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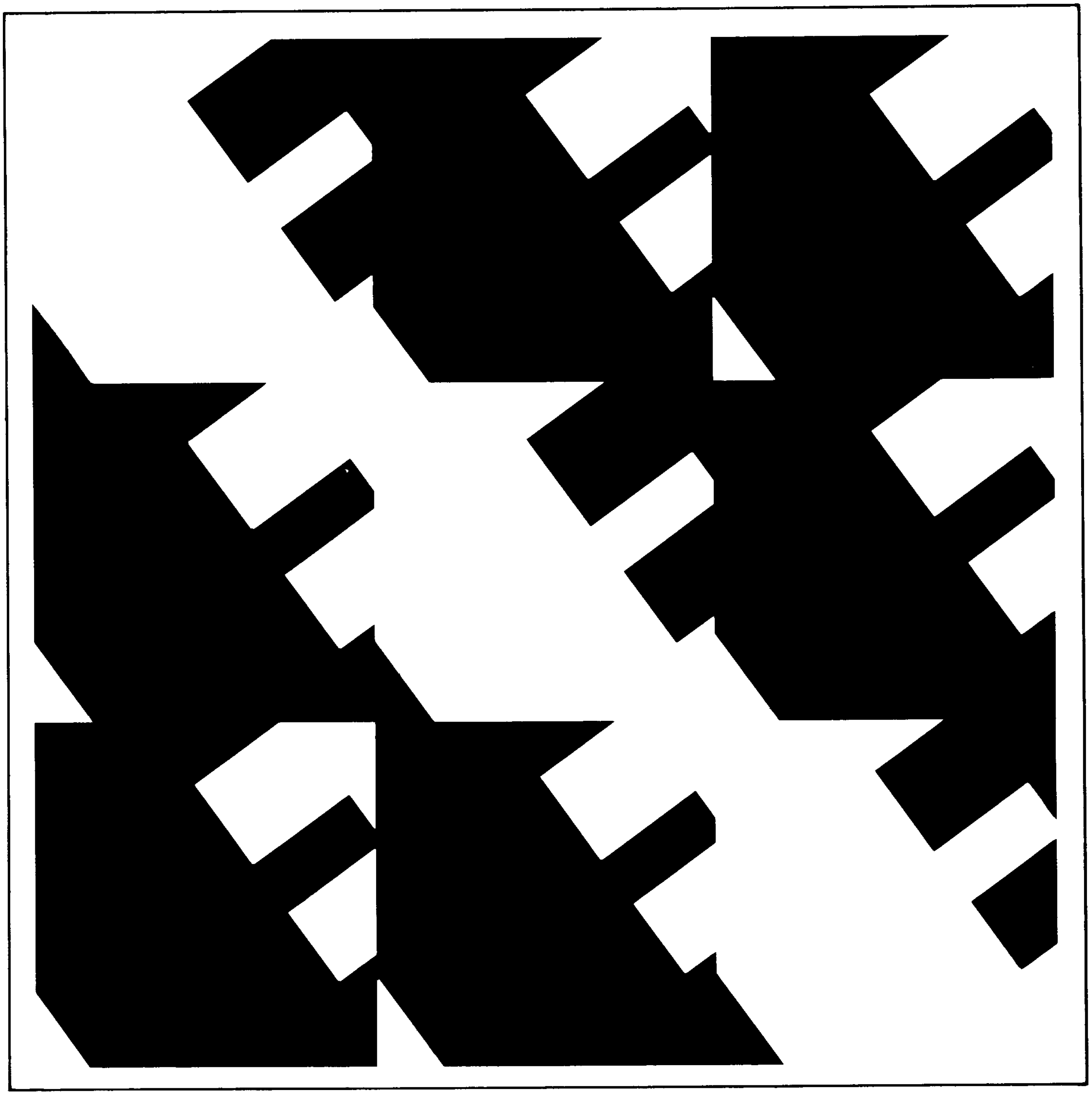
ANSI/IEEE Std 575-1988

IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths



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IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths

Sponsor

Insulated Conductors Committee of
IEEE Power Engineering Society

Approved March 13, 1986
IEEE Standards Board

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American National Standards Institute

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Foreword

(This Foreword is not a part of ANSI/IEEE Std 575-1988, IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths.)

This guide has been prepared because of the increasing use of single-conductor cable systems brought about by the extended use of solid dielectric metallic sheathed cable and revival of interest in single-conductor oil-filled cable.

The activities of the IEEE working group have closely paralleled those of CIGRE Working Group 21-07. The close cooperation of the CIGRE group and the Chairman, E. H. Ball, has been most welcome. The IEEE group acknowledges with gratitude the rights to reproduce parts of the text and some of the drawings from the report produced by the CIGRE group.

Over a period of many years Task Group 3-51 met many times and inevitably there were many changes in both membership and chairmen. The original group who contributed most of the engineering content, even though many of them have now retired or resigned, are included in the Task Group as follows:

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J. M. Cooney and D. J. Horrocks, although not members of the working group, have been responsible for much of the technical work and editing, and their contributions are also gratefully acknowledged.

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An American National Standard

IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths

1. Introduction and Scope

1.1 Introduction. Since the first installation in 1935, high-pressure, oil-filled, pipe-type cable has become the dominant system in North America for cables operating at 60 kV and above. For the two decades following 1935, the number of installations of self-contained cables decreased steadily.

However, with the development of low loss, high dielectric-strength insulating materials and improved cable jackets in the mid-1960's, and their application at subtransmission and transmission voltages, there has been renewed interest in the use of single-conductor cables and the problems of the induced voltages and currents associated with their use. Many of these problems (for example, failure of sheath insulators, failure of cable jackets, and sheath corrosion) have been recognized since metallic-sheathed cables were first used, and the fundamentals of calculating sheath voltages and currents have been defined for many years. However, the increased ampacity requirements and short-circuit capabilities of modern power systems have accentuated some problems, while improvements in sheath insulations have virtually eliminated others.

Thus it has become evident that there is a need for some guidelines whereby the cable engineer can select the sheath-bonding method that best fits the needs of a particular installation.

Although the following text was written on induced voltages and currents in metal sheaths, the principles apply equally to concentric neutrals or cable shields.

1.2 Scope. This guide describes the most common sheath-bonding systems now in use and the methods of calculating sheath voltages and currents, particularly as applied to three-phase systems operating at 60 kV and above, with the neutral grounded directly or through an impedance.

The user is cautioned to make sure that a design does not contravene any local or national regulations.

2. References

This guide shall be used in conjunction with the following publications.

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[14] KLEWE, H. R. S. Interference Between Power Systems and Telecommunication Lines. London: Arnold, 1958.

[15] KUWAHARA, K. and DOENCH, C. Evaluation of Power Frequency Sheath Currents and Voltages in Single Conductor Cables for Various Sheath-Bonding Methods. *IEEE Transactions (Power Apparatus and Systems)*, Special Supplement, 1963, pp 206-235, Item 3784.

[16] OGORODNIKOV, V. E. Surges on Metallic Cable Sheaths. Montreal: Canadian Electrical Association Winter Meeting, Paper, 1964.

[17] *Protection of Sheath Insulating Joints on High-Voltage Cable Circuits*. Ontario, Canada: Ontario Hydro Research Division, Report no 62-78.

[18] SEARING, H. R. and KIRKE, W. B. Reduction of Sheath Losses in Single-Conductor Cable. *Electrical World*, vol 92, Oct 6, 1928, pp 685-688.

[19] SIMMONS, D. M. Calculation of Electrical Problems of Underground Cables. *The Electric Journal*, vol 29, May-Nov, 1932.

[20] WATSON, W. and ERVEN, C. C. Surge Potentials on Underground Cable Sheath and Joint Insulation. *AIEE Transactions*, June 1963, pp 239-249.

[21] WOLLASTON, F. D. and KIDD, K. H. Cable Sheath Jacket Requirements to Withstand Abnormal Voltage Stresses. *AIEE Transactions (Power Apparatus and Systems)*, pt III, Feb 1962, pp 1116-1123.

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3. Recent Developments

Modern polymeric-insulated cables usually embody a semiconducting insulation shield, with some provision for fault-current return by a concentric metallic path in the form of helically applied wires or tapes, or by a solid metallic sheath.

Further coverings, when employed, are primarily for mechanical and corrosion protection but the introduction of low-cost cable jackets capable of withstanding high electrical stress has, in addition to providing the necessary mechanical and corrosion protection, permitted higher standing voltages on the sheath or shield and the use of bonding systems for increased circuit ampacities.

Sheath voltage limiters, which protect sheath insulators and cable jackets, have been developed. These sheath voltage limiters are designed to limit the

(1) Transient voltages associated with lightning
(2) Switching surges
(3) Fault initiation

The use of sheath voltage limiters is intended to reduce the problems of failures of sheath insulators and cable jackets encountered in early installations.

---

[1] IEC publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

4. Guidelines: Summary

4.1 Safety precautions and practices in design, construction, operation, and maintenance should be based on the principle that the voltage on the insulated sheath of a transmission cable may be considered analogous to the voltage on the conductor of nonshielded secondary cables.

4.2 Solidly bonded and grounded sheaths are the simplest solution to the problem of sheath voltages, and special bonding methods, by which are meant systems other than solidly bonded and grounded sheaths, are only justified on the basis of economics (usually at loads above 500 A) or at extremely heavy loads where all heat generation has to be minimized.

4.3 The simplest and most effective method of special sheath bonding is single-point bonding; a major disadvantage is that maximum cable length is governed by the permissible sheath standing voltage. As a result, when very low limiting values of sheath voltage are specified, this method will not be applicable. Single-point bonding may require a separate ground-return conductor whereas cross bonding does not.

4.4 Of the other bonding systems in use, cross bonding is the most widely used. This system is especially suitable for long cable lengths.

4.5 Cable sheaths are usually expected to be nominally at ground potential but in a specially bonded system they may have appreciable voltages with respect to ground. Under some circumstances, even solidly bonded and grounded sheaths can be well above ground potential. Some utilities allow sheath standing voltages as high as 300 V. With present-day jacket materials, sheath voltages of 600 V are possible.

4.6 Complete suppression of circulating sheath currents may not always be possible because of practical difficulties in the choice of cable lengths and spacings. It may then be necessary to calculate these residual sheath currents and assess their effect on the cable rating.

4.7 The use of special bonding gives rise to sheath overvoltages during system transients and faults and the values of these overvoltages must be considered. For higher voltage systems a sheath-voltage-limiting device is needed, and in all cases consideration must be given to the coordination of the sheath insulation levels in relation to the overvoltages to which this insulation will be subjected.

4.8 Failure of a part of the sheath insulation or of a sheath voltage limiter may result in considerable sheath currents and losses and hence may cause overheating of the cables. Consideration must therefore be given to the duty imposed on the sheath-voltage-limiting device and to the monitoring and maintenance of the complete systems in operation.

5. Bonding Methods

5.1 Introduction. The sheath of a single-conductor cable for ac service acts as a secondary of a transformer; the current in the conductor induces a voltage in the sheath. When the sheaths of single-conductor cables are bonded to each other, as is common practice for multiconductor cables, the induced voltage causes current to flow in the completed circuit. This current causes losses in the sheaths. Various methods of bonding may be used for the purpose of minimizing sheath losses. Formerly, where special bonding was employed for the prevention of sheath losses on lead-sheathed cables without an insulating jacket, the sheaths were subjected to ac voltages, and the bonding was designed to keep the magnitude of the induced voltages within small limits so as to prevent the possibility of sheath corrosion due to ac electrolysis.

Various levels of permissible sheath voltage to ground were proposed at certain times, ranging from 12 V to 17 V, to prevent corrosion due to electrolysis. At the present time, cables are usually manufactured with an insulating jacket, so that induced voltages no longer constitute a corrosion problem, and voltages comparable to secondary cable voltages may be acceptable.

The problem of sheath losses becomes particularly important when large, single-conductor cables comprising a circuit are placed in separate ducts, or spacing between directly buried cables is increased to reduce the effects of mutual heating, as significantly higher voltages are induced in the cable sheaths. The major purpose of special sheath bonding for single-conductor cables is the prevention or reduction of sheath losses.

5.2 General

5.2.1 Single-conductor, bare lead-sheathed cables have been installed in ducts and successfully operated in North America for many decades. The operating sheath voltage was limited to a certain value (normally 12 V-17 V between sheath and ground), which was governed predominantly by considerations of electrolytic corrosion. Metallic-sheathed single-conductor cables are now protected by jackets of various kinds. Where once these coverings were to serve only as an anticorrosion protection of the sheath under normal operating conditions, more recently the properties of the jacket are dictated by requirements arising out of abnormal operation of the electrical circuits so that the jacket itself has become an insulator. Limitations remain on the upper value of permissible induced voltages, but at a much higher level. They are as follows:

(1) Breakdown voltage (puncture voltage) of the insulating jacket under fault conditions

(2) Flashover voltage of sheath sectionalizing joints.

5.2.2 Any sheath bonding or grounding method must perform the following functions:

(1) Limit sheath voltages as required by the sheath sectionalizing joints

(2) Reduce or eliminate the sheath losses

(3) Maintain a continuous sheath circuit to permit fault-current return, and adequate lightning and switching surge protection

To satisfy these requirements either fully or partially, the cable sheaths are divided into a number of sections by means of sheath sectionalizing joints. The length of these sections is determined by the permissible sheath voltage levels for normal and fault conditions.

The methods of bonding these sections are discussed in 5.3. In all cases, a cable with an insulating jacket is assumed.

5.3 Design. In the design of special sheath-bonding arrangements, consideration must be given to the following aspects:

(1) The choice of sheath-bonding system to be adopted (see 5.8).

(2) Cable sheaths are usually expected to be nominally at ground potential but in a specially bonded system they may have appreciable voltages with respect to ground. Consideration should be given to any safety aspects that may arise and to any limiting values of sheath voltage that are specified.

(3) Complete suppression of circulating sheath currents may not always be possible because of practical difficulties in the choice of cable lengths and spacings. It is then necessary to calculate the residual sheath currents and assess their effect on the cable rating.

(4) The use of special bonding gives rise to sheath overvoltages during system transients and faults and the magnitudes of those overvoltages must be considered. For higher voltage systems, a sheath voltage limiter will be needed and in all cases consideration must be given to the coordination of the sheath insulation levels in relation to the overvoltages to which this insulation will be subjected.

(5) Failure of a part of the sheath insulation or of a sheath voltage limiter may result in large sheath currents and losses and hence may cause overheating of the cables. Consideration must therefore be given to the duty imposed on the sheath voltage-limiting device and to the monitoring and maintenance of the complete system in operation.

For single-conductor cable circuits carrying large currents in excess of 500 A, special bonding is often economically desirable as the reduction in losses allows an appreciably smaller conductor size to be used.

There is no clear-cut point at which special bonding should be introduced and the extra cost of the larger conductor size cables needed for a solidly bonded system must be balanced against the cost of the additional equipment and the maintenance cost arising from the greater complexity of a specially bonded system.

5.4 Single-Point Bonding. The simplest form of special bonding consists in arranging for the sheaths of the three cables to be connected and grounded at one point only along their length. At all other points, a voltage will appear from sheath to ground that will be a maximum at the farthest point from the ground bond. The sheaths must therefore be adequately insulated from ground. Since there is no closed sheath circuit, except through the sheath voltage limiter (if any), current does not normally flow longitudinally along the sheaths and no sheath circulating current loss occurs (sheath eddy loss will still be present).

5.4.1 Sheath Standing Voltages. Values of sheath standing voltage can be found using Fig 1. For a typical circuit having a conductor current

$$I = 1000\ \text{A} \qquad \frac{S}{d} = 2$$

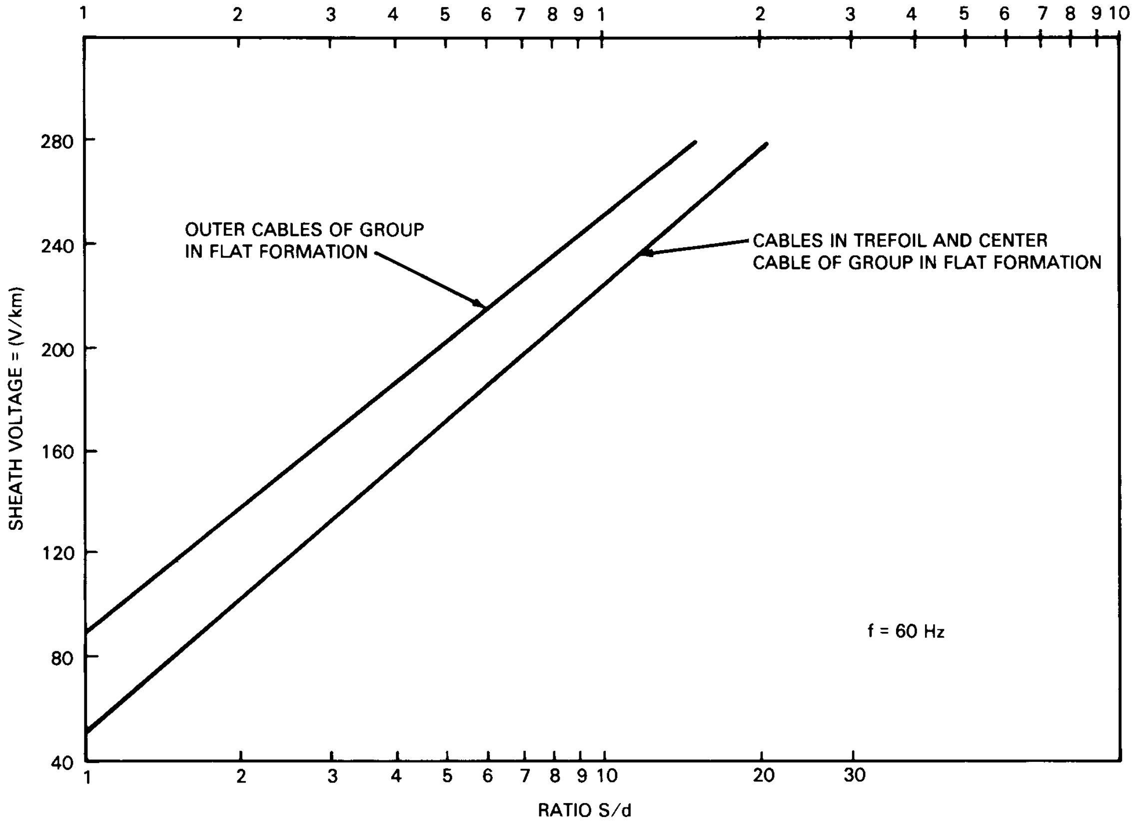


Fig 1
Induced Sheath Voltage Gradient for a Conductor Current of 1000 A

where

S = center-to-center cable
d = mean sheath diameter

the sheath voltage will be 103 V/km and 138 V/km for trefoil and flat formation respectively. Since the cable sheath may at some points be exposed to contact by personnel who might expect it to be at or near to ground potential, it is common practice to specify a maximum voltage permissible during full-load operation. It is recognized that this voltage will be greatly exceeded during system transients and short circuits. The maximum sheath voltage permitted at full load varies considerably between countries.

5.4.2 Multiple Lengths. When the circuit length is such that the sheath-standing-voltage limitation is exceeded when the ground bond is connected at one end of the circuit, this bond may be connected at some other point, for example, the center of the length. The sheath standing voltage on each of the two minor sections so formed is then correspondingly reduced. When the circuit is too long to be dealt with by this means it may be sectionalized by the use of sheath sectionalizing joints so that the sheath standing voltage for each minor section is within the limitation imposed.

5.4.3 Parallel Ground Continuity Conductor. During a ground fault on the power system, the zero-sequence current carried by the cable conductors returns by whatever external paths are available. Since a single-point, bonded cable sheath is grounded at one position only, it cannot, except in the case of a cable fault, carry any of the returning current. This being so, unless some parallel external conductor is available or is provided to serve as an alternative path, the return

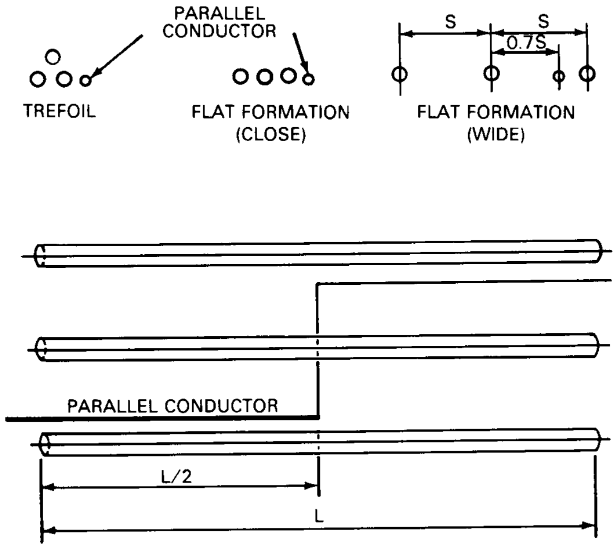


Fig 2
Transposition of Parallel Conductor to Reduce Induced Voltage with Power Cables in Flat Formation or Trefoil

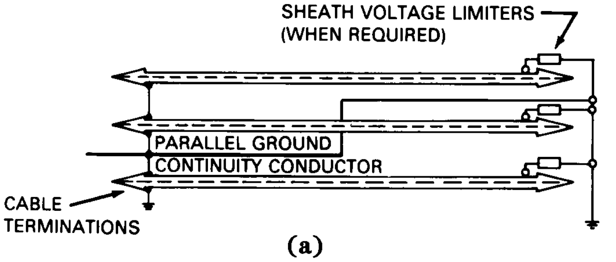
current can flow only by way of the ground itself. Because the resistivity of the ground is very high compared with that of good conductors, the return current is very widely diffused through the ground and the mean effective depth of the power frequency components is many hundred meters. Because the returning current, on average, is so remote from the conductor current, the voltage gradients induced along parallel conductors, including the cable sheaths, are very high.

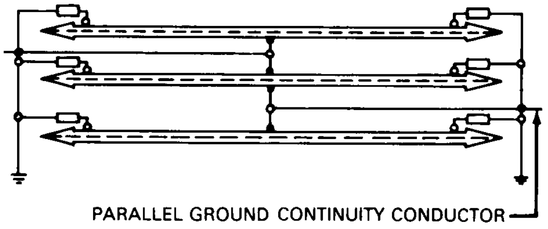
Furthermore, in the absence of a parallel ground conductor, the occurrence of a ground fault in the immediate vicinity of a cable could cause a major difference to arise between the ground potentials at the two ends of a cable system. Depending to some extent on the particular design of the voltage limiters (if any) employed, hazards could then ensue to personnel or equipment.

Accordingly, it is recommended that a single-point bonded cable installation be provided with a parallel ground continuity conductor that is grounded at both ends of the route. The spacing of this conductor from the cable circuit should be sufficiently close to limit the voltage rise of the sheath to an acceptable level during a single-phase fault. The size of this conductor must be adequate to carry the full expected fault current for the cable system.

The parallel ground continuity conductor is usually insulated so as to avoid any corrosion risk and it will be subject to voltage induction from the power cables in the same way as any other parallel conductor. To avoid circulating currents and losses in this conductor it is preferable, when the power cables are not transposed, to transpose the parallel ground continuity conductor using the methods described in Appendix D, D3.

5.4.4 Circuit Arrangements. Figures 3 and 4 show the application of single-point bonding to single length and multiple length circuits respectively. These diagrams do not show the disconnecting boxes to permit testing of the sheath insulation.





(b)

NOTE: Other patterns of ground conductor transposition may be used. See Appendix D, D4.

Fig 3
Single-Point Bonding Diagrams for Circuits Comprising One Cable Length Only
(a) End-Point Bonding (b) Midpoint Bonding

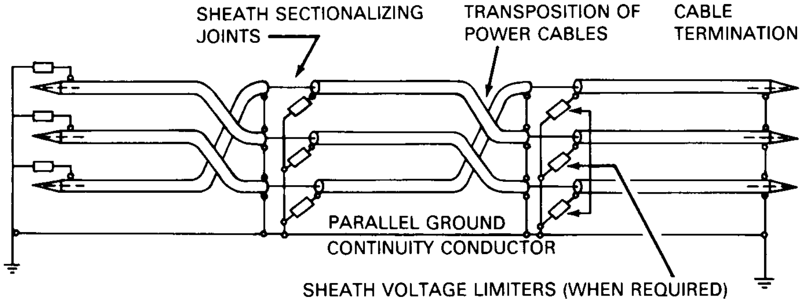


Fig 4
Single-Point Bonding Diagram for Circuit Comprising Three Cable Lengths

5.5 Impedance-Bonding Methods. In impedance-bonding methods, the cable sheath sections are bonded together in some manner through an impedance. This impedance may consist of simple reactors or of devices such as saturable reactors and bonding transformers. In all these methods a certain amount of sheath current is permitted so as to reduce losses and sheath voltages. To provide ground connections, the impedance devices are normally designed with center taps or grounding points.

At one time resistors were used, however, in general, resistance bonding is not practical, since the resistors have to be sized to take the fault currents and they are considered very large for high fault currents.

Although a partial suppression of induced sheath voltages is obtained using impedance-bonding methods, there are a number of disadvantages that limit the application of these methods. The principal disadvantages are as follows:

(1) Additional manhole space is required.

(2) The impedance devices are relatively expensive since they must be designed to withstand fault currents.

(3) In normal operation, 3rd harmonics may be introduced into the sheath, and these may cause interference on nearby telephone lines. Stray direct currents, entering through the grounding, may cause saturation of the iron cores and upset the operation of the reactors or transformers.

5.6 Cross Bonding

5.6.1 Basic Circuit Arrangement. Cross bonding consists essentially in sectionalizing the sheaths into minor sections and cross connecting them so as to approximately neutralize the total induced voltage in three consecutive sections, as shown in Fig 5.

With untransposed cables, as illustrated in Fig 5, it is impossible to achieve an exact balance of induced sheath voltages unless the cables are laid in trefoil. When, for the reasons given in Appendix D, D3, the cable conductors are transposed at each joint position, the induced sheath voltages will be neutralized irrespective of cable formation provided the three minor sections are identical. Figure 6 shows how this can be done for a circuit of three minor sections only. The sheaths are bonded and grounded at both ends of the route. In this arrangement, the three minor sections together are termed a major section.

5.6.2 Longer Cable Circuits. Cross bonding can be extended to longer cable circuits by the methods described in 5.6.3 through 5.6.7.

5.6.3 Sectionalized Cross Bonding. This cross-bonding system is often called Kirke-Searing bonding, although the system used by H.R. Searing and W.B. Kirke did not involve transposition of cables [18].[2] When the number of minor sections is divis-

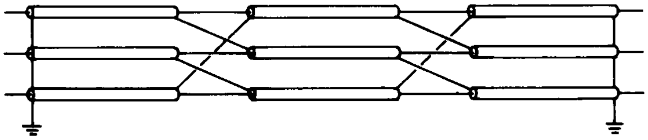


Fig 5
Cross-Bonded Cables Without Transposition

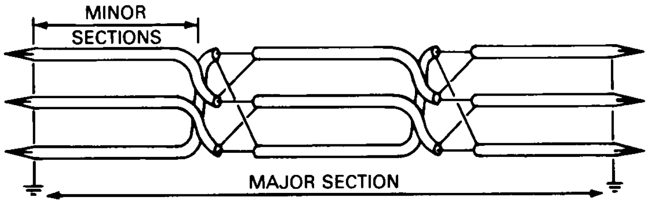


Fig 6
Cross-Bonded Cables with Transposition

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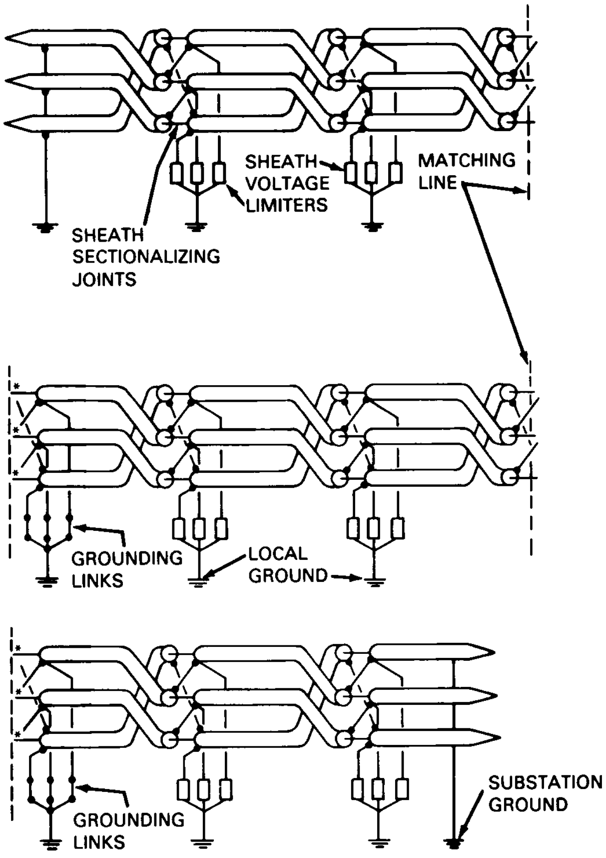
[2] The numbers in brackets correspond to those of the references in 1.2.



*THESE JOINTS MAY ALSO BE WITHOUT SHEATH SECTIONALIZING INSULATORS, AND MAY BE CONNECTED DIRECTLY TO THE LOCAL GROUND.

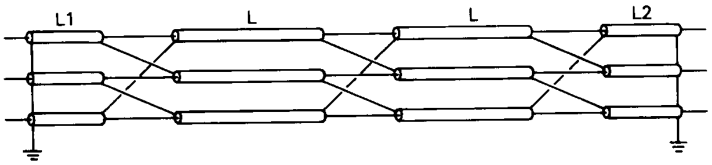
Fig 7
Sectionalized Cross-Bonded Cable with Three Major Sections

ible exactly by three, the circuit can be arranged to consist of one or more major sections in series. At the junction of two major sections and at the ends of the circuit, the sheaths are bonded together and grounded, although the grounds at the junctions of major sections will generally be only local ground rods (See Fig 7 in which each separate major section is connected as in Fig 6).

5.6.4 Modified Sectionalized Cross Bonding. In this modified version of the sectionalized cross-bonding system, it is not necessary to have the number of minor sections exactly divisible by three. Balanced voltage conditions within a given major section consisting of four minor sections can be achieved by subdividing one minor section into two subsections, as follows:

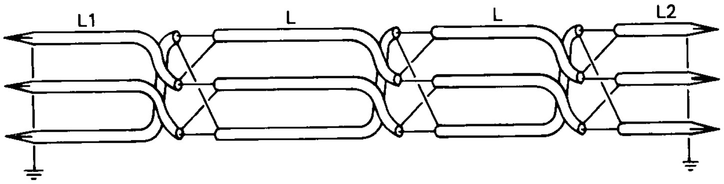
(1) One short length (or subsection) followed by two equal lengths (or minor sections) with another short length (or subsection) completing the major section; the combined length of the two subsections should be equal to the length of one minor section as shown on Figs 8 and 9.

(2) One short length (or subsection) followed by one longer length (or minor section) then



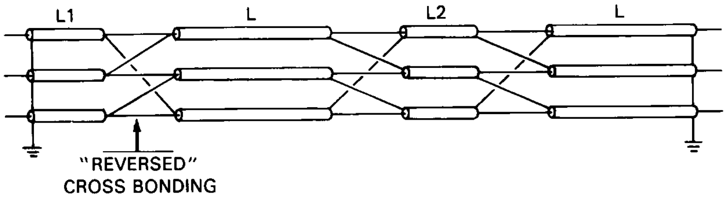
L1 and L2 = LENGTH OF SUBSECTIONS
L = LENGTH OF MINOR SECTIONS
L1 + L2 = L

Fig 8
Modified Sectionalized Cross-Bonding
Type 1 Without Transpositions



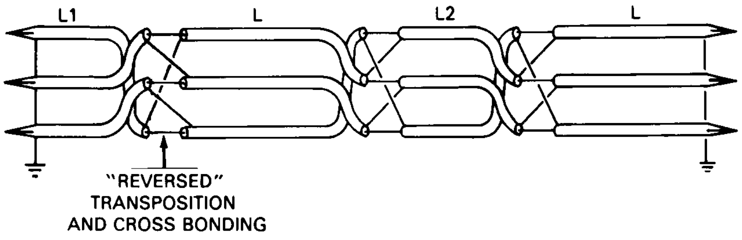
L1 and L2 = LENGTH OF SUBSECTIONS
L = LENGTH OF MINOR SECTIONS
L1 + L2 = L

Fig 9
Modified Sectionalized Cross-Bonding
Type 1 with Transpositions



L1 and L2 = LENGTH OF SUBSECTIONS
L = LENGTH OF MINOR SECTIONS
L1 + L2 = L

Fig 10
Modified Sectionalized Cross-Bonding
Type 2 Without Transpositions



L1 and L2 = LENGTH OF SUBSECTIONS
L = LENGTH OF MINOR SECTIONS
L1 + L2 = L

Fig 11
Modified Sectionalized Cross-Bonding Type 2 with Transpositions

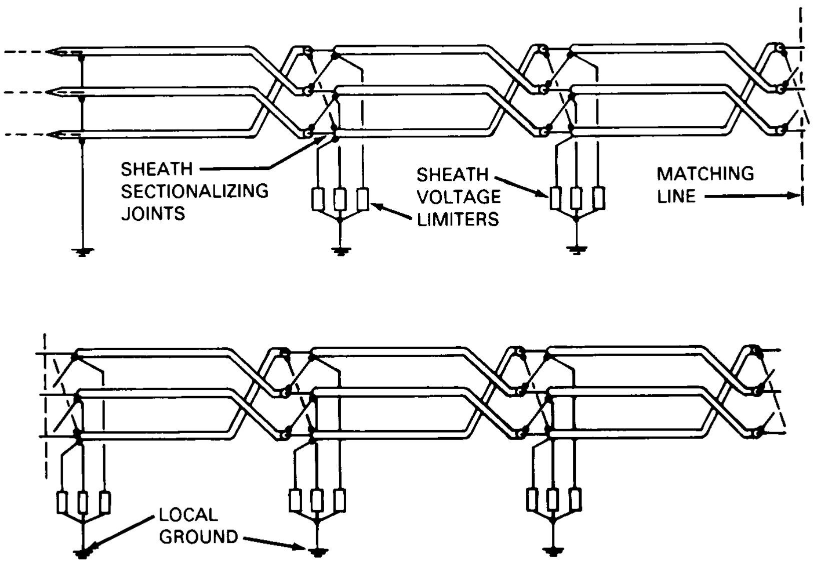


Fig 12
Continuous Cross Bonding

another short length (or subsection) followed by one longer length (or minor section) to complete the major section; the two longer lengths (or minor sections) should be equal and the combined length of the two subsections should be equal to the length of one minor section as shown on Figs 10 and 11. In this case, the first cross bonding must be *reversed.*

5.6.5 Continuous Cross Bonding. In this system the sheaths are cross bonded at the end of each minor section throughout the whole cable route. The three sheaths are bonded and grounded at the two ends of the route only, as shown in Fig 12. It is again generally desirable that the cables are transposed so that each conductor occupies each of the three positions for one third

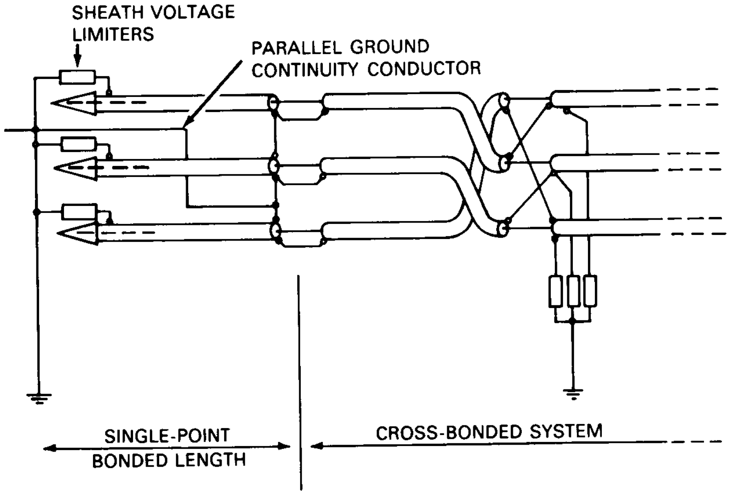


Fig 13
Termination of Cross-Bonded System with Single-Point Bonded Length

of the total length. The number of matched minor sections should preferably be exactly divisible by three, but this becomes less important as the total number of minor sections increases (see 5.6.7).

5.6.6. Mixed Systems. When the number of minor sections is not exactly divisible by three, the system may consist of a mixture of Kirke-Searing (regular and modified) and single-point bonded lengths. When necessary, on account of a large number of minor sections having unequal lengths, the cross bonding may be of the continuous type. Figure 13 shows the arrangement of a final single-point bonded length at the end of a cross-bonded system.

5.6.7 Imbalanced Systems. It is not generally possible to divide the route length into exactly matched minor section lengths, nor is it always possible to maintain a constant spacing of the cables throughout the route. In continuous cross-bonded systems, it may also be desirable to have a total number of minor sections not exactly divisible by three. In practical systems, there is therefore generally some imbalance, and it may be necessary to calculate the circulating sheath currents that are present so as to assess their effect on the cable rating. See [13] and [15] for methods of calculation.

5.7 Sheath Sectionalizing Joints. When the sheath losses of single-conductor cables must be reduced or eliminated, sheath sectionalizing joints are required for interrupting the electrical continuity of the sheath circuit. To perform their function satisfactorily there are several major factors involved in the design of these joints. Mechanically they must be rugged, impervious to moisture, and fluid tight under all operating conditions. Electrically, they must be designed to withstand the voltage stresses occurring under fault, and lightning and switching surge conditions.

One of the quantities that must be evaluated before a sheath sectionalizing joint can be used in a bonding scheme is the insulation strength required at the joint. This can be determined by calculating the maximum voltage appearing across the joint due to faults and lightning and switching surges. This subject is discussed in Appendix E.

5.8 Choice of Bonding System. Impedance-bonding methods are less satisfactory than the other methods described. For this reason these methods are not recommended for general use.

Bonding transformers may be economical in some isolated cases such as

(1) Suitable balancing for cross bonding is impossible and single-point bonding is unacceptable (that is, no empty duct is available for a ground continuity conductor).

(2) A spare cable (a fourth cable for a single circuit or a seventh cable for a double circuit) is installed; in this case, reconnecting the cross bonding whenever the spare cable is needed is a lengthy and complex operation, whereas reconnecting of bonding transformers is simple and straightforward.

Users of this method may refer to 5.5 and [9], [10], [20], [21], and [39].

Further discussion will therefore be limited to consideration of the other bonding methods.

5.8.1 Use of Single-Point Bonding. A minimum of three minor sections are needed to form a cross-bonded system, and it is normal practice to use sheath sectionalizing insulators only at joint positions. Hence, cross bonding is not normally applicable to cable circuits comprising only one or two lengths, and, for such circuits, single-point bonding is widely used.

5.8.2 Advantages of Cross Bonding. Although the cable sheaths of a single-point bonded system are generally of a cross-sectional area and conductivity that makes them quite capable of carrying short-circuit currents due to through faults in the power system, they are unable to do so because they are grounded at one point only. A parallel ground continuity conductor is therefore recommended (see 5.4.3), and this adds appreciably to the cost of the cable system.

The principal advantage of cross bonding is that, while induced sheath currents are inhibited during normal balanced load operation, the sheaths do form a continuous path from end to end of the cable circuit and are grounded at both ends. Sheath currents can therefore flow during ground faults, and the necessity for the parallel ground continuity conductor is removed. In addition to the economy achieved by the elimination of the ground conductor, the cable sheaths function more effectively as screening conductors during ground faults than a parallel ground continuity conductor. Hence, the voltages induced in parallel cables are less during ground faults in a cross-bonded system than for a similar single-point bonded system.

5.8.3 Choice of Cross-Bonded System. For long cable circuits, there is a choice between sectionalized cross bonding (see 5.6.3 and 5.6.4) and continuous cross bonding (see 5.6.4). The relative advantages are as follows:

5.8.4 Advantages of Sectionalized Cross Bonding

(1) Since each major section forms a separate electrical mesh, it is relatively straightforward to calculate the sheath currents when the lengths or spacings of the minor sections are not uniform.

In a nonuniform section having an equilateral cable configuration the ratio of sheath loss with cross bonding to that with solid bonding is given by

$$\frac{x}{y} = [1-3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)]$$

where

x = cross-bonded loss
y = solidly bonded loss
$\lambda_1, \lambda_2, \lambda_3$ = per unit lengths of the three minor sections, that is $\lambda_1 + \lambda_2 + \lambda_3 = 1$

EXAMPLE: When

$\lambda_1 = 0.4$
$\lambda_2 = 0.2$
$\lambda_3 = 0.4$

the loss with cross-bonded sheaths is 4% of the loss with solidly bonded sheaths

(2) The sheath bond at the junction of each major section allows fault current due to a cable failure to be distributed between the three sheaths except within the major section containing the fault.

(3) The sheath bonds and grounds at the junctions of major sections tend to reduce transient sheath voltages.

(4) The number of sheath voltage limiters required is reduced.

(5) The sheath bonds at the junction of major sections ensure that there will be no charging current flow beyond the neutral points of the bonds irrespective of any inequality in the lengths of the minor sections.

5.8.5 Advantages of Continuous Cross Bonding

(1) The effects of nonuniform minor sections

may be reduced when they form part of a total sheath circuit containing a number of sections. It may also be possible to use a total number of sections not exactly divisible by three.

(2) It is possible to monitor sheath currents throughout the whole circuit, irrespective of the number of minor sections, at one point along the length.

(3) At least for low-resistance faults, the monitoring of the sheath insulation and sheath voltage limiters becomes easier because there are only two sheath bonds and ground links to be removed, even on a long circuit, to enable tests to be applied from the ends of the cable circuit.

5.9 Sheath Standing Voltage

5.9.1 Single-Point Bonding. Figure 1 shows the sheath voltages per kilometer due to balanced loads in the cable conductors.

5.9.2 Sectionalized Cross Bonding. In any minor section, the sheath standing voltage per kilometer will be as stated in Fig 1 and the longest minor section shall be taken for calculating the maximum standing voltage. With the modified bonding method described in 5.6.4(1) the maximum standing voltage thus calculated is reduced as much as 13% (see Appendix D, D5). This maximum reduction applies when the two short lengths (or subsections) are equal (that is, L1 = L2 = 0.5 L). See Figs 8 and 9.

When the major section is nonuniform, the sheath standing voltage can be taken as that calculated for the longer of the two grounded minor section lengths. When the nonuniformity causes appreciable sheath current, there will be some reduction of the sheath standing voltage.

5.9.3 Continuous Cross Bonding. When the whole system between sheath bonds consists of a number of uniform minor sections exactly divisible by three and the cables are transposed so that each conductor occupies each of the three positions for one third of the total length, then no sheath current flows, and the maximum sheath standing voltages per meter are as stated in Fig 1. In a practical system having variable lengths of minor sections, the sheath standing voltage can be taken as that calculated for the longest minor section length. When appreciable sheath current flows, the sheath standing voltages is reduced somewhat.

5.9.4 Double-Circuit Systems. Where two closely spaced circuits are present, the sheath standing voltages are modified by the presence of the second circuit.

Because of the infinite variety of geometrical arrangements coupled with differences in individual cable loading and phase rotation, a universal solution to sheath standing voltages on multiple circuits cannot be given here. Some of the more common double-circuit geometries are described in [15] and [19].

A general solution requires the use of a digital computer and linear algebra. However, when discretion is used in the selection of phase rotation and position, the effect of adjacent circuits does not significantly increase standing voltages provided these circuits have equal or lower balanced phase currents.

A solution to a simple parallel double circuit is given in Appendix D, D2.

6. Sheath Voltage Limiters

6.1 Introduction. Sheath sectionalizing insulators in cross-bonded cable systems and the insulators in a single-point bonded-cable system may flashover due to overvoltages generated by lightning, switching surges, or faults on the power system. It is necessary to provide some form of protection for these insulators under system transient conditions. At present, sheath voltage limiters are used for this purpose. The three main types are

(1) Nonlinear resistances

(2) Nonlinear resistances in series with spark gaps

(3) Spark gaps

6.2 Nonlinear Resistances. Nonlinear resistances can provide good protection for transient voltages. They do, however, have a limited capacity to absorb energy and are not designed to carry a 60 Hz fault current. They must be sized to withstand 60 Hz fault-current overvoltage due to system faults external to the cable circuit, although they are not normally expected to survive overvoltages resulting from faults internal to the cable circuit. The surge energy and 60 Hz voltages, to which the resistor is subjected, dictates the characteristics of the resistor. Distribution class arresters are often adequate for the surge energy requirements when selected to withstand the power-frequency fault voltage without discharging. High humidity tends to reduce the effectiveness of nonlinear resistances, and they must, therefore, be protected from moisture by a suitable case or encapsulation.

6.3 Nonlinear Resistances in Series with Spark Gap. Nonlinear resistances in series with spark gaps are widely used as surge arresters. In contrast with the sheath voltage limiters described in 6.2, surge arresters have the advantage that 60 Hz currents flowing in them will be interrupted and the maximum energy dissipated in the nonlinear resistances will be correspondingly less. However, although modern arresters will sparkover with a minimum overvoltage on steeply rising waves, they have the disadvantage that their response is slower than that of the nonlinear resistance alone.

6.4 Spark Gaps. The spark gap is the simplest of the three voltage limiters, but has the disadvantages that it may be damaged by high 60 Hz currents following initial sparkover, and its response is slow, particularly to very steeply rising transient overvoltages. The gap length may be increased so that 60 Hz fault-current voltages will not maintain an arc. This, however, will reduce the spark gap's protective value, particularly for steeply rising voltage waves.

A spark gap has been developed [2] that provides reliable surge protection, at the terminals, for cable sheaths. The electrode arrangement of the spark gap (referred to as a ring gap) is designed to cause a motoring action of the arc that eliminates serious erosion of the electrodes. These spark gaps are capable of conducting arcs of high current densities without deterioration of the electrodes, and are used for protecting cable sheaths at the terminals on circuits up to 10 km in length.

Spark gaps require periodic inspection and maintenance, and it is therefore suggested that they be used only to protect single-point bonded circuits at the terminations where the gap is readily accessible. It is recommended that they not be used in cross-bonded systems where the gaps may be installed in underground boxes and be relatively inaccessible.

6.5 Selection of Sheath Voltage Limiters. In selecting a sheath voltage limiter, the following criteria should be considered:

(1) The limiter should be suitable for continuous operation with an applied voltage equal to the sheath standing voltage under either normal or emergency load (5.9).

(2) The limiter should be able to withstand the 60 Hz overvoltages resulting from system faults. Caution should be used in selection of nonlinear resistance-type limiters because of problems associated with 60 Hz overvoltages discussed in 6.2 (see Appendix E).

With nonlinear resistance-type limiters, a maximum time should be specified; this is normally twice the maximum fault clearing time for the system to allow for reclosing.

When calculating 60 Hz voltages appearing across sheath voltage limiters, allowance should be made for the limiters that are star or delta connected.

(4) Spark gaps and surge arresters should be able to withstand impulse currents for the same duration as specified for the impulse requirements for the main lightning (surge) arresters on the system.

A nonlinear resistance-type limiter should be able to absorb, without damage, the energy dissipated due to switching, including switching associated with a fault external to the cable circuit. Experience and calculations indicate that the energy dissipated in the nonlinear resistances due to switching is not an important design criterion for normal cross-bonded circuits. However, for long single-point bonded circuits or lengths of single-point bonded cable that terminate long circuits, the switching surge energy may be important, and calculations should be made for these cases [1], [11], and [12]. The calculations should be performed using a computer, since normal methods cannot readily be used because of the presence of the nonlinear circuit element. Typical switching transient waveshapes should be assumed. See [2], [3], [4], [5], [7], [8], [9], [15], [16], [17], and [20].

6.6 Use of Sheath Voltage Limiters

6.6.1 Single-Point Bonded Cables. Sheath voltage limiters are connected between the unbonded ends of the cable sheaths and ground, generally with a separate limiter at each cable termination. When the limiters are installed together as a unit, connections between sheaths and the limiter unit, which may be 2 m to 3 m long, should be made with low surge-impedance coaxial cables capable of carrying the limiter design current.

Generally, the end of the cable circuit that is liable to be subjected to the higher incoming transient voltages, due to lightning or switching, should be grounded. However, when the ground resistance is very much lower at one end, it is preferable to ground the sheath at that end. It may also be preferable to install the sheath voltage limiter inside a substation rather than in a location accessible to the public, since there is some risk of explosive failure of the limiter. As there may be conflict between these factors, local conditions will determine their relative importance.

6.6.2 Cross-Bonded Systems. In direct-buried installations, cross-bonding connections are made with links in surface link boxes, so that individual cable sheaths may readily be isolated for voltage testing of cable jackets. The sheath voltage limiters are then located in or adjacent to the link boxes so that maintenance is possible by removing the manhole cover. In these installations, the connections between the buried joint and the link box may be as long as 10 m. Bonding leads should be low surge-impedance coaxial cables, as short as possible, to minimize the effect of the connections on the efficiency of the sheath voltage limiters. The bond leads must be capable of carrying the system short-circuit currents.

In tunnels or in ducts, or other installations, where the joints are in manholes, the sheath voltage limiters may be connected across the sheath sectionalizing insulators with relatively short leads. The cross-bonding leads should also be as short as possible to minimize the magnitude of front surges. The conductor cross section must be adequate to carry system short-circuit currents.

7. Effect on Parallel Telephone and Control Cables

While the purpose of special, power-cable sheath bonding is to reduce sheath currents and attendant sheath losses, sheath currents in communication cables, induced by the inductive influence of the power-cable system, are utilized to provide beneficial shielding effects. It is the magnitude of the voltages induced in enclosed circuits of the communication cables that are pertinent and that must be evaluated. In Appendix D, D4 guidelines are given on the unfavorable consequences of cross-bonded power-cable sheaths and the optimization (by transposition) of the circuit geometrics to reduce the influence. In this section some additional factors are briefly noted.

7.1 Coupling. The coupling of the power circuit to the communication circuit is evaluated in terms of the mutual impedance. Residual or zero-sequence components of the power circuit often have a ground return (that is, overhead lines). The induced currents in the communication cable sheath also return through the ground. Although most of the zero-sequence components of buried power cable normally return through the sheath or separate neutral conductor, some portion may return through the ground. These factors introduce uncertainties in the calculations of the mutual impedance, which can, however, be calculated with reasonable accuracy using Carson's equations [6]. Since the magnitude of the ground return current has a relatively large effect on the mutual impedance, the approximation that all zero-sequence current returns through the sheath cannot be made.

While the coupling of the fundamental power frequency under steady-state balanced conditions can be minimized by suitable transposition, there may be present odd triple harmonics (3rd, 9th, 15th, etc) that add in phase, and therefore, are not neutralized by circuit geometry.

7.2 Shielding. The design of the communication cable sheath and other outer coverings is a fundamental factor in the reduction of the voltage induced in the communication cable pairs. The reduction factor (often referred to as shielding factor) is defined as the ratio of the induced electromotive force (emf) between the cable conductors and ground to the longitudinal electromotive force (emf) that is induced when metallic cable coverings are absent. It may be expressed (where nonmagnetic materials are used) as

$$r_\mathrm{u} = \frac{R}{\sqrt{R + (\omega L_\mathrm{e})^2}}$$

where

r_u = reduction factor of the communication cable
R = dc resistance of the grounded metallic cable coverings including the ground resistances, Ω/km
ω = angular frequency
= $2\pi f$
L_e = inductance of the ground circuit, H/km (approximately 2 mH/km)

From the above expression it can be seen that the induced longitudinal or common-mode voltage on the enclosed pairs of the cable is equal to the *IR* drop in the sheath ground circuit including the grounding resistances. It is therefore fundamental to provide low-resistance grounds. The use of magnetic materials for outer coverings improves the shielding efficiency substantially, unless the magnetic field strength results in saturation.

7.3 Common-Mode and Metallic Voltages. The common-mode voltage or longitudinal voltage is the voltage between the cable pairs and ground. It is the prime consideration relative to connected equipment or personnel hazards and is normally of prime significance during faults in the power system. The so-called metallic voltage is the voltage between the two wires of a pair and is manifested by pair to ground imbalance that converts the longitudinal voltage to the transverse voltage. It is associated with noise introduced into the communication circuit. When the affected pair is used in a protective circuit for power-circuit relaying, false tripping of a protected power circuit may occur. Objectionable audio noise can be introduced into voice frequency circuits at quite low field strengths by power frequency harmonics (compare with 7.1). This effect is the consequence of the response of the human ear, the sensitivity of which increases rapidly from 60 Hz to 1000 Hz.

It becomes evident that the inductive effects on parallel telephone and control cables are dependent on many factors, including circuit geometries, mutual impedance, frequency, ground resistivity, shield factors, wave shape, design of connected equipment and the like. Quantitative estimations are facilitated by computer. In unusual situations, where established practice is not applicable, verification by field tests may be required (see [14] and [32]).

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Appendixes

(These Appendixes are not a part of ANSI/IEEE Std 575-1988, IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths, but are included for information only.)

Appendix A

Terminology

bonding lead. The insulated conductor forming the connection between the sheath of a buried cable or joint and a link in the link box.

NOTE: In systems where the installation of link boxes is not necessary (such systems are described in 6.6.2 of this guide), the bonding lead is the insulated conductor forming the connection between any of the following components of the system: sheath, joint casing, bases (wiping bells) of terminations, ground bus, and ground rod.

continuous cross bonding. A form of cross bonding applicable to circuits consisting of at least four minor sections in which the cable sheaths are successively cross bonded at each junction between adjacent minor sections throughout the cable route. At each end of the route the sheaths are solidly bonded and grounded.

cross bonding. The form of special bonding in which the cable sheaths in consecutive minor sections are cross connected so that each continuous sheath circuit surrounds the three-phase conductors consecutively.

flat formation. Three cables laid in a plane with equal spacing between adjacent cables.

insulated sheath system. A cable system in which the metallic sheath of each cable is individually insulated throughout its length except where any necessary grounding or inter-sheath connections are made.

joint sleeve insulation. The external insulation applied to the metallic joint sleeve of a specially bonded cable.

link box. A box in which bonding or grounding connections, or both, are made through removable links and which may also contain sheath voltage limiters.

minor section. The length of cable system between sheath sectionalizing positions or between sheath sectionalizing positions and terminations.

parallel ground continuity conductor. A conductor laid parallel to a cross-bonded circuit to provide a continuous metallic ground connection between the grounding systems at the ends of the cable route.

sectionalized cross bonding. The form of cross bonding in which three consecutive minor sections are taken to form a single unit (termed a *major section*). The three sheaths are solidly bonded at both ends of a major section and may be grounded at these points. At the two intermediate positions the cables are transposed and the sheaths are so interconnected that each continuous sheath circuit through the major section occupies the same geometrical position in the cable formation. For long cable routes there may be a number of major sections.

screening conductor. A conductor laid in parallel with a current-carrying loop and itself forming part of a closed circuit in which induced currents may flow whose magnetic field will oppose the field of the current-carrying loop.

sheath sectionalizing joint. A joint in which the metallic screen and casing are electrically interrupted, the interruption in the casing of the joint being by means of a *sheath sectionalizing insulator*.

sheath standing voltage. The voltage to ground appearing on the sheath of a specially bonded cable when balanced full-load currents are flowing in the cable conductors; normally quoted at the point along the cable length at which it is a maximum (that is, at the ungrounded extremity of a minor section in the case of single-point bonding and at a cross-bonding point in the case of cross bonding). When the voltages differ for the three-phase cables, the highest value is normally quoted.

sheath voltage limiter. A device connected to a sheath or to the sheaths of specially bonded cables intended to limit sheath overvoltages during system transients.

single-point bonding. The form of special bonding in which the three-cable sheaths of a minor section are solidly bonded together and grounded at one point only. For long cable routes this may be repeated a number of times.

solid bond. An intersheath connection of minimum practicable impedance.

special bonding. Methods of bonding and grounding the sheaths of single-conductor cables so as to minimize the sheath circulating currents resulting from induction from the conductor currents.

transportation

(1) *in relation to power cables.* The practice of laying single-conductor cables so that each phase cable successively occupies, over equal lengths of the route, each of the three geometrical positions in the laying formation.

(2) *in relation to parallel conductors.* The practice of laying a parallel conductor alongside a minor section of untransposed power cables so that, in relation to the plane of symmetry of the cable laying formation, the conductor over half of the section length occupies one position and over the other half occupies a symmetrically opposite position.

trefoil. The formation of three cables so laid as to be mutually equidistant (when viewed in cross section, the lines joining the cable centers form an equilateral triangle).

uniform major section. A major section consisting of three similar uniform minor sections having equal lengths.

Appendix B

Discussion of Early Practices and Problems

Early self-contained cables were insulated with a combination of oil and paper and were constructed with a metallic sheath, which acted both as a barrier to moisture ingress and as a return path for fault currents. The most common sheathing material was lead, and these cables were frequently installed with a protective jacket with the sheaths solidly grounded.

In North America, they were usually installed in ducts and manholes. In Europe, particularly in Britain, cables were often armored and directly buried. Many of these directly buried cables were protected with hessian wrappings and bituminous compounds. As a general rule, power losses in the sheaths were recognized but accepted.

As system voltages and currents increased, these losses assumed a greater importance, and various methods of reducing these losses were devised over the years from 1910 to the mid-1930's. Most of these methods required the use of insulators inserted in the sheaths to break the sheath circuit into smaller electrical sections.

Although these systems were reasonably successful, the sheath insulators were often a source of problems because of leaks that permitted cable oils to leak out and moisture to penetrate the cables.

Because of factors, such as ac corrosion and personnel safety, and also because of a natural reluctance to depart too far from the practice of solidly grounding the sheaths, a sheath voltage limit of approximately 12 V to 17 V seems to have been commonly adopted in the early days.

Appendix C

Current Practice

C1. Practice in the United States

Current practice in the United States appears to permit a steady-state sheath voltage of 65 V-90 V, although there is not much evidence to substantiate this. A standard practice presently does not exist in the United States, and this is one of the reasons why this guide was developed.

Some examples of current US practice are as follows:

(1) Installation by one utility of a single-point bonded system with a maximum steady-state sheath voltage of 65 V.

(2) An installation in New England of a cross-bonded system with a limitation of 86 V.

C2. Canadian Practice

Practice varies from province to province. In their installations of underground low-pressure oil-filled (LPOF) cables, one utility utilizes the sectionalized cross-bonding method to minimize sheath losses and also provide a low-impedance path for fault current. At all cross-bonded positions, 3 kV lightning arresters are installed to minimize the transient overvoltage on the sheath and joint casing insulation.

The sheath bonding and grounding arrangements are such that the standing sheath voltage at maximum load current does not exceed 100 V to ground at any point along the cable.

To ensure the system will adequately withstand anticipated transient overvoltages, the components of the circuit acted on by these overvoltages are subjected to specified withstand levels with respect to ac and impulse voltages.

Another utility has installed cross-bonded cable systems in the past without any sheath sectionalizing joint insulator protection. However, some joint insulators have failed in service and the system is not considered satisfactory without some method of joint insulator protection. The present method being utilized by this utility is single-point bonding with ring gaps at the terminals. Standing sheath voltages of 300 V-400 V on emergency load are permitted at the terminals. However, with increasing load currents and circuit lengths this method is approaching its limit as it is not proposed to exceed 600 V at the terminals.

One rather unusual method of bonding has been adopted by another utility for cable routes with unequal lengths between manholes. This could be described as a modified sectionalized cross-bonding scheme and is described in detail in 5.6.4 of this guide.

C3. British Practice

C3.1 British Practice. Cables in Britain have from very early days had some form of outer jacket over the sheath. Initially, these were constructed by lapping various layers of self-vulcanizing rubbers and pvc in conjunction with bitumastic compounds in hessian tapes. Because these were electrically sound and of reasonable electrical strength, it was judged that, even when special bonding comes into vogue, there is little likelihood of sheath voltages ever becoming high enough to puncture any form of anticorrosion jackets. Polyvinyl chloride, polyethylene, and high-density polyethylene extruded jackets have replaced these more complicated constructions.

This is contrary to the practices in the United States where bare lead sheaths were in regular use and sheath voltages were limited to 12 V or thereabout. Special bonding circuits were introduced into Britain in the late 1950's, at which time the maximum standing sheath voltage was limited to 50 V below ground and to 25 V at the terminations. These maximum permissible levels were mandatory for the central electricity generating board (CEGB) from 1959 to 1965, when it was made permissible to increase the sheath voltage below ground from 50 V to 65 V. The 65 V level is the value used now, except in special installations in CEGB-owned tunnels. The River Severn cable has induced sheath voltages of 100 V at full load at various parts along the route but the terminations are limited to 25 V.

The reason for selecting 50 V in the late 1950's is not clear, but it was increased to 65 V because it was limiting drum lengths and increasing the cost of many cable circuits.

Factory testing of the jackets has always been mandatory, and it has been normal practice to carry out a 10 kV direct-current test for one minute as follows:

(1) Immediately after laying
(2) After jointing (splicing)
(3) Just before commissioning tests on the main insulation

To ensure a good ground is available, the outer jacket surface is normally coated with graphite during manufacture.

The effectiveness of the extruded jackets in resisting corrosion is considerably better than the earlier taped servings, but both have a very satisfactory record.

It is essential with fully insulated systems to ensure that the disconnecting links are replaced before the commissioning tests are carried out. When the sheaths are allowed to *float*, the effects are catastrophic. To obviate this hazard, quite formal customer/contractor link box precommissioning inspection, certification, and locking procedures have been introduced.

C3.2 Practice in Europe. In Europe, a standard practice does not exist, but the following information is an indication of the position in various countries.

In the Netherlands, a recognized limit on sheath voltages has not been agreed upon. There is a 25 V limit in France for voltages on exposed metal at a termination, but there is no limit for sheath voltages on insulated metal.

In Norway, a fixed limit has not been agreed upon, but in practice a sheath voltage limit of 60 V is used. In Italy, a fixed value has not been agreed upon, but exposed metal is normally limited to approximately 25 V.

Appendix D

Calculation of Induced Voltages

D1. Induced Voltages — General

Any conductor p, lying parallel with a set of three conductors carrying balanced three-phase currents will have a voltage gradient E_p induced along its length, given by

$$E_p = \mathrm{j}\omega I_b \,(2.10^{-7}) \left[\tfrac{1}{2} \log_e \left(\frac{S_{ap}\, S_{cp}}{S_{bp}} \right) + \mathrm{j}\, \frac{\sqrt{3}}{2} \log_e \left(\frac{S_{cp}}{S_{ap}} \right) \right] \text{V/m} \qquad \text{(Eq D1)}$$

where

I_b = current (A) in conductor b, rms value
ω = angular frequency of system ($2\,\pi f$)
S_{ap} = axial spacing of the parallel conductor and phase a conductor
S_{bp} = axial spacing of the parallel conductor and phase b conductor
S_{cp} = axial spacing of the parallel conductor and phase c conductor

and these spacings may be in any convenient common unit.

It is assumed that the phase rotation is such that

$$I_a = aI_b$$

$$I_c = a^2 I_b$$

where

$$a = -\frac{1}{2} + \mathrm{j}\,\frac{\sqrt{3}}{2} \qquad \text{(Eq D2)}$$

and

$$I_b = I_0\,(1 + \mathrm{j}\,0)$$

where

I_0 = magnitude of the load current

Clearly, as the spacings of the parallel conductor increases in relation to the mutual spacings of the group of cables the induced voltage tends to zero. Similarly, if the three cables of the group are regularly transposed at even intervals, the induced voltages in the parallel conductor sum to zero over a complete cycle of transposition.

D2. Voltage Gradients Induced in the Cable Sheath

The voltage gradient induced in a cable sheath may be considered as a special case in which the parallel conductor is a sheath at a spacing from the conductor that it embraces equal to the mean radius of the sheath. When no other current-carrying conductor is in the vicinity, the three-sheath voltage gradients for a group of cables in any formation carrying balanced three-phase conductor currents are then given by

D2.1 General Case of Any Cable Formation

$$E_a = j\omega I_b\left(2.10^{-7}\right)\left[-\frac{1}{2}\log_e\left(\frac{2S_{ab}^2}{dS_{ac}}\right) + j\frac{\sqrt{3}}{2}\log_e\left(\frac{2S_{ac}}{d}\right)\right] \text{ V/m} \qquad \text{(Eq D3)}$$

$$E_b = j\omega I_b\left(2.10^{-7}\right)\left[\frac{1}{2}\log_e\left(\frac{4S_{ab}S_{bc}}{d^2}\right) + j\frac{\sqrt{3}}{2}\log_e\left(\frac{S_{bc}}{S_{ab}}\right)\right] \text{ V/m} \qquad \text{(Eq D4)}$$

$$E_c = j\omega I_b\left(2.10^{-7}\right)\left[-\frac{1}{2}\log_e\left(\frac{2S_{bc}^2}{dS_{ac}}\right) - j\frac{\sqrt{3}}{2}\log_e\left(\frac{2S_{ac}}{d}\right)\right] \text{ V/m} \qquad \text{(Eq D5)}$$

where

d = geometric mean sheath diameter (arithmetic mean may be assumed)

S_{ab} = axial spacing of phases a and b

S_{bc} = axial spacing of phases b and c

S_{ac} = axial spacing of phases a and c

D2.2 Trefoil Formation Single Circuit. For cables in trefoil where $S_{ab} = S_{bc} = S_{ac}$ these equations reduce to

$$E_a = j\omega I_b\left(2.10^{-7}\right)\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\log_e\left(\frac{2S}{d}\right) \text{ V/m} \qquad \text{(Eq D6)}$$

$$E_b = j\omega I_b\left(2.10^{-7}\right)\log_e\left(\frac{2S}{d}\right) \text{ V/m} \qquad \text{(Eq D7)}$$

$$E_c = j\omega I_b\left(2.10^{-7}\right)\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\log_e\left(\frac{2S}{d}\right) \text{ V/m} \qquad \text{(Eq D8)}$$

D2.3 Flat Formation Single Circuit. For the other common formation of cables laid flat in which the axial spacing of adjacent cables = S, the sheath voltage gradients are given by

$$E_a = j\omega I_b\left(2.10^{-7}\right)\left(-\frac{1}{2}\log_e\frac{S}{d} + j\frac{\sqrt{3}}{2}\log_e\frac{4S}{d}\right) \text{ V/m} \qquad \text{(Eq D9)}$$

$$E_b = j\omega I_b\left(2.10^{-7}\right)\log_e\frac{2S}{d} \text{ V/m} \qquad \text{(Eq D10)}$$

$$E_c = j\omega I_b\left(2.10^{-7}\right)\left(-\frac{1}{2}\log_e\frac{S}{d} - j\frac{\sqrt{3}}{2}\log_e\frac{4S}{d}\right) \text{ V/m} \qquad \text{(Eq D11)}$$

D2.4 Double-Circuit Systems. It is impossible in this text to cover all possible combinations of geometry for multiple circuits but a solution to a simple parallel double circuit is given below.

Assumptions

(1) Three or six cables are connected in three-phase circuits

(2) All conductor currents are equal in magnitude

(3) For three cables — any arrangement is permissible

For six cables — point or line symmetry is assumed

This means a line 0-0 or a point 0 may be placed between the two circuits so that the distance from cable $a1$ to 0 equals the distance from cable $a2$ to 0

where

$a1$ = a phase of Circuit 1
$a2$ = a phase of Circuit 2

The same must be true for cables $b1$ and $b2$ and $c1$ and $c2$.

(4) Positive phase-sequence rotation (phase a leading) was assumed in the equations. The effect of reversing phase sequence can be simulated on input to the program by interchanging cable positions 1 and 3 and 4 and 6 in the context S_1 through S_9.

Conductor currents are as follows:

$$\left.\begin{aligned} I_a &= -\frac{1}{2} + \mathrm{j}\frac{\sqrt{3}}{2} \text{ (assigned to cables 1 and 4)} \\ I_b &= \ \ 1 + \mathrm{j}\ \ 0 \ \ \text{(assigned to cables 2 and 5)} \\ I_c &= -\frac{1}{2} - \mathrm{j}\frac{\sqrt{3}}{2} \text{ (assigned to cables 3 and 6)} \end{aligned}\right\} \text{S-1}$$

Open-circuit voltages on sheaths to neutral are as follows:

$$\left.\begin{aligned} E_{a0} &= I_a \cdot \mathrm{j}X_{aa} + I_b \cdot \mathrm{j}X_{ab} + I_c \cdot \mathrm{j}X_{ac} \\ E_{b0} &= I_a \cdot \mathrm{j}X_{ab} + I_b \cdot \mathrm{j}X_{bb} + I_c \cdot \mathrm{j}X_{bc} \\ E_{c0} &= I_a \cdot \mathrm{j}X_{ac} + I_b \cdot \mathrm{j}X_{bc} + I_j \cdot \mathrm{j}X_{cc} \end{aligned}\right\} \text{S-2}$$

where

$$\left.\begin{aligned} X_{aa} &= k \log_e \frac{1}{r_{sm} \cdot S_{14}} \\ X_{ab} &= k \log_e \frac{1}{S_{12} \cdot S_{15}} \\ X_{ac} &= k \log_e \frac{1}{S_{13} \cdot S_{16}} \\ X_{bb} &= k \log_e \frac{1}{r_{sm} \cdot S_{25}} \\ X_{bc} &= k \log_e \frac{1}{S_{23} \cdot S_{35}} \\ X_{cc} &= k \log_e \frac{1}{r_{sm} \cdot S_{16}} \end{aligned}\right\} \text{S-3}$$

where

k = a constant
= $2.08 \cdot 10^{-6} \cdot f$
S_{12} = distance from cable 1 to cable 2
S_{23} = distance from cable 2 to cable 3
S_{13} = distance from cable 1 to cable 3
S_{14} = distance from cable 1 to cable 4
S_{25} = distance from cable 2 to cable 5
S_{36} = distance from cable 3 to cable 6
S_{15} = distance from cable 1 to cable 5
S_{35} = distance from cable 3 to cable 5
S_{16} = distance from cable 1 to cable 6
r_{sm} = mean sheath radius (meters)

Figure 1 of this guide shows values of the sheath voltage gradient calculated from the equations in D2 (1), (2), (3), and (4) for a single circuit in both trefoil and flat formation of the cables as a function of the ratio S/d.

D3. Screening and Transposition

The voltage gradients calculated by the equations in D2 are due to the magnetic field of the three-phase currents only. When any other current-carrying conductors are in the vicinity, these voltages will be modified. In particular, if any parallel conductor is present, which is bonded so as to carry induced current, then the voltage gradient in any other parallel conductor will be reduced. This reduction depends on the disposition of the conductors and the impedance of the current-carrying loop of which the *screening* conductor forms a part.

Power cables frequently have communication or protection cables laid with them in the same trench, and it is clearly desirable to reduce to a minimum the voltage induction in these parallel cables. When the sheaths of single-conductor power cables are continuous and grounded at both ends of the route, they act as screening conductors and thus reduce somewhat the voltage induction in the parallel cables. In a specially bonded system, however, the power cable sheaths no longer carry currents, and hence the screening effect is absent, at least for balanced loads in the power cables. (During imbalanced loads or faults, sheath currents will flow in the case of cross-bonded cables, and hence an important screening effect is present in this case. There will also generally be a screening effect due to the sheath or armor wires of the parallel cable itself.)

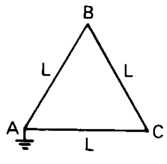
The voltage induction in parallel cables resulting from balanced loads can be reduced or eliminated by transposition, and this is particularly desirable for specially bonded cables for the reasons given above. Transposition has the additional advantage of balancing the impedances of the three-phase cables. The transposition of heavy power cables is not generally practicable except at joint positions, however, and hence the complete transposition cycle of the three phases will occupy three cable lengths. For cable circuits that consist of only one or two lengths, it is not usual to transpose the power cables, but the parallel conductor may be transposed as indicated below.

Figure 2 shows the methods to be used for transposition of the parallel cable or conductor. When the power cables are laid in flat formation with wide spacing, the parallel conductor should be between the power cables at the position shown. If there is insufficient space between the power cable to adopt this position precisely, the parallel conductor should still be between the power cables. If the cables are touching or in trefoil, the parallel conductor should be laid immediately alongside the power cables. In all cases the parallel conductor should be transposed at the center of the section length or route length to an identical position on the other side of the formation.

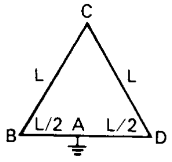
D4. Sheath Standing Voltages

(see 5.9.2)

The two corresponding vector diagrams for the cross-bonded sections are



For Figs 5 and 6



For Figs 8 and 9

On both diagrams, point A corresponds to the grounded positions. In the first diagram the maximum standing voltage will occur at point B and is of magnitude E, whereas in the second diagram the maximum standing voltage will occur at point C and is of magnitude $\sqrt{3}/2\ E$, then the voltage reduction is $(1 - \sqrt{3}/2) \cdot 100\%$ or 13.4%.

Appendix E

Transient Voltages and Voltage Withstand Requirements of Protective Jackets

Power Frequency Sheath Overvoltages

E1. General

System faults produce an initial transient overvoltage followed by a power-frequency sheath overvoltage caused by the passage of the fault current. This power-frequency overvoltage is not generally high enough to be important in relation to the sheath insulation design, but, as it persists for the duration of the fault, it may be important in relation to the duty requirements of the sheath voltage limiters.

The cable installation must clearly be capable of safely withstanding the effects of any fault in the system external to the cables. A fault in the cables themselves inevitably involves repair work and hence it is not so important if the sheath insulation adjacent to the fault is also damaged. The sheath bonding design should preclude the damage cascading to other parts of the cable system. Following system faults, sheath voltage limiters may be damaged, requiring inspection and possible replacement. The sheath voltage gradients due to external faults of three types

E1.1 Three-phase symmetrical fault

E1.2 Phase-to-phase fault

E1.3 Single-phase ground fault

are given in the equations of E3.1, E3.2, and E3.3.

In deriving these equations, the following simplifying assumptions are made:

(1) The short-circuit current is known and is unaffected in value by the characteristics of the cable system.

(2) For fault of type E1.2 and E1.3 the current in the healthy phase conductor(s) is negligible in comparison with the short-circuit current, except for the case of impedance grounding of the neutral (see E2).

(3) No other screening conductors are present (except for the parallel ground continuity conductor in the case of faults of type E1.3 in single-point bonded systems).

(4) The system consists of balanced minor and major sections in the case of sectionalized cross bonding and a number of uniform minor sections exactly divisible by three in the case of continuous cross bonding. (For design purposes, it is satisfactory to use these simplified equations also for practical systems in which imbalance does exist.)

E2. Neutral Grounding

For faults of type E1.1 and E1.2, no zero-sequence current flows. The equations given in E3 for faults of this type are therefore equally applicable to systems having the neutral directly grounded or to those having impedance or resonant grounding of the system.

For faults of type E1.3 in systems having impedance or resonant grounding, it is no longer permissible to ignore the normal load currents in the system. The calculation of sheath voltages during a single-phase ground fault therefore requires the superposition of the voltages due to the symmetrical positive sequence load currents and those due to the fault currents. The voltages due to the fault current can also be calculated by considering the asymmetrical fault currents as the superposition of an asymmetrical positive sequence system and a zero-sequence system with currents of the same magnitude. The superposition of these currents results in two currents of equal magnitude but separated in phase by an angle of 60° flowing in the unfaulted phases, while the faulted phase remains without current. The sheath voltages resulting from these currents can all be calculated from the following equations and superimposed. However, in general, for systems having impedance or resonant grounding of the neutral, the sheath voltages resulting from faults of type E1.3 will be much lower than those due to faults of type E1.1 and E1.2, and hence for design purposes faults of type E1.3 in these systems can be ignored.

E3. Single-Point Bonding

E3.1 Three-Phase Symmetrical Fault. The sheath voltage gradients are given in Appendix D, D2, using the appropriate value of I.

E3.2 Phase-to-Phase Fault. In the general case of any cable formation, assuming a fault between phases a and b with no ground current flowing, when I_{ab} is the fault current, the sheath voltage gradients are

$$E_a = j\omega I_{ab}\,(2.10^{-7})\,\log_e \frac{2S_{ab}}{d} \quad \text{V/m} \qquad \text{(Eq E1)}$$

$$E_b = j\omega I_{ab}\,(2.10^{-7})\,\log_e \frac{2S_{ab}}{d} \quad \text{V/m} \qquad \text{(Eq E2)}$$

$$E_c = j\omega I_{ab}\,(2.10^{-7})\,\log_e \frac{S_{bc}}{S_{ac}} \quad \text{V/m} \qquad \text{(Eq E3)}$$

E3.3 Single-Phase Ground Fault (Solidly Grounded Neutral). Precise calculation of sheath overvoltages under ground-fault conditions requires a knowledge of the proportion of the return current that flows in the ground itself and the proportion that returns by way of the parallel ground continuity conductor. This depends on a number of factors, which are not usually accurately known. Fortunately, however, the overvoltages of practical interest are those between sheaths and the parallel ground continuity conductor, and these can be simply calculated by the assumption that this conductor carries the whole of the return current. This assumption is normally accurate and leads to sheath overvoltages that are slightly higher than those observed in practice.

For a ground fault in phase a and the general case of any cable formation, when I_{ag} is the fault current, the sheath to ground conductor voltages are

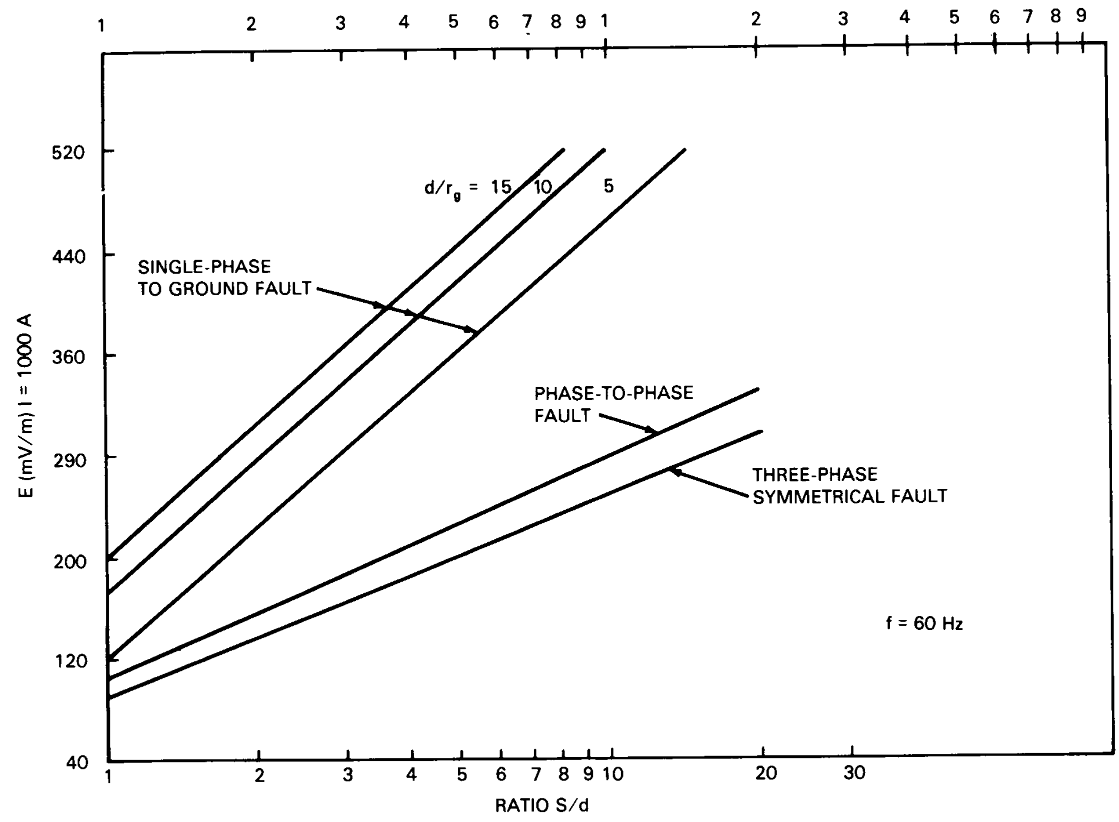


Fig E1
Induced Sheath Voltage Gradient (Sheath-to-Ground Conductor) for Various Faults in Single-Point Bonded-Cable System (Flat Formation)

$$E_a = I_{ag}\left[R_g + j\omega\,(2.10^{-7})\log_e \frac{2S_{ag}^2}{dr_g}\right]\ \text{V/m}$$

(Eq E4)

$$E_b = I_{ag}\left[R_g + j\omega\,(2.10^{-7})\log_e \frac{S_{ag}S_{bg}}{r_gS_{ab}}\right]\ \text{V/m}$$

(Eq E5)

$$E_c = I_{ag}\left[R_g + j\omega\,(2.10^{-7})\log_e \frac{S_{ag}S_{cg}}{r_gS_{ac}}\right]\ \text{V/m}$$

(Eq E6)

where

S_{ag}, S_{bg}, S_{cg} = geometric mean spacings between cables *a*, *b*, and *c*, respectively, and the ground conductor
R_g = resistance of ground conductor, Ω/m
r_g = geometric mean radius of ground conductor (for stranded conductors take 0.75 overall radius)

E3.4 Magnitude of Voltages. Typical maximum values of sheath voltages calculated from these equations are given in Fig E1 for a circuit in flat formation, for a current of 1000 A having a transposed ground conductor. For a three-phase symmetrical fault, the maximum voltage is reached in the outer cables and is the same as in Fig 1 of this guide but increased for higher current. For the phase-to-phase fault, the highest sheath voltage results when the fault is between the outer cables so that $S_{ac} = 2S$. For a ground fault assuming the ground conductor to be laid as shown in Fig 2 of this guide

$$S_{ag} = S_{cg} = S$$

$$S_{bg} = 0.7S. \qquad \text{(Eq E7)}$$

The highest of the three-sheath voltages for a fault in phase a is E_a, and since the effect of R_c can generally be neglected, the above equation for E_a can be expressed as

$$E_a = \mathrm{j}\omega I_{ag}\,(2.10^{-7})\,\log_e\left[\left(\frac{S}{d}\right)^2 \frac{d}{r_g}\right] \text{ V/m} \qquad \text{(Eq E8)}$$

Figure E1 shows the effect of varrying d/r_g over a typical range of values. It is clear that the overvoltages per meter due to the single-phase fault is much greater than for the other types of fault, for systems having solidly grounded neutral. For systems having impedance or resonant grounding of the neutral, the phase-to-phase fault is the most important.

E4. Cross Bonding

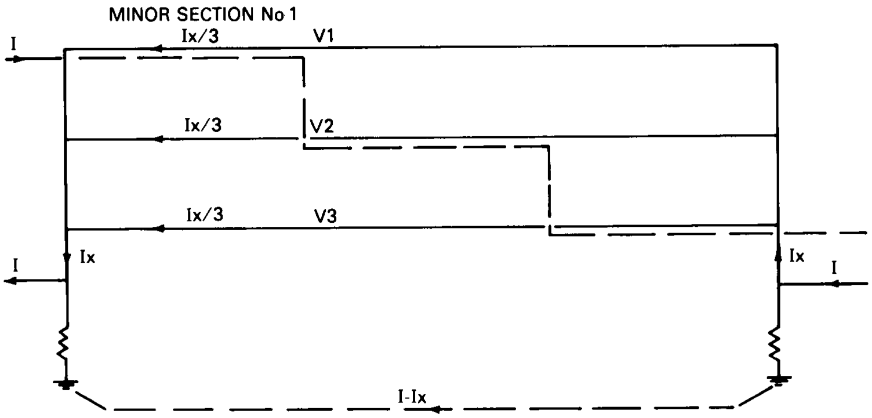
E4.1 Three-Phase Symmetrical Fault. The sheath voltage gradients are given by Appendix D, D2.3, Eqs D9, D10, and D11, using the appropriate value of I and using the longest minor section length in the case of sectionalized cross bonding or continuous cross bonding.

E4.2 Phase-to-Phase Fault. This is a balanced condition as regards induced sheath voltages, and hence no sheath current flows. The sheath voltage gradients at the cross-bonding points are as given by E3.2 equations, using the longest minor section length in the case of sectionalized cross bonding or continuous cross bonding.

E4.3 Single-Phase Ground Fault. In this case, the returning current divides between the sheaths and ground, and the calcuation of sheath voltages becomes more complex. The effect of the ground currents is important in relation to the voltages between sheaths and ground, and to calculate these it is necessary to know the values of ground resistivity and of ground-plate resistance appropriate to the circuit. The voltages between sheaths can be calculated as follows for a sectionalized cross-bonded system (The behavior of continuously cross-bonded cables during faults of this type is still being studied).

E4.3.1 Cables in Trefoil. Figure E2 shows a single major section of cables in trefoil having the

Fig E2
Single Major Section of Cross-Bonded Cables During Single-Phase Fault



sheaths grounded at both ends.

A current I_x circulates in the path formed by the three sheaths and the ground and divides equally between the three sheath circuits.

The voltages induced in the three sheaths of Fig E2, minor Section No 1 are as follows:

$$E_a = \frac{I_x}{3}\,(Z_{ss} + 2Z_{sg}) - I(Z_{ss} - R_s) \quad \text{V/m}$$

$$E_b = \frac{I_x}{3}\,(Z_{ss} + 2Z_{sg}) - IZ_{sg} \quad \text{V/m}$$

$$E_c = E_b \quad \text{V/m}$$

where

I = fault current as shown in Fig E2

The voltages between sheaths at the cross-bonding points are then

$$V_{ab} = Il\,(Z_{sg} - Z_{ss} + R_s) \quad \text{V}$$

$$V_{bc} = 0 \quad \text{V}$$

$$V_{ac} = Il\,(Z_{sg} - Z_{ss} + R_s) \quad \text{V}$$

where

Z_{ss} = self-impedance of sheath with ground return (Ω/m), by definition;

$$\mathrm{j}\omega\,(2.10^{-7})\,\log_e\left(\frac{2}{d}\right)$$

Z_{ag} = mutual impedance of sheath with ground return (Ω/m)

R_s = resistance of sheath (Ω/m)

l = length of minor section (m)

These impedances are functions of frequency and of ground resistivity but in these equations this factor disappears and

$$V_{ab} = \mathrm{j}\omega Il\,(2.10^{-7})\,\log_e\left(\frac{2S}{d}\right) \quad \text{V}$$

$$V_{bc} = 0 \quad \text{V}$$

$$V_{ac} = -V_{ab} \quad \text{V}$$

E4.3.2 Cables in Flat Formation. When the cables are laid flat, the current I no longer divides equally between the sheaths, but it can be assumed to do so with little error. Assuming also that the ground plate resistances are zero

$$I_x = I\left(\frac{3Z_{ss} - 3R_s + 2Z_{oog} + 4Z_{oig}}{3Z_{ss} + 2Z_{oog} + 4Z_{oig}}\right) \quad \text{A}$$

where

Z_{oog} = mutual impedance between sheaths of outer cables with ground return (Ω/m)

$$\mathrm{j}\omega\,(2.10^{-7})\,\log_e \frac{1}{2S}$$

Z_{oig} = mutual impedance between sheaths of inner and outer cables with ground return (Ω/m)

$$\mathrm{j}\omega\,(2.10^{-7})\,\log_e \frac{1}{S}$$

then

$$E_a = \frac{I_x}{3}\,(Z_s + Z_{oog} + Z_{oig}) - I\,(Z_s - R_s) \quad \text{V/m}$$

$$E_b = \frac{I_x}{3}\,(Z_s - 2Z_{oig}) - IZ_{oig} \quad \text{V/m}$$

$$E_c = \frac{I_x}{3}\,(Z_{ss} + Z_{oog} + Z_{oig}) - IZ_{oog} \quad \text{V/m}$$

$$V_{ab} = l\left[\frac{I_x}{3}(Z_{oog} - Z_{oig}) + I\,(Z_{oig} - Z_{ss} + R_s)\right] \quad \text{V}$$

$$V_{bc} = l\left[\frac{I_x}{3}(Z_{oig} - Z_{oog}) + I\,(Z_{oog} - Z_{oig})\right] \quad \text{V}$$

$$V_{ac} = l\left[\;I\,(Z_{ss} - R_s - Z_{oog})\right] \quad \text{V}$$

and substituting for I in the equations for V_{ab}, V_{bc}.

$$V_{ab} = \frac{Il}{3}\left[(Z_{oog} + 2Z_{oig} - 3Z_{ss} + 3R_s) + 3R_sF)\right] \quad \text{V}$$

$$V_{bc} = \frac{Il}{3}\left[\,2\,(Z_{oog} - Z_{oig}) + 3R_sF\right] \quad \text{V}$$

where

$$F = \frac{(Z_{oig} - Z_{oog})}{3Z_{ss} + 2Z_{oog} + 4Z_{oig}}$$

and all terms containing R_s can generally be disregarded.

Then

$$V_{ab} = -\mathrm{j}\omega Il\,(2.10^{-7})\,\log_e\left(\frac{2(2)^{\frac{1}{3}}S}{d}\right) \quad \text{V}$$

$$V_{bc} = -\mathrm{j}\omega Il\,(2.10^{-7})\,\log_e\,(2) \quad \text{V}$$

$$V_{ac} = -\mathrm{j}\omega Il\,(2.10^{-7})\,\log_e\left(\frac{4S}{d}\right) \quad \text{V}$$

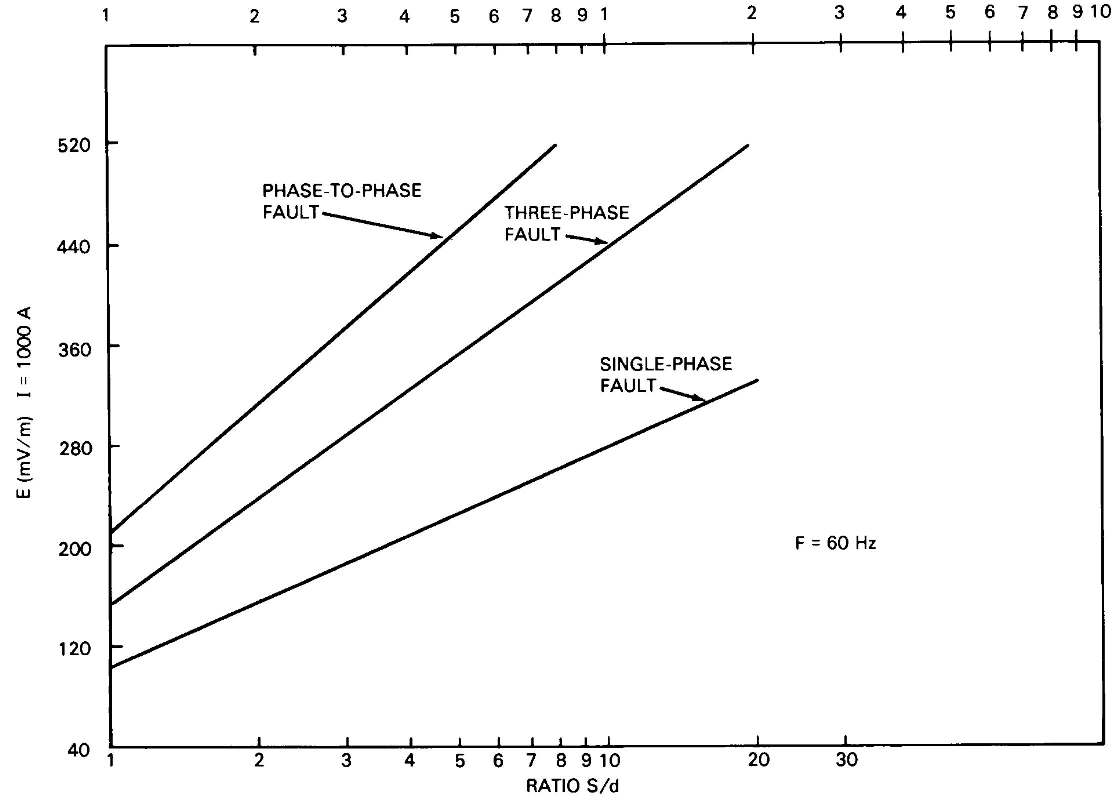


Fig E3
Maximum Induced Sheath Voltage Gradients (Sheath to Sheath) for Various Faults in Sectionalized Cross-Bonded Cable System (Flat Formation)

E4.4 Magnitude of Voltages. Figure E3 shows these voltages between sheaths at the cross-bond position per unit length of 1 m of the minor section length calculated from the equations above for single-phase faults and compared with the voltages due to three-phase symmetrical faults and for phase-to-phase faults and for a short-circuit current of 1000 A. It is evident that the voltage due to the phase-to-phase fault is the greatest.

The sheath voltage limiter generally consists of a star connected device having the star point grounded to a local ground. The resistance of these local ground plates are often high but some current will flow into the ground during a single-phase fault. The calculation of these currents and of the voltages between the sheaths and the ground plates is complex and requires a knowledge of the ground-plate resistances and the ground resistivity along the cable route. These values are not generally known, especially at the design stage, and hence it is usual to consider the duty of the sheath voltage limiter only in terms of the voltage between sheaths. Experience and measurements indicate that the sheath-to-ground voltage rise is not generally sufficient to damage the sheath-voltage limiter, but, when there is any doubt, the star point should not be grounded, when this is permissible, with respect to transient overvoltages.