DEVELOPING TESTING PROCEDURES FOR HIGH VOLTAGE INNOVATION TECHNOLOGIES

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ABSTRACT

This paper describes the methodology and approach for developing HV and short-circuit testing specifications for innovation technologies. The paper describes the process used for adapting existing international equipment standards to test fault current limiting technologies. It also identifies the main aspects to ensure the testing of innovation technologies successfully fulfils the purchasers' and manufacturers' expectations and requirements.

INTRODUCTION

Western Power Distribution (WPD) has successfully installed three Fault Current Limiters (FCLs) on Birmingham's 11kV distribution network as part of FlexDGrid [1]. The rigorous testing implemented by WPD ensured the safety and success of these installations.

HV testing is critical to ensure distribution equipment operates in accordance with the technical specification agreed between manufacturer and purchaser. Testing is also implemented to ensure the equipment does not pose a risk to either operator safety or to the operation of the wider electrical distribution network.

The testing requirements of innovation technologies involve more careful design compared to traditional technologies. This is because of their relative immaturity in the product development lifecycle. There is therefore an increased emphasis on developing rigorous testing procedures to reduce the increased risk associated with installing this type of equipment.

The problem associated with testing innovation equipment is two-fold. Firstly, there is no standardised testing procedure that is directly applicable for the device under test. This is in contrast to transformers, for example, that have substantial international testing standards such as those detailed in the IEC 60076 series of specifications [2]. Secondly, the behaviour of high-voltage innovation equipment is usually only known through software modelling. These two factors provide challenges to developing a rigorous testing procedure and specification.

This paper will describe the methodology used to produce the testing procedure for the three FCLs installed as part of FlexDGrid. This includes an analysis of the existing international standards and their applicability to the FCL technologies. The paper will then go on to present the main tests that were implemented on each device and describe the specific differences to the tests identified in the existing international standards. The methodology used to determine the optimum test-circuit configuration for the short-circuit testing of the devices shall also be discussed.

The importance of a device's software model to determine and agree test parameters is discussed. This paper also investigates how the data collected from the testing of innovation technologies is important for the further development of the software model and design of the innovation technologies.

APPLICABILITY OF EXISTING STANDARDS

The first FCL to be installed as part of FlexDGrid was a Pre-Saturated Core Fault Current Limiter (PSCFCL). The PSCFCL technology is based on a traditional transformer design with modifications to enable the saturation of the AC windings under normal load conditions. The IEC 60076 series of standards for power transformers was therefore applicable in this instance. The governing test standard that was chosen was IEC 60076-6 "Power Transformers-Part 6: Reactors". This standard was chosen because the PSCFCL construction closely resembles a series reactor rather than a transformer as the device does not provide any voltage transformation. The tests described in Section 8 of IEC 60076-6 "Current-limiting reactors and neutral-earthing reactors" were selected as they were more closely aligned to the PSCFCL. This formed an initial basis of the testing specification.

The remaining two FCLs installed were Resistive Superconducting Fault Current Limiters (RSFCLs). The RSFCL technology relies on the properties of superconducting materials to limit fault current. There are currently no international standards that specify HV testing regimes for this type of equipment. In this instance, it was decided that the RSFCL would be treated as an item of metal-enclosed switchgear since the RSFCL does not operate on the principle of electromagnetic induction and also issues a 'trip' signal to disconnect itself from the distribution network. In this case, the IEC 62271 series of specifications covering switchgear was selected [3]. The governing standard that was utilised was IEC 62271-1 Part 200: "AC metal-enclosed switchgear and controlgear for rated voltages above 1kV and up to and including 52kV".

ROUTINE AND TYPE TESTS

PSCFCL Routine Tests

The standard tests associated with reactors and power transformers were carried out on the PSCFCL. These included tests such as: insulation resistance, winding resistance, AC impedance and losses measurement, AC withstand, lightning impulse, partial discharge and temperature rise tests.

The PSCFCL utilises a DC winding with variable DC bias current to ensure that the magnetic core of the device is saturated under normal load conditions. Therefore the tests associated with impedance and losses measurements had to be modified to specify the DC bias that was implemented for each of the tests. The measurement of the total losses consisted of the sum of the AC losses and the DC losses. To make the DC losses applicable to the calculation, the DC bias was set appropriately for each step in applied load current. Table 1 shows the steps in DC bias current required at the corresponding load currents to keep the device in saturation. The acceptance criteria for the impedance and load loss tests were inclusive of the DC bias and determined by specifying a maximum voltage drop across the device. The acceptance criteria were agreed by the manufacturer and purchaser in the equipment contract.

AC Load Current RMS (A)	DC Bias Current (A)
400	130
800	220
1000	270
1250	320
1575	365
2000	490

Table 1: DC bias level vs. applied load current

PSCFCL Short-Circuit Tests

A characteristic of the PSCFCL is that the device's fault current limiting performance reduces as a function of increasing DC bias (and hence load current) that exists prior to the inception of a fault. This was determined and calculated from the electrical model of the device. The short-circuit tests to determine the fault limiting performance were implemented with the appropriate DC bias level to ensure the device was tested under the most onerous condition.

The methodology used for the fault current limiting performance testing of the PSCFCL did not require significant modification to the short-circuit testing procedure as documented in IEC 60076-6. The sequencing of the tests adhered to IEC 60076-6, Clause 8.9.13.2. This section of the standard describes that the routine tests including measurement of impedance and losses as well as a winding overvoltage test are carried out both before and after the short-circuit tests. However, since the PSCFCL is more closely aligned to a reactor, the winding overvoltage test, being an induced voltage test, is not applicable. IEC 60076-6, Clause 8.9.9, requests that a lightning impulse test be performed in lieu of the winding overvoltage test.

Additional tests were specified to be undertaken after the completion of the short-circuit tests as a precaution because of the relative immaturity of the PSCFCL technology. With reference to the short-circuit testing procedure for power transformers (IEC 60076-5, Clause 4.2.7.4) an additional AC separate source withstand test was performed as a further check to ensure no damage had been caused to the device's insulation during the tests.

The PSCFCL device is contained in an oil-filled tank similar in nature to a power transformer. As such, the device was de-tanked after the completion of the short-circuit tests. The active part was removed from the tank for inspection of the core and windings and compared with its state before the test, in order to reveal possible apparent defects such as changes in lead position, displacements etc. This is described in IEC 60076-5, Clause 4.2.7.4.

It is important to note that the PSCFCL rides through a network fault unlike the RSFCL which disconnects from the network after 100ms. This requires more stringent impedance and insulation testing as the short-circuit current is present for longer durations, typically up to three seconds if the fault is cleared by back-up protection.

RSFCL Routine Tests

The standard tests as described in IEC 62271-1 Part 200 were implemented on the RSFCL. These included tests such as: power frequency voltage withstand, lightning impulse, partial discharge and short-time withstand current tests.

The RSFCL requires a cooling system to ensure that the cryogenic material is maintained at the required set-point temperature. In this case, the temperature rise test for the RSFCL had to be significantly different to the test stated in IEC 62271-1; however, the same principles were applicable. The test set-up was specified so that the configuration of the RSFCL and the cooling system mirrored the actual site installation as closely as possible. IEC 62271-1 recommends that the test duration is chosen to allow stable temperatures to be achieved. Temperature rise tests for power transformers usually last between six and fifteen hours [4]. It was proposed to use the example of power transformer temperature rise testing and run the device at its rated current and voltage for eight hours continuously. A conservative temperature rise test was chosen to ensure that the device could maintain its rated current whilst also regulating the temperature and pressure of the cryogenic material within pre-defined limits.

RSFCL Short-Circuit Tests

The testing specification was required to describe the fault limiting performance testing of the RSFCL. It was specified that the temperature and pressure of the cryogenic material was set to the nominal values prior to the start of the test to match what would exist at site.

The prospective peak short-circuit current as defined in the contract was set with the RSFCL disconnected from the circuit. A three-phase short circuit was then applied with the RSFCL in the circuit and with the highest prospective peak short-circuit current applied to each phase in turn i.e. three tests in total. This was implemented to ensure that each phase was covered in the test, and no single phase was overstressed. An important aspect of the short-circuit testing was that the RSFCL had to be given sufficient time in between short circuits to allow the temperature and pressure of the cryogenic material to reduce to its nominal set-point as the temperature prior to the application of the short circuit has an effect on the performance of the device.

SHORT-CIRCUIT TEST SET-UP

Overview

Short-circuit testing was required for both FCL technologies to determine the fault limiting performance of the devices. These tests were implemented in third-party test laboratories.

Test Location

The PSCFCL and the RSFCL were tested at different independent laboratories, each with a different electrical network configuration for the short-circuit testing. There are two main types of testing facility: those where the supply is derived from a grid connection and the other where the supply is provided by a generator set. The PSCFCL was tested at Ausgrid's Testing and Certification Lab in Sydney, Australia. The testing station has a direct feed from Ausgrid's 132kV network. The RSFCL was tested at KEMA's test laboratory in Arnhem, Netherlands. This testing station has a number of generator sets to provide its electrical supply. Figure 1 and Figure 2 show photographs of the PSCFCL and RSFCL undergoing the short-circuit testing respectively.

With regards to the location of the testing, it is the manufacturer's responsibility to select a testing laboratory that is suitable for the proposed tests in the testing specification. The testing station shall be capable of providing the required short-circuit rating and required X/R ratio. The manufacturer should also take into account the anticipated duration of the testing, the availability of the testing station with regards to the project programme and the logistics required for the transportation of the device.

Figure 1: PSCFCL during short-circuit testing in Sydney, Australia

Figure 2: RSFCL during short circuit testing at the KEMA laboratory, Arnhem, Netherlands

Test-Circuit Configuration

The connection diagrams of the PSCFCL and RSFCL are shown in Figure 3 and Figure 4, respectively. The test circuits for both devices were configured to match the on-site configuration as closely as possible. In the case of the RSFCL, this required the device to be energised to 11kV prior to the application of the short circuit i.e. VCB1 is closed prior to applying the short circuit which is done by closing VCB2.

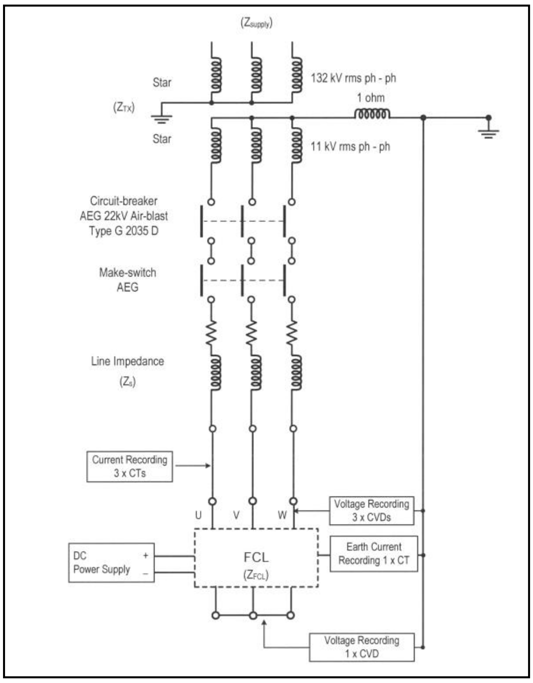

Figure 3: Connection diagram showing the short-circuit test set-up for the PSCFCL

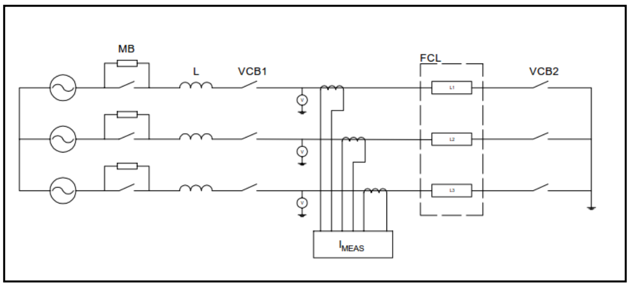

Figure 4: Connection diagram showing the short-circuit test set-up for the RSFCL

General Recommendations

The test pass criteria for the short-circuit testing were formulated at the contract negotiation stage of the project and are specific to the site where the technology was installed. For both of the technologies, the prospective peak current and X/R ratio was adjusted to the values specified in the testing specification. It is critical that these values correspond to the site where the device is to be installed so that the testing closely matches the 'in-service' condition.

The short-circuit testing specification for both technologies was designed to include regular insulation resistance measurement tests either before/after individual tests or before/after groups of tests. This was implemented to make it easier to determine the location and cause of a device failure in the testing sequence, should this occur.

DEVICE MODELLING

The PSCFCL and RSFCL are both examples of new innovation equipment that are relatively immature in their product lifecycles. The testing of the devices under controlled conditions in the laboratory afforded the manufacturers the opportunity to validate the electrical models of their respective devices. As such they may carry out more testing than normal.

The factory and the type testing at the third-party independent laboratory allowed the manufacturers to measure various electrical parameters during the tests. The analysis of the data had two main functions. The first application is to validate the modelled fault current limiting behaviour of the device. The models are then refined to optimise the design of future generations of equipment. For example, it may be the case that certain safety margins can be reduced because the software model was conservative compared to the real-world scenario. This may lead to reduced material requirements and a smaller device size. The second major application was to use the data as the basis for an analysis of the design methodology. The output of this analysis is used by the manufacturer to refine the design processes to improve the performance of the device.

In the case of the PSCFCL, specific additional tests were carried out during the short-circuit testing. The testing specification for the PSCFCL included tests at varying DC bias currents to allow the manufacturer to understand the effect of the varying DC bias on the fault limiting performance of the device. This had direct feedback into the manufacturer's design for subsequent devices.

The first RSFCL device to be installed had a continuous current rating of 1600A. The cooling system of the device was specified by the manufacturer using its system modelling tools. The device failed its initial temperature rise test at the manufacturer's facility. The cryogenic material was not able to be kept at the set-point temperature. This was found to be caused by higher-than-expected electrical losses from the device that the system modelling did not take into account. The implementation of a rigorous testing procedure was key to identifying that the device was unable to maintain stable temperatures. The data from the temperature rise testing was also critical to update the manufacturer's system models to reflect the real-world condition and to ensure the next generation of devices did not experience the same issue.

DESIGN REVIEW

To produce a thorough testing specification requires that the purchaser performs a review of the manufacturer's detailed designs. A review of the detailed design gives the purchaser a greater understanding of the technical and operational aspects of the innovation technology. This in turn ensures that the purchaser can request specific tests, or adaptations to existing tests, to satisfy their requirements and to ensure the device fully meets their expectations with regards to the device's operation and safety.

CONCLUSIONS

It is critical that a piece of innovation equipment such as a PSCFCL or RSFCL is tested rigorously before being installed on the distribution network. Therefore, the testing specification forms an important role in defining the tests to be performed on the device, the order of the test procedure, the test pass criteria and the electrical test configuration. There are, however, no existing international standards that can be referred to for these devices.

In the absence of specific standards, the purchaser and manufacturer must work collaboratively to select the existing standards that are applicable to the type of technology that is under test, taking into account the device's purpose and operational characteristics. After the relevant standards (or sections of standards) have been selected, further work has to be undertaken to agree on a testing specification that ensures the performance of the device is fully tested and is safe to operate on the distribution network.

The purchaser shall be responsible for performing thorough reviews of the manufacturer's detailed designs to ensure that the outcome of the testing specification conforms to its expectations and requirements for a fully functional, operational and safe device.

The manufacturer shall be responsible for the selection of testing facilities that are able to meet the high-voltage and short-circuit current demands as agreed in the testing specification and the contract between the manufacturer and purchaser. The manufacturer and purchaser shall also work collaboratively to identify the technology-specific characteristics so that the testing configuration at the factory and laboratory match the 'in-service' conditions of the device as much as possible.

It is important that the testing specification also includes specific additional tests, if necessary, to allow the manufacturer to optimise the electrical models of the device and to improve the physical design of the equipment and components.

It is a conclusion of this paper that the testing of innovation technologies should be done entirely in the manufacturer's factory and in third-party laboratories due to the infancy of the technologies. This methodology ensures that any test failures occur before the device has been transported to site, reducing the risk of cost and time impacts to the project.

Flowchart for Future Test Specifications

The flow chart in Figure 5 summarises the points discussed in this paper and proposes a methodology for the development of test specifications for innovation equipment.

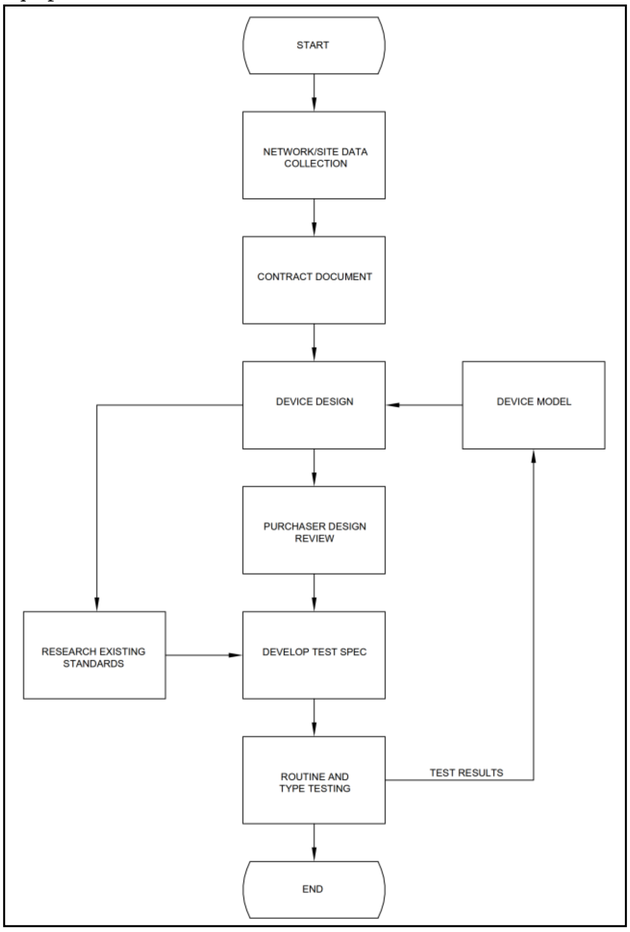

Figure 5: Flowchart showing testing methodology for innovation technologies

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