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6/15/2010
75FR33853 1

RULES AND DIRECTIVES BRANCH USNRC
2010 JUL 27 AM 9: 41
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U.S. Nuclear Regulatory Commission
Rules, Announcements and Directives Branch
Office of Administration
Washington DC 20555-0001

Attached are comments on June 2010 Draft Regulatory Guide DG-1240

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Principal

SUNSI Review Complete
Template = ADM-013

E-RIDS = ADM-03
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DC HiPot Testing of Aged XLPE-Insulated Cables

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These comments on DC HiPot testing are being provided in response to Draft Regulatory Guide DG-1240. The writer was the EPRI project manager (now retired) for the study that evaluated the effect of DC testing on aged and unaged extruded cables.

The use of dc high voltage testing to detect gross defects in XLPE insulated cables had been standard utility and industrial practice into the 1970s and beyond. The purpose of such testing was intended to assure that such cables would not fail after being placed in service. DC was considered to be particularly effective for this purpose as XLPE cables have inherently high dc breakdown strengths (relative to AC), have low leakage currents and, as a practical matter, the equipment is easy to handle in the field.

Some background on field testing and procedures is reviewed here first. One basic document in this area is "IEEE 400 Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems". This 'Omnibus' document reviews presently accepted methods of cable testing, and refers to Type 1 and Type 2 field tests.

Type 1 field tests are intended to assure reliability after a defective region has been removed and repair(s) have been made. The tests are referred to as 'go/no go' or 'pass/fail' and apply a moderately increased voltage over the cable system for a defined duration. DC high potential tests fall into this category. The dc overvoltage test had, historically, been applied successfully to paper/oil, lead covered (PILC) cables for many years.

Type 2 field tests are intended to provide guidance on the deterioration of the cable system, and may offer information about the overall condition of the cable system, or indicate the location of defects that may represent regions of potential future failure. These are referred to as diagnostic tests and may involve use of slightly increased overvoltage(s) applied for short duration, (or no overvoltage). Partial discharge tests and loss measurements fall into this category.

The Omnibus document hence provides an overview; specific tests are covered in detail in various 'sub-documents'; IEEE P400.1 covers direct voltage (dc) Testing.

Two procedures (both 'go/no go') are relevant to this summary. Acceptance testing in the field is conducted after the cable system has been installed, but before it has been placed in service. Such testing is intended to detect gross defects and damage due to installation procedures. Maintenance testing is performed during the operating life of the cable system and is intended to detect deterioration resulting from aging. The latter testing is applied when a cable section or failed region has been removed and replaced with un-aged cable or an accessory. Acceptable dc test voltages for installation and maintenance testing as a function of rated voltage, conductor size and insulation wall thickness have been defined (1). Testing is related to phase to phase cable rated voltage; for a 15 kV cable having nominal 175 mil wall (a common MV construction) acceptance testing voltage would be 55 kV for 15 minutes; for maintenance testing (recall this test is applied to aged and repaired segments) the dc stress applied for this construction is 40kV/ 5 minutes. The applied stress increases as rated voltage increases.

It is important to note several cautions clearly defined by the industry, relative to dc testing procedures. (a) Before performing any dc overvoltage test, practical handling issues need to be evaluated and addressed; for example, equipment must be disconnected from the cable circuit (e.g., surge arresters, motors, etc) to preclude potential damage. Manufacturer's literature describes these issues.

(b) Proper grounding is critical after the test is performed; industry procedure is to assure that solid grounds must be maintained for at least 4 times the test durations.

(c) Manufacturer's have requested that they be consulted prior to testing of cables that have been in service for over 5 years.

This summary provides an 'overview' of issues related to dc high potential testing; the IEEE Guide, manufacturer's literature and technical articles should be consulted for details.

The use of DC overvoltage (HiPot) testing, while originally adapted for PILC cables, was routinely adopted and applied (as a withstand and condition assessment test method) to XLPE insulated cables when they replaced PILC, for reasons noted above. When this occurred, no consideration was given at that time to the significant differences between laminated and extruded cables and materials, and how they differ in response to applied voltage stress (2).

As indicated, we are concerned here only with testing of installed cables. This category includes acceptance and maintenance testing (see below). Factory testing of new extruded cables using DC is beyond the scope of this document.

Around the 1970s, a perception had arisen on the part of some utility users that the DC application may be harming the life of extruded XLPE-insulated cables. This was opposite of what the test was designed to do, and went against current thinking of the time. However, no technical/experimental evidence was available, solely a perception based on observation and history, that some cables seemed to be failing after such testing. This was brought to the attention of EPRI (3), and a limited number of tests were performed during an existing distribution cable project to seek to clarify the matter (4). It turned out that the ac breakdown strengths of XLPE-insulated distribution cables tested before and application of the DC HiPot showed no statistical difference. (The dielectric strength test was the conventional method for determining functional use of the cables.) From this limited 'shotgun' series of tests, it appeared that DC was not harmful.

However, because of ongoing concerns, the EPRI utility advisory structure requested a deeper study. This study had the following objectives

a) Determine whether dc testing is harmful to present day XLPE distribution cables and if so, under what conditions.

b) Investigate the effect of dc testing (proof and maintenance) on both un-aged and aged cables, and the effect of such proof testing on a cable system comprised of an and aged cable, splice and a new cable.

c) If harmful, provide guidance on the level of dc that may be harmful and suggest alternatives.

It is noted that that one of the objectives was to focus on seeking differences in response between aged and un-aged cables. The prior tests (4) were performed by applying dc to un-aged cables only, and maintenance test procedures (1) did not discuss the concept of distinguishing between aged and un-aged cables.

At this point it is worth commenting on the fundamental difference in the manner in which charge is distributed in a cable under ac vs. dc stress. Under ac, <u>capacitance</u> is the overriding factor influencing stress distribution and the stress is distributed in inverse proportion to the capacitance of the dielectric. Therefore the highest stress is close to the conductor. Under dc, the voltage distribution is determined by the insulation <u>resistance</u> and space charges (5), the latter of which can vary with aging. It has been noted that the permittivity (or dielectric constant, of specific inductance capacitance) which is a measure of capacitance, does not in general vary as much as the resistivity (6). For our purposes, what is of significance is that the XLPE can be expected to respond differently in a fundamental manner to DC stress (even if not continuous), as compared to ac operating conditions. The literature has reports indicating that XLPE can accumulate space charge under dc applied stress (7).

The conclusive EPRI-sponsored project (8) was performed by Detroit Edison (N. Srinivas was principal investigator) and the study on full size distribution cables took place over a 7 year period. Initial studies were performed by applying dc (in accordance with industry guidelines) and--as before --sought to determine the influence of DC by performing ac breakdown strength tests after dc application. As before, this specific diagnostic test did not distinguish between XLPE cables that had dc applied and those that did not. However, differences between dc - tested and non-dc-tested XLPE cable's response started to show up when the diagnostic was switched away from an AC breakdown strength test to a voltage endurance test; i.e., determining the time to failure during (accelerated) aging.

The potentially harmful effect of DC hipot testing was shown as a result of the following experimental study which is worth reviewing, as it more closely simulated what happens in service (compared to an intentional dielectric strength test where the stress on the aged or unaged cable is intentionally raised in the laboratory).

Extruded 15kV XLPE cables were aged until failure in a pipe using the accelerated water treeing test; this involved cables being immersed in water, with water also being placed in the strands and aging taking place at 3X rated voltage. [Year(s) were required for failure to occur]. The failure region was then cut out (failure for these segments could be located visually) and the two aged segments were then spliced to segments of new, un-aged XLPE cables (from the original extrusion run). There were now two 'matched pairs' of aged cable/splice/un-aged cable test samples. [In actual fact there were scores of these samples prepared]. Now, one matched pair was subjected to dc hipot testing (via industry procedures) and the other was not. Then, both sets of cable /splice/cable specimens were re-immersed in water and the same accelerated water treeing test was continued. These samples were (again) aged to failure. (The splice was intentionally overdesigned to assure that it did not fail).

What happened now, after the second aging cycle, was that the previously-aged cable segments always failed before the previously un-aged cable segments (not a surprise), but ALSO, <u>the dc tested previously aged segment always failed before the non-dc tested previously aged cable segment</u>. What was remarkable is that this happened 100% of the time, in every test. There was no statistical analysis required, or even possible; the dc tested aged cable segment always failed prior to the non-dc tested aged cable segment. The DC tested, originally un-aged cable segment never failed first, clearly demonstrating that that the dc stress affected aged and un-aged XLPE differently. The failure times were not constant but the failure sequence was. (It can also be noted that gross defects, which if present would be expected to cause 'immediate' failure, were never located.)

The experimental study clearly demonstrated the potential harmful effect of applying DC to aged XLPE cables. The questions that arise and why is this so, and how can understanding same lead to improved test procedures. The technical literature reveals and clarifies the issues.

It was noted above that application of DC on a cable will result in a stress distribution that is significantly different from application of ac. The high voltage DC will generate space charges within the XLPE and these will remain. (Grounding is intended to reduce the trapped charge.) When AC is later applied, the presence of the space charges causes an increased level of localized stress (7). The latter is a well known factor leading to water and electrical trees. The industry specifications allow DC test voltages that are 2-3 times greater than the ac breakdown voltage stress (in order to detect defects).

The application of dc, while intended to locate defects, may however generate space charge that, in turn, allows an increase of localized stress that can lead to failure. The degree of degradation of the XLPE cable at the time of testing determines what happens at the time of testing or at a later time; a highly degraded XLPE cable with significant degree of oxidation will facilitate greater charge trapping than a slightly degraded cable.

A literature search revealed that there is substantial evidence from laboratory work to support the potential harmful effect of dc. For example, Hozumi and co-workers (9) showed that when dc is applied to aged and unaged specimens of polyethylene (not cables), and when aging is continued, the dc-treated specimens held greater trapped charge than the non-dc treated specimen after equal aging times. Also, the level of trapped charge increased upon continued ac aging. Other work reported that space charges may be formed when impurities, such as an antioxidant, dissociate thermally with the help of acetophenone, and that the dissociated products are attracted toward electrodes under a dc field to form the hetero space charges (11). Additional work by Srinivas on non-spliced cables (8) showed that multiple applications of DC during aging reduced the life during accelerated aging (AWTT).

The EPRI study (8) noted that the presence or absence of volatiles such as acetophenone can influence space charge trapping; no specific quantitative study was performed at that time. A more recent (1998) paper focusing on acetophenone-coated polyethylene (10) showed that the influence of the acetophenone is complex, is related to the applied stress, and can decrease the dc breakdown strength. This parameter would obviously complicate the observed response of an aged cable.

In essence, the application of dc to an ac XLPE cable may lead to premature loss of life under conventional service aging. Factors that influence this include degree of aging (oxidation), presence of impurities and operating temperature as well as operating voltage stress.. The 5 year time frame after installation and energization, initially suggested by manufacturers for not applying DC, represents a 'good start', but does not (and can not) take into account the degree of aging and degradation at any specific location, after any fixed time. Since cables age unevenly along their lengths, after any constant aging time the susceptibility to dc will vary by location.

Since users cannot control these parameters, the safest approach is to avoid applying dc to any aged XLPE- insulated cable.

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