for additional system grounding points.

Additional System Grounding Points

On systems where 10 minute rated neutralizers with their automatic by-passing equipment are applied, automatic grounding of transformer neutrals at locations other than at the point of neutralizer installation may be necessary to obtain proper magnitude and distribution of short-circuit currents for selective ground relaying. Additional neutral grounding equipments, similar to the neutralizer by-passing equipment, can be applied. The closing of these additional grounding switches can be initiated by zero-sequence voltage. Zero-sequence voltage may be obtained, for example, by connecting a potential transformer between the power transformer neutral and ground, or by some other available method. Hence, simultaneous closing within adequate limits of all the grounding switches can be obtained without interconnecting their control circuits.

INSTALLATION AND OPERATION

The ground-fault neutralizer is effective in clearing only single line-to-ground faults. A major factor in its effectiveness is the type of line construction. It is desirable, therefore, that the line construction be such that most of the faults occurring will originate as single line-to-ground faults.

If an overhead ground wire is located in such a manner that the phase conductors are enveloped by a wedge formed by extending two lines through the ground wire at angles not greater than 45 degrees with respect to a vertical line through the ground wire, in conjunction with low ground resistance, it will effectively shield the line from most direct lightning strokes. By making use of this direct-stroke theory, a transmission line can be constructed so that the top conductor in a triangular configuration will serve as a quasi-ground wire. In addition, if the insulator pin of the top conductor is grounded, this conductor will have a somewhat lower impulse strength to ground than the other two phases. Consequently, a large percentage of lightning strokes to the line will be intercepted by the top conductor creating a line-to-ground flashover which will be cleared by the neutralizer. The downlead should have a sufficiently low ground resistance so that lightning currents will not raise the potential of the pole top to a value high enough to cause flashover of the other two phase conductors. This type of construction has proved very effective in establishing excellent operating records.

Other structure configurations will give various de-