Working Group PC37.302 - "Guide for Fault Current Limiter Testing"
Sponsored by IEEE Switchgear ADSCOM
Fall Switchgear Committee Meeting
San Diego, CA

October 3, 2012
Minutes

Mischa Steurer called the meeting of the Working Group to order at 8:10 AM EDT with 15 members and guests present.

- Introductions of the attendees were made.

- The agenda was approved.

- The minutes of our September 13, 2012 meeting were approved.

- Three conference calls have been held since the April 30, 2012 Switchgear meeting. (6/25/2012, 8/20/2012 and 9/13/2012)

- A SharePoint website is being used for our Working Group. The draft Guide document, CIGRE Reports and other pertinent IEEE and IEC Standards have been placed on the SharePoint for WG use.

  Contact Paul Bishop pcbishop@bishopgroup.net to request user name / password for the SharePoint site.

  You can access the website at http://www.bishopgroup.net/links.htm
  Click on "view" next to Advanced Electrical Power Systems
  Click "OK" on pop-up (Digital Certificate)
  Enter user name and password
  Navigate to "FCL Testing Task Force"
  Documents under "Shared Documents" can be checked out for editing.
  New documents can be uploaded but must be checked in for others to view

- A copy of the latest draft of document "IEEE PC37.302™Draft Guide for Fault Current Limiter (FCL) Testing" has been made available to the group on the share point site.
  - Writing assignments are noted therein.
  - Please send an e-mail to steurer@caps.fsu.edu if you would like to volunteer to draft a particular section.
  - New material should be added by sending changes to Tim Chiocchio at Chiocchio@caps.fsu.edu. Please accept all changes and then track changes in order to make new material easily identifiable.

- Chairman's Report:
  - The next face to face meetings of our WG will be held on May 2-3 in Galveston, TX in conjunction with the IEEE Spring PES Switchgear Committee meetings. Registration information is available at: http://www.ewh.ieee.org/soc/pes/switchgear/NextMeeting/Future_Meetings.html#

  - An editorial group was formed to complete the final draft of the Guide for balloting by the end of 2012. Members include: Ram Adapa, Joachim Bock, Andreas Brandt, Gil Carmona, Tim Chiocchio, Francisco DeLaRosa, Jerry Earl, Paul Leufkens, Franco Moriconi, Christian Schacherer, Gerald Schoonenberg, Judith Schramm and Jim van de Ligt. Please send an e-mail to Mischa Steurer if you are interested in serving on this group.

- The editorial group will continue to meet by web / conference calls in preparation for a one and a half day meeting targeted for the week of February 4th, 2013 at Georgia Tech / NEETRAC in Atlanta to review the final draft and resolve any issues.

- The next conference call for the editorial group will be held on Monday, 10/29/2012 from 10:30AM – 12:30PM EST.

- Paul Leufkens will coordinate a Panel Session on FCLs at the 2013 IEEE PES General Meeting in Vancouver.

- Section 3.1 FCL definition modified: a device which limits the prospective peak and/or RMS fault current in an alternating current power system to the specified value by providing condition-based increase in resistive and/or reactive impedance between normal conducting mode and current limiting mode. The FCL may consist of discrete functionally integrated, spatially separated equipment. **Adopted as new Definition**

- **Mischa Steurer** will investigate the possibility of combining Section 6.12 Circuit Breaker Operation and 6.13 Protective Devices.

- Presentations:
  - Francisco DeLaRosa made a presentation from his sub-group (attached) on the impact of a lightning surge current through an FCL when the FCL is in CL mode or in the transition between C mode and CL mode. Their conclusion was the probability of a lightning strike to the substation was very low and damage to FCL equipment due to shielding failures was extremely low. **Francisco DeLaRosa, Jim van de Ligt and Mischa Steurer** will draft text for 6.2.7 to acknowledge the issue and point to C57.16-2011 requirements to perform lightning surge tests through series reactors to stress turn to turn insulation.

  - Chapter 6.11 "Recovery" - Judith Schramm - The definitions for recovery in the current draft of the document were completely reviewed and completely re-worked. New definitions for recovery and partial recovery were developed.

    - Recovery is defined as the process of resetting to C mode after a fault current event.
    - Partial recovery is defined as the process of regaining rated current limiting capability after a fault current event without resetting to C mode but with rated or reduced continuous current capability.
    - Recovery time is the time from the clearing of a fault current event to the moment when the FCL regains continuous current and fault current limitation capabilities.
    - Rated recovery time is the time from the clearing of a maximum rated fault current event to the moment when the FCL regains rated continuous current and maximum rated fault current limitation capabilities.
    - Partial recovery time is the time from the clearing of a fault current event to the moment when the FCL regains rated fault current limitation capabilities.
    - Rated partial recovery time is the time from the clearing of a maximum rated fault current event to the moment when the FCL regains rated fault current limitation capabilities.

  - The Carried Over Action Item list was reviewed and updated:
    - **OPEN – Judith Schramm** will review literature to recommend voltage waveshapes for liquid N_2 based insulation systems. After discussion, it was decided to write a paragraph summarizing the issue for the Guide with a list of references.

    - **OPEN – Chapter 6.14 "EMC" – Andreas Brandt -** Provided material for review in latest draft of the Guide.

    - **OPEN – (No Change) Chapter 6.13 "Protective Devices" – Jim van de Ligt**

    - **OPEN – (No Change) Jim van de Ligt** volunteered to investigate fuse standards IEEE 37.41 regarding "rated minimum breaking current" (test duty 3).

- **OPEN – (No Change) Chapter 6.17 "Polarity" – Jerry Earl**

- **OPEN – (No Change) Chapter 6.18 "Visual Inspection" – Paul Leufkens** – Provided material for review. Text still needs to be developed for the Guide.

- **OPEN – (No Change) Section 7 "Production Tests" – Jim van de Ligt**

- **OPEN – (No Change) Section 8 "Field Tests" – Gil Carmona** volunteered to take over this section

- Section Chairs:

  First priority
  - 6.1 "Power Frequency Voltage Withstand" (Jim van de Ligt)
  - 6.2 "Lightning Impulse Voltage" (Francisco De La Rosa)
  - 6.5 "Partial Discharge" (Francisco De La Rosa)
  - 6.7 "Continuous Current" (Tim Chiocchio)
  - 6.8 "Short-time Withstand Current" (Andreas Brandt)
  - 6.10 "Current Limiting" (F. Moroconi, P. Deo, T. Shah)
  - 6.11 "Recovery" (Judith Schramm)
  - 6.14 EMC – (Andreas Brandt)

  Second priority
  - 6.3 "Switching Impulse Voltage" (Joanne Hu, Jim van de Ligt)
  - 6.4 "Chopped-Wave Voltage Impulse" (Tim Chiocchio)
  - 6.6 "Control Circuit Voltage Withstand" (Jim van de Ligt)
  - 6.9 "Harmonic Distortion" (Francisco De La Rosa)
  - 6.13 Protective Device – (Jim van de Ligt)
  - 6.15 Audible – (Gil Carmona)
  - 6.16 "Vibration" (Andreas Brandt)
  - 6.17 Polarity – (Jerry Earl)
  - 6.18 Visual Inspection – (Paul Leufkens)
  - 6.19 FCL Technology -- Specific Tests (Tim Chiocchio)
  - Section 7 - Production (Routine) Tests – (Jim van de Ligt)
  - Section 8 – Field Tests – (Gil Carmona)

Mischa Steurer adjourned the meeting at 5:10 PM EDT.

Submitted by:
Frank Lambert

Approved by:
Mischa Steurer

REVIEW OF LIGHTNING STROKES PASSING THROUGH FAULT CURRENT LIMITERS IN A POWER SUBSTATION

Subject

Investigate the impact of a lightning surge on a Fault Current Limiter (FCL) when lightning strikes on the source side of the FCL during limiting stage. To illustrate this, Fig. 1 depicts a simplified diagram showing a lightning strike hitting the source side of a Solid State Fault Current Limiter (SSFCL) while it is limiting a fault current. The SSFCL used in the illustration is just as an example since the question addressed is for the general FCL situation.

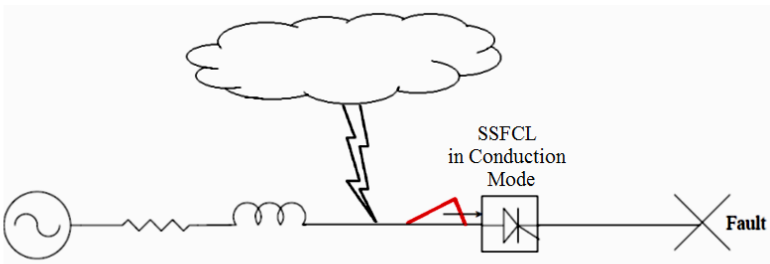

Fig. 1. Lightning Strike hitting the Source Side of a SSFCL

Shielding Failure

The striking distance, for practical purposes the "attractive range", of a substation shielding system denoted here as r_s, is a function of the lightning current amplitude according to the electrogeometrical model in [1], and can be calculated as:

$$r_s = 8I^{0.65} \text{ - - - - - - - - - - (1)}$$

where r_s is the striking distance in meters and I is the return stroke current in kA.

When the shielding system of a power substation does not intercept an approaching cloud to ground lightning strike, this is known as a shielding failure. This occurs only if the striking distance leaves live wires and equipment exposed to approaching lightning strikes. Fig. 2 illustrates a downward lightning strike originating on the left side of the overhead cloud being safely intercepted by the substation shielding wire system. Notice that the strike distances from the two shielding wires, denoted as $r_{1,}$ overlap above the live parts of the substation, providing an effective shielding. Shielding cables are earthed at several points, so currents intercepted by them are securely conducted to ground.

Nevertheless, the second strike to the right hand side of the cloud makes its way to the live conductor inside the substation following a failure of the shielding system to intercept it. Notice that the striking distance r_2 of the shielding system in this case is so small that it does not extend enough to overlap above the live conductors and falls short of providing an effective shielding. Lightning currents entering the live conductors in a substation following a shielding failure can pass through any fault current limiter if it happens to be in their way. However, stroke currents involved in shielding failures are typically of small amplitude, as it will be shown.

Shielding systems are generally designed using the electrogeometrical model concept described by eq. (1) to make sure that the protective zones provided by the shielding cables overlap as those with radius r_1 in Fig. 2, for currents larger than the critical current that can produce insulation flashover.

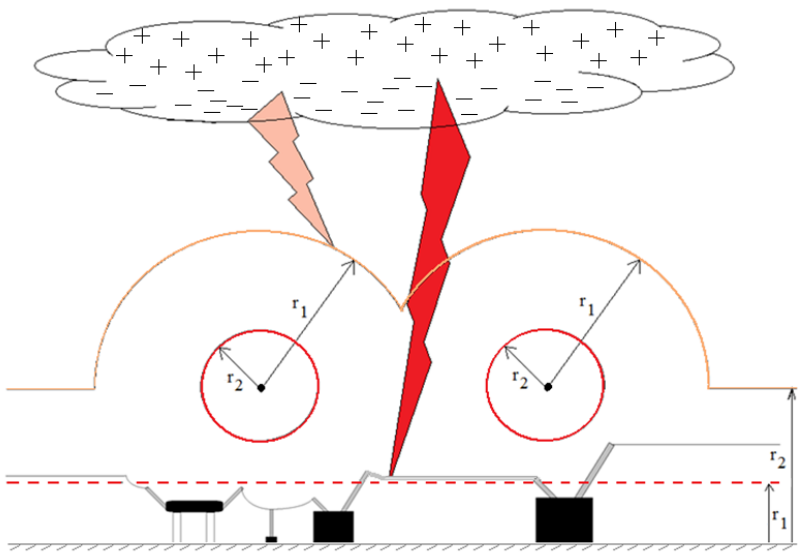

Fig. 2. Illustration of Substation Shielding Failure

Critical Stroke Current

Substation equipment is designed to withstand impulse voltage surges, like those produced by switching and lightning overvoltages. When lightning hits a phase conductor, two waves of current traveling in opposite directions from the point of contact are created in the conductor. This means that the overvoltage created by these traveling waves of current reaches peaks as high as half the stroke current times the surge impedance of the conductor. If this overvoltage rises above the insulation withstand of the line conductors across the air, a phase-to-phase flashover develops. If the basic impulse insulation level (BIL) of the equipment is exceeded, a phase-to-ground insulation flashover occurs.

The lightning surge current that will produce insulation flashover across equipment insulation, let us call it “critical current”can be, according to [2], expressed as follows:

$$Is = \frac{BIL(1.1)}{\left(\frac{Zs}{2}\right)} = \frac{(2.2)BIL}{Zs} \quad ---------- (2)$$

where:

- Is is the peak amplitude of the lightning current above which insulation flashover occurs in kA.
- BIL is the basic lightning impulse level of the insulation in kV.
- Zs is the surge impedance of the conductor through which lightning current passes in Ohms.
- 1.1 is a factor that accounts for the reduction of stroke current when hitting a conductor instead of zero impedance earth.

For a distribution class system with BIL in the range of 110 kV and a typical surge impedance of 300 ohms, the peak lightning critical current Is, calculated from (1), is 0.7 kA. A 138 kV line, with a BIL of 650 kV, would see a critical lightning current of 4.8 kA. Lightning currents below or equal to those calculated using eq. (2) will penetrate the substation shielding system but will not produce insulation flashover. Any Fault Current Limiter in the substation can be exposed to those currents. Larger lightning currents which can potentially be more harmful to equipment will be intercepted by the shielding system.

Probability for Lightning Current Peak Amplitude

Reference [3] provides an equation to calculate the probability for a lighting stroke to exceed a given value. This can be expressed as follows:

$$P(I) = \frac{1}{1+\left(\frac{I}{24}\right)^{2.6}} \text{ - - - - - - - - - - } (3)$$

where

- $P(I)$ is the probability that the peak current in any stroke will exceed I
- I is the specified crest current of the stroke in kA

From eq. (3) it is evident that the probability for lightning currents larger than 4.8 kA, those that would not penetrate the shielding system in a 138 kV substation provided it is properly designed, is around 98%. This can also be expressed as a <u>2% probability for lightning currents below 4.8 kA that would reach the substation bus</u>. In other words, the probability for lightning currents passing through fault current limiters installed on or across substation busses as a result of shielding failures for systems with BIL 650 kV and below, is 2% or smaller. Notice that only half of the lightning current, <u>2.4 kA</u> in this illustration, would pass through a fault current limiter since the other half would travel in the opposite direction in the struck conductor.

Ground Flash Density

The next question is how many lightning ground flashes are likely to strike a particular substation. This depends on the lightning activity of the specific area, which is usually expressed in terms of ground flash density (GFD). This can be obtained from available GFD maps or estimated from isokeraunic levels available from most National Weather Service offices around the world using the following relationship described in [3]:

$$GFD = 0.12\, T \text{ - - - - - - - - - - } (4)$$

where:

- *GFD* = number of flashes to earth per square kilometer per year, and
- *T* = average annual isokeraunic level (number of thunderstorm days per year)

The expected number of lightning ground flashes terminating in a power substation per year can then be estimated as:

$$Ns = \frac{GFD\ (A)}{1000^2} \text{ - - - - - - - - - - (5)}$$

where:

- Ns the expected number of lightning flashes in on a power substation
- A is the substation area in square meters.

Illustration on Potential Number of Lightning Events on the Source Side of Fault Current Limiters that can Potentially Pass Through FCL's in a Substation

An extreme case regarding lightning incidence in the USA is Central and South Florida, with GFD levels of around 14 flashes/km^2/year [4]. A typical distribution substation occupies around 1 acre or more [5]. The estimated number of flashes expected to strike a 1 acre (4046.856 m^2) area in a location with GFD of 14 estimated from eq. (5) is:

$$Ns = \frac{GFD\ (A)}{1000^2} = \frac{14\ (4046.856)}{1000^2} = 0.0566 \text{ flashes/year}$$

From the reasoning above, only around 2%, of these flashes would penetrate the substation shielding system, hit the bus bars and potentially pass through a Fault Current Limiter. These would be low-amplitude-current flashes below 4.8 kA. Thus the expected number of flashes in the 1-acre area in this example would reduce to Ns (2/100) = 0.001132, or one flash every 888 years! This can be considered inconsequential. This probability should be reassessed for substations of different dimensions, being even smaller for areas of moderate or low lightning activity.

The idea in this assignment was to assess the need for recommending a FCL surge current test to reproduce the event of a lightning surge on the source side of the FCL right at the time when the FCL is in the limiting stage, i.e. limiting a downstream fault. The analysis presented here does not consider the probabilistic nature of the fault event. However, merely considering the amplitudes of lightning current surges that can penetrate a shielding system and potentially pass through fault current limiters in substations with operating voltages 138 kV and below, it appears that they would be of little significance. This statement should be confirmed by every FCL manufacturer, though.

Conclusion

Considering the amplitudes of lightning current surges that can penetrate a shielding system and potentially pass through fault current limiters in substations with operating voltages 138 kV and below, it appears that they would be of little significance to require a separate lightning surge current test on the FCL.

<u>This statement should yet need to be confirmed by every FCL manufacturer.</u>

References

[1]] IEEE Working Group, “Estimating lightning performance of transmission lines II—Updates to analytic models,” IEEE Transactions on Power Delivery, vol. 8, No. 3, pp. 1254–1267, July 1993.
[2] Gilman D. W. and Whitehead, E. R., “The Mechanism of Lightning Flashover on High Voltage and Extra-High Voltage Transmission Lines,” *Electra*, no. 27, pp. 65–96, Mar. 1973.
[3] IEEE Std. 998-1996 (R2002), IEEE Guide for Direct Lightning Stroke Shielding of Substations, Reaffirmed 1 August 2002.
[4] F. De La Rosa, *Power Systems*, Chapter 6.3.1, CRC Press, Edited by Leonard Grigsby, 2007
[5] H. L. Willis, Walter G. Scott, “Distributed Power Generation: Planning and Evaluation”, Chapter 1, page 18, Marcel Dekker, 2000