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IEEE Guide for the Evaluation of the Remaining Life of Impregnated Paper-Insulated Transmission Cable Systems

IEEE Power Engineering Society

Sponsored by the
Insulated Conductors Committee



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**Insulating Conductors Committee
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Abstract: This guide provides technical information regarding factors that can affect the life of an impregnated paper-insulated transmission cable system, and it reviews available methods to evaluate the remaining life of such systems and preventive maintenance to extend their service life.

Keywords: extra high voltage (EHV) cable, high-pressure fluid-filled (HPFF) cable, high-pressure gas-filled (HPGF) cable, impregnated paper-insulated transmission cable systems, self-contained liquid-filled (SCLF) cable, thermal-mechanical bending

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Introduction

(This introduction is not part of IEEE Std 1425™-2001, IEEE Guide for the Evaluation of the Remaining Life of Impregnated Paper-Insulated Transmission Cable Systems.)

The end of the Second World War saw unparalleled growth in the use of electrical energy in many areas of the world, driven by rapid population increases, reconstruction of urban infrastructure, industrialization, and newly found prosperity. In order to meet the growing electrical energy demands, utilities made very large investments in new generation, substations, transmission, and distribution plants. In heavily populated, high load density urban areas, where sufficient rights-of-way were unavailable, transmission lines were installed underground.

Many of these underground transmission lines have now reached, or will soon reach, the end of their theoretical lives. This is understandably a time when many owners are alerted to the possibility of the mortality of their lines and require information on remaining service life. Sometimes they are also alerted by rising maintenance costs, as equipment failure rates increase with age. In other cases, the maximum current ratings of underground cables are rapidly approached because of rising electrical loads or increased power transfers, prompting review of uprating possibilities and system reinforcement alternatives. These issues inevitably result in discussions on the remaining life of transmission cables and life extension strategies, usually with significant financial ramifications.

From a broad perspective, it has been the practice to assume that end-of-life occurs when damage is so extensive that it becomes no longer economic to repair or maintain the cable system, or when failures are so frequent that the reliability of supply is compromised. However, failure of a localized part of the system may not necessarily mean end-of-life for the whole. It is, therefore, useful to evaluate the remaining life of a cable system in the context of the mortality of its individual components and its condition as a whole.

Participants

This guide was prepared by the members of Working Group C4 (3-58) of the Cable Systems Subcommittee of the Insulated Conductors Committee of the IEEE Power Engineering Society. It is attributed to the efforts of many cable industry engineers who took the time to attend the working group meetings, participate in the discussions, and comment on and edit the final document.

The following is a list of participants in Working Group C4 (3-58). Special appreciation goes to members with an asterisk after their name for their effort in preparing the text.

S. Michael Foty*, *Chair*

Joseph T. Zimnoch*, *Vice Chair*,

Mark S. Allen
Richard W. Allen, Jr.
Earle C. Bascom III
Sankar P. Basu
Jean Marie Braun
John H. Cooper*
Stan Croall*
John Densley
Swapan Dey
Claus Doench
John S. Engelhardt*

Anthony Ernst
Reza Ghafurian
Edwin I. Hahn
David J. Horrocks
Joseph S. Jue
Takashi Kojima*
Albert Kong
Stephen Kozak
W. Graham Lawson*
G. Allen MacPhail*
Shantanu Nandi

John Owen*
Gary A. Polhill
David W. Purnhagen
Haran S. Radhakrishna*
George Ed Rogers
Gerry Sheerin*
Nirmal Singh
Lawrence Y. Tang
Frank Teti
Steve Walldorf*
Jay A. Williams

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Roy W. Alexander
Theodor A. Balaska
Earle C. Bascom III
Martin Baur
Michael G. Bayer
Kenneth E. Bow
Paul S. Cardello
Jack E. Cherry
John H. Cooper
John R. Densley
S. Michael Foty
Robert B. Gear
Hans R. Gnerlich
Wolfgang B. Haverkamp

Stanley V. Heyer
Lauri J. Hiiuala
Carlos Katz
Lawrence J. Kelly
Albert Kong
Frank L. Kuchta
Carl Landinger
Gabor Ludasi
Glenn J. Luzzi
G. Allen MacPhail
Matthew S. Mashikian
John E. Merando, Jr.
Daleep C. Mohla
Shantanu Nandi

Arthur V. Pack, Jr.
Neal K. Parker
Ronald J. Ponist
Radhakrishna V. Rebbapragda
Robert A. Resuali
Gilbert L. Smith
Nagu N. Srinivas
John Tanaka
William A. Thue
Daniel J. Ward
Nick Ware
Roland H. Watkins
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Joseph T. Zimnoch

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IEEE Guide for the Evaluation of the Remaining Life of Impregnated Paper-Insulated Transmission Cable Systems

1. Overview

1.1 Scope

This guide provides technical information regarding factors that can affect the life of an impregnated paper-insulated transmission cable system, and it reviews available methods to evaluate the remaining life of such systems and preventive maintenance to extend their service life.

1.2 Purpose

This guide provides technical background, discussion, and advice to those needing to evaluate the remaining life of impregnated paper-insulated transmission cable systems. Guidance is given for both high-pressure fluid-filled (HPFF) (see Association of Edison Illuminating Companies CS2-97 [B12]¹) and self-contained liquid-filled (SCLF) (see Association of Edison Illuminating Companies CS4-93 [B13]) cables, which use a dielectric liquid as the filling and pressurizing medium (dielectric fluid), and for high-pressure gas-filled (HPGF) (see Association of Edison Illuminating Companies CS2-97 [B12]) cables, which use nitrogen gas as the filling and pressurizing medium. The information presented here is intended to provide a complete and concise summary and overview, with frequent references to the technical literature for those who wish to investigate specific subjects in more detail. Emphasis is placed on practical, realistic, and economical methods for performing field and laboratory sampling and testing, and later analysis to determine the actual condition of a cable installation.

This guide describes the various aging mechanisms that act on cable components. This includes aging of the outer protective coverings and the fluid-containing sheaths and pipes. It also includes thermal-mechanical aging of SCLF cable sheaths and their mechanical aging due to creep and fatigue, and thermal-mechanical aging of HPFF insulation due to flexural fatigue resulting from cyclic loads. Thermal and electric stress aging due to cable heating effects and the applied voltage are covered as well.

¹The numbers in brackets correspond to those in the bibliography in Annex A.

Methods are presented to assist in evaluating the extent of cable aging. Both intrusive and nonintrusive techniques are described; however, emphasis is placed on the latter. Treatment of the subject includes a description of traditional evaluation methods used in the past, supplemented by newer and emerging methods. Emerging methods include dissolved gas and metals analysis of dielectric fluids, as well as tests for other byproducts of the decomposition of cellulose, which can be used to gauge insulation aging and diagnose incipient failure mechanisms. Finally, advice is provided on preventive maintenance methods, for use in extending the actual service life of a cable system well beyond its economic life.

It is intended that this guide be revised periodically to reflect new developments in diagnostic technology and experience gained with long service-operating cables.

1.3 Unit conversion factors and acronyms

Metric units are used. Unit conversion factors are given in Annex B.

All acronyms used are defined at their first use.

All technical terms are as per IEEE definitions.

2. Cable thermal environment

The cable operating temperature is a direct function of its loading and of the thermal resistivity of surrounding soils (see AIEE Committee Report [B4], Mochlinski [B71], and Schmill [B91]). Although a cable operated continuously or frequently at loads exceeding its design limits will overheat even if the cable thermal environment is unchanged, changes to the environment in which a cable is placed may result in the cable operating at temperatures exceeding design temperatures. Overheating accelerates cable aging (see Kurtz [B66]) or forces cable derating (see AIEE Committee Report [B4]).

For the purpose of this discussion, the cable thermal environment includes, in the case of land cables, the backfill in which it is embedded, the surrounding soil, the surface cover, the water table, and the proximity to external heat sources. In the case of submarine cables, the marine environment and sediments in which the cables are placed have to be considered. The cable environment can change with time due to either natural or man-made processes.

This clause discusses changes in the cable thermal environment and the methods that could be used to mitigate harmful influences on cable service life.

2.1 Thermal resistivity

The thermal resistivity of the backfill in which cables are embedded, and that of the surrounding soils, are dependent on their moisture content or degree of saturation (see Radhakrishna, et al. [B88]). Figure 1 shows the dependency of thermal resistivity on moisture content for some typical soils and cable backfills (see Adams and Baljet [B1] and Radhakrishna, et al. [B88]). Typically, the thermal resistivity can double or triple with the depletion of moisture content below a certain critical level (see Adams and Baljet [B1] and Radhakrishna, et al. [B88]), which leads to thermal instability (see Adams and Baljet [B1] and Radhakrishna [B86]) and cable overheating (see Arman, et al. [B11]).

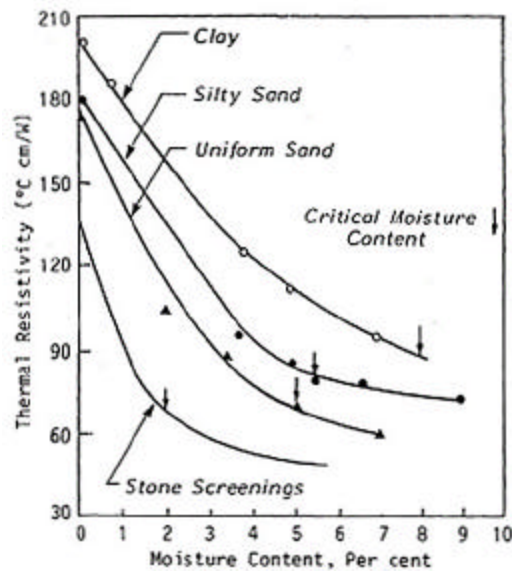


Figure 1—Thermal resistivity of typical soils (see Adams and Baljet [B1])

Moisture content is governed by seasonal variations and changes in weather pattern, which determine how much moisture is delivered to the soil. However, this can be modified by excessive cable loading, which causes moisture migration away from the soils surrounding the cable.

In addition, backfill thermal resistivity is dependent on other factors such as material composition and method of installation. Operating cables are often accessed for maintenance and repairs by excavating the backfill, or the backfill may be disturbed by construction activities. These disturbances may go undetected. If backfill reinstatement is not done properly, it can result in the development of areas of high thermal resistivity (hot spots), which over time could adversely affect the life of the cables. SCLF cables and HPGF cables, which have no intrinsic forced cooling facility to smooth the effect of hot spots, are especially susceptible.

In the case of submarine applications and in certain types of sediments, the heat from cables can cause thermal drying of the immediately surrounding material. This drying can be severe enough, even when water depth is in the tens of meters, to result in thermal runaway (see Tulloch and Cronin [B96]). Also, there is a possibility in organic-rich sediments, of methane gas generation due to the heat from cables, which can impede heat dissipation and lead to cable overheating. The overall effect on the thermal performance of submarine cables should be evaluated by thermal testing of sediments along the cable route.

2.2 Other factors affecting the thermal environment

During a cable's operating life, its thermal environment may change due to the growth of trees, the installation of other heat producing underground plants such as steam pipes or other power cables, the raising of grade elevations, the changing of the nature of soil cover, and excavations that are not properly reinstated.

Such changes are causes of moisture depletion, increased thermal resistivity, or increased ambient temperature of the soils surrounding the cables. They all result in potentially harmful cable operating temperatures and subsequent premature aging.

2.3 Methods to investigate changes in the thermal environment and evaluate their impact on cable service life

The following steps may be taken to investigate, assess, and record the impact of changes in the thermal environment:

- a) Maintain a comprehensive record of changes along the cable route through regular patrols and review of construction permits.
- b) Carry out assessment of new construction plans with particular attention to buried heat sources or plans, which may reduce soil moisture content (see Anders and Radhakrishna [B8]).
- c) Review, periodically, the operating record to determine cable loading history, conductor and sheath temperatures (if available), and failures (if any).
- d) Determine, periodically, the in situ thermal parameters and their variance from the values used in the original design by conducting a soil thermal survey, giving special attention to areas where disturbances to the thermal environment have been noted (see Boggs, et al. [B32]).
- e) Determine backfill thermal stability under actual operating conditions by obtaining a sample of backfill adjacent to the cable and carrying out a thermal stability test with a thermal property analyzer (TPA) (See Boggs et al. [B33]) and a thermal probe (see Black, et al. [B31] and Boggs, et al. [B33]).
- f) Take corrective measures, including cable derating, if necessary, to avoid premature cable aging when results of the thermal survey analysis, together with the cable loading history, indicate probable cable overheating (see Anders and Radhakrishna [B8]).

2.4 Methods of mitigation

At locations where analysis indicates thermally unstable conditions, the backfill or surrounding soils could be replaced with backfills that are thermally more stable, such as compacted well-graded sand or crushed screenings of sound rock (see Adams and Baljet [B1]). Fluidized thermal backfills (FTB) are well suited for upgrading the cable thermal environment because of their ease of application and low thermal resistivity even under dry condition (see Radhakrishna [B87]). Although it makes future cable access difficult, concrete, because of its good thermal properties (see Thue [B95]), is sometimes used as thermal backfill at locations where high compressive strength is required for mechanical protection.

Where hot spots are detected, local cooling could be achieved through slow circulation of the dielectric fluid in the pipe of HPFF cables (see Chato, et al. [B36]). Where this is not feasible, and in the case of SCLF and HPGF, external cooling devices would have to be installed to moderate the cable temperature. These can be water circulation or soil irrigation systems (see Baldwin, et al. [B27] and Brooks, et al. [B34]). If such methods are not sufficient, it may be necessary to thermally insulate the interfering heat source, use refrigerant-filled heat dissipation tubes (see Croall, et al. [B38]), or build a ventilated manhole around the hot spot created by the cable crossing of another heat generating utility.

Where new required cable loading would result in severe cable overheating, forced cooling systems that use external heat exchangers to cool the dielectric fluid may be necessary. However, it is usually difficult and expensive to retrofit existing cables with forced cooling.

Further, the need for elaborate mitigation methods can be reduced by

- a) Improving coordination and planning procedures in-house and with other utilities
- b) Reviewing, in detail, planned construction activities along the cable routes

- c) Enforcing the use of proper materials and procedures for the reinstatement of cable backfills
- d) Applying real-time monitoring of cables and cable backfills, especially at hot spots (see Croall, et al. [B38]).

3. Corrosion and mechanical protection

To achieve the dielectric strength required for operation at transmission voltages, the impregnated paper insulation must be kept under hydraulic pressure using a dielectric fluid (mineral oil, synthetic liquid, or nitrogen gas). Jacketed metallic enclosures are used to contain the fluid: a steel pipe for HPFF and HPGF cables and, usually, a lead, copper, or aluminum sheath for SCLF cables. These enclosures, when buried, may be subjected to corrosive environments and damage from external sources.

A weakened enclosure will eventually result in leakage of dielectric fluid and potential partial discharge and moisture ingress into the insulation, ultimately leading to cable failure. As the costs of repair and cleanup, and the loss of revenue associated with cable unavailability, can be substantial, it is imperative that the integrity of pressure containment components be maintained.

3.1 Mechanical protection

Some of the external factors that may cause damage to a cable system include excavation, boring, excessive ground loading or vibration, settlement of the soil and substrate, and corrosive soils. Mechanical protection is required to prevent accidental cable contacts and cable damage, and it is critical to cable system reliability and length of service. Although damaging the cable may result in service interruption and have potentially serious environmental and cost implications, contacting an energized cable may represent a grave hazard and should be avoided.

To protect against accidental contact, the first line of defense could be to provide clear, visible, above-ground markers indicating both the presence of high-voltage cables, the name of the utility, and the “One Call” phone number. In addition, some utilities install a buried cautionary marker tape above the cables and strong barriers such as casing pipes, steel plates, concrete slabs and side walls, or reinforced concrete duct banks.

Patrolling cable routes, monitoring excavation by third parties, and participating in Public Utilities Coordinating Committees that coordinate work on public road allowances, are the most efficient means of ensuring the continued mechanical protection of cables.

3.2 Causes of corrosion

Corrosion of the cable metallic enclosures may be caused by two basic mechanisms (see Husock [B50]):

- a) Galvanic corrosion occurs naturally when a metallic structure is in contact with the soil. With the soil acting as an electrolyte, differences in potential may develop between the structure and an adjacent structure of dissimilar metal. Potential differences may also develop along the structure where it is in contact with dissimilar soils. If a continuous electrical path is created as a result of breaches in a cable enclosure protective jacket, such potential differences will cause a current flow. Corrosion (metal loss) occurs at the points where this current leaves the enclosure (anode) through a jacket or coating breach to enter the soil and flow to the cathode.
- b) Electrolytic corrosion, also known as stray current corrosion, results from the flow of externally generated dc currents that enter the cable metallic enclosure at grounding locations or at points where the jacket is breached, and exit the enclosure at other points to return to source. Again, corrosion occurs at the points where the current leaves the enclosure through a jacket or coating breach to enter the soil.

In addition, corrosion may be exacerbated by inadequate design or installation practices, by interference caused by lack of coordination with cathodic protection systems on neighboring structures, or by the malfunction or inadequate maintenance of the cable cathodic protection (CP) system.

3.3 Methods of providing corrosion protection

3.3.1 Protective jackets and coatings

An external jacket provides the primary protection against corrosion of a cable metallic enclosure. Jackets are primarily designed to isolate the enclosure from corrosive environments. They also help reduce the magnitude of protective currents for cathodically protected circuits and provide, in the case of SCLF cables, the electrical insulation necessary to control sheath currents and provide mechanical protection during cable pulling. See IEEE Std 532™-1993 [B55] for guidance on the selection and application of protective jackets.

Initially, protective coatings of HPFF and HPGF cable pipes were usually made of asphalt mastic or reinforced coal tar enamel. More recently, they have been made predominantly of high density polyethylene, but PVC and polypropylene have also been used (see NACE Publication 10A172 [B72]). SCLF cables, on the other hand, were not initially jacketed. Several jacketing materials have been tried since the early 1930s, and in the early 1950s, reinforced neoprene jackets were in standard use. Since the early 1960s, polyethylene has become the predominant material for SCLF cable jackets in North America.

To ensure the quality of external jackets, electrical tests are performed with a coating discontinuity “holiday” tester at the factory prior to shipping and in the field prior to backfilling (see NACE Std RP0274-98 [B76]). In general, HPFF and HPGF cable pipes with asphalt mastic coatings were tested at 35kV dc. Those with reinforced coal tar coatings and those with polyethylene coatings were tested at 15kV dc. Because jacket thickness of SCLF cables varies from 2 mm to 3.6 mm (depending on the cable diameter), the electrical test voltages used range from 3kV ac (7kV dc) to 11.5kV ac (28kV dc), depending on the type and thickness of the jacket.

However, jackets cannot be made perfectly insulating because small imperfections can be present in the material and holidays can be developed during factory application. Jackets can also be damaged by handling during storage, transportation, or installation, or developed later in service by transient overvoltages, by high operating temperatures, or by external agents such as chemicals in the ground, or by dig-ins. These factors cannot always be avoided, and currents may be able to flow into or out of the metallic enclosure. Because of this limitation and to ensure corrosion protection, jackets and coatings are normally supplemented by a cathodic protection system, mainly in the case of HPFF and HPGF cables.

3.3.2 Cathodic protection

Many publications are available that cover the theoretical and practical aspects of cathodic protection design: Husock [B50], NACE Std RP0169-96 [B73], NACE Technical Committee T-2 [B77], Parker [B82], Pope [B85], to list a few.

Cathodic protection systems neutralize the corrosive effects of galvanic activity or stray dc currents at points where the jacket is breached by ensuring that current always flows from either a galvanic or an impressed current anode into the metallic enclosure (cathode). Two types of cathodic protection systems are in common use:

- a) Galvanic, zinc or magnesium sacrificial anode systems generate protective currents as a result of the natural potential differences, which exist between their material and that of the cable metallic enclosure. In the process, they are consumed at a rate that is a function of the magnitude of the protective current and the anode material. In general, galvanic sacrificial anode systems are used when a relatively small protective current is required and where the soil resistivity is relatively low.

- b) Impressed current systems use an external source, usually a rectifier, to provide the protective currents. They are used where larger or variable protective currents are required, or where soil resistivity is relatively high, requiring larger driving potentials.

To limit the protective current requirements while providing a low impedance path to ground faults, the metallic enclosure of cathodically protected cables is usually connected to ground through a stainless steel resistor, polarization cell, voltage limiting gap, or, more recently, solid state devices.

3.4 Methods of assessing cathodic protection systems

Surveys and tests provide means for detecting and evaluating the potential causes of corrosion. A systematic program can be broken into the following activities:

- a) Gathering Information, including data on the location and operation of dc transit systems, cathodic protection systems used by others, and other equipment operating on direct current in the general location of the line.
- b) Performing Corrosion Protection Surveys, which include jacket fault locating surveys, enclosure-to-soil and enclosure-to-other-subsurface-structures potential surveys, and current discharge measurements. Recently, real-time monitoring techniques of cathodic protection parameters have also been introduced (see Hoppe, et al. [B48]).
- c) Maintenance Testing to assess the condition of the corrosion protection system, including drainage bonds, rectifiers, and polarization cells.

3.4.1 Jacket and coating integrity testing

Traditionally, jacket integrity testing is done in two steps. First, a jacket resistance test is conducted. The jacket resistance is then calculated. With the circuit de-energized and grounded and the pipe isolated from all grounds, including cathodic protection rectifiers and anodes, a voltage is applied between the pipe and ground and the resulting current across the jacket measured. If the resistance per surface area is found to be larger than $100 \text{ k}\Omega/\text{m}^2$ for reinforced coal tar coatings, or $1 \text{ M}\Omega/\text{m}^2$ for asphalt mastic or polyethylene, the coating is considered sound. Although this method can identify pipe sections with problem coating, it does not pinpoint the actual coating damage location. This usually requires the use of an above-ground potential survey (see Peabody [B83]).

In recent years, a less labor-intensive investigative technique has been introduced in some parts of the pipeline industry for monitoring coating integrity. This involves measuring the rate of attenuation of the field intensity of an injected high-frequency signal. Measurements are made from ground surface at regular intervals. With a sound jacket, the field intensity declines uniformly as the distance increases from the signal source. Sudden declines in field intensity generally indicate the presence of coating damage. This technique has been used in some transmission utilities to evaluate HPFF pipe coatings. In these successful applications, it has been used in combination with traditional fault locating techniques to pinpoint coating damage sites.

The effectiveness of this technique looks promising when specific damage sites are present; however, more experience is required before the scope of this technique as a cable maintenance tool is fully evaluated. Some of the factors in the electrical transmission industry hampering the adoption of the technique include the effect of ground return current paths paralleling the pipe, and access to ground electrode sites remote from station ground grids.

It is believed that the most promising maintenance application of the technique lies in a comparison of the results of successive coating surveys when identical connection conditions have been established.

3.4.2 Enclosure-to-soil potential surveys

Enclosure-to-soil potential measurements are taken at close intervals along the cable route using a copper–copper sulfate reference electrode (see Husock [B49]). The measurements provide a continuous potential profile along the metallic enclosure. For a sound jacket, successive readings should be substantially the same; a less negative value would indicate a jacket discontinuity. The degree of the change in potential is indicative of the size of the discontinuity.

For adequate cathodic protection, the potential difference must meet the criterion of protection for the particular metal used for the enclosure. Although unprotected coated steel pipes usually have a potential to a copper–copper sulfate electrode of -0.5 V to -0.7 V, good cathodic protection is considered to have been achieved when the pipe potential is in general, between -0.85 V and -1.0 V (see Hymes [B51]). More negative potentials may be necessary but should be used with caution as they may cause jacket disbonding. The generally accepted criterion for protection of lead sheathed SCLF cables is a potential difference to a copper–copper sulfate reference electrode of -0.7 V (see NACE Std RP0194-94 [B75]).

Because this type of potential measurement is influenced by operating dc transit systems and other sources of stray currents, it is normal to carry out the measurements very early in the morning or over the weekend.

3.4.3 Measurement of currents in the metallic enclosure

IR Drop measurements (see Edison Electric Institute [B41]) are usually made at manhole locations to establish the magnitude and direction of stray dc currents. The magnitude of the current is indicative of the severity of the corrosion problem, whereas the change in direction indicates the cable section where the stray currents leave the metallic enclosure.

Measurement of ac currents in the bonding leads of SCLF cables can help in identifying cable sections with damaged jackets. They also provide input for determining actual cable operating temperatures.

3.4.4 Testing of empty cable pipes prior to installing new cable

In the case of HPFF and HPGF cable systems, two situations may develop requiring special consideration:

The first situation involves a utility that installs a double-pipe circuit from point “A” to point “B,” but initially pulls cable into one pipe leaving the adjacent parallel pipe empty for a future cable circuit. The spare pipe is usually maintained under a slight nitrogen pressure in the range of 175 kPa. It is not uncommon for the spare pipe to be left empty for 10 or more years before load growth or system changes require installation of the second circuit.

A variation of the arrangement described in the proceeding paragraph is to initially fill the parallel pipe with dielectric fluid and use it as a return pipe for fluid circulation and temperature averaging, or forced cooling. In these applications, the parallel pipe may be one or two sizes smaller than the cable pipe and without flared end/chill ring welds because the intent was not to install conductors later for use as an additional circuit. On the other hand, where the pipe was installed with flared end/chill ring welds and is of suitable size, consideration may be given to pulling in cables for use as an additional circuit.

The second situation involves increasing the capacity of an existing HPFF or HPGF cable circuit by pulling out the original cables and replacing them with larger conductor size or higher voltage-rated pipe-type cables or other alternative types of high-voltage cables.

In the cases described in the two preceding paragraphs, the pipes could have been buried in the ground for many years and may have been subjected to external mechanical damage and corrosive attack. Thus, it is critical to assess the current condition of the pipes prior to pulling in any new cables. This can be done by the following multistep procedure:

- a) Disconnect all grounds from the pipe, and measure the end-to-end pipe coating resistance.