Award/Application Number
DE-FC26-06NT42796
January 20, 2012

Electric Power Delivery Testing Feasibility Study

Task 6 Final Report

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Task 6 – Final Report**6.1 Introduction**

This Final Report covers the completion of the Electric Power Delivery Testing Feasibility Study. The objective of this project was to research, engineer, and demonstrate high-power laboratory testing protocols to accurately reproduce the conditions on the electric power grid representing both normal load switching and abnormalities such as short-circuit fault protection. Test circuits, equipment, and techniques were developed and proven at reduced power levels to determine the feasibility of building a large-scale high-power testing laboratory capable of testing equipment and systems at simulated high-power conditions of the U.S. power grid at distribution levels up through 38 kiloVolts (kV) and transmission levels up through 230 kV. The project delivered demonstrated testing techniques, high-voltage test equipment for load testing and synthetic short-circuit testing, and recommended designs for future implementation of a high-power testing laboratory to test equipment and systems, enabling increased reliability of the electric transmission and distribution grid.

6.2 Summary of previously completed Task 1 to Task 5

The project started in June 2006 and was completed in June 2008.

Task 1 which simulated and engineered the load simulation circuits and testing protocols and Task 2 which simulated and engineered the transmission short-circuit test circuits and testing protocols were completed in June 2007. The Task Reports for each of these tasks previously submitted to DOE meet the objectives of engineering and design of test circuits that meet the project objectives. Load simulation circuits at 15 kV up to 2000 A, 29 kV up to 2000 A, and 38 kV up to 1200 A were successfully simulated, engineered, and design detailed for demonstration testing, and fully reported in the Task 1 report. Testing for transmission-voltage short-circuit testing was successfully simulated, engineered and design detailed for demonstration testing, and fully reported in the Task 2 report. The results of both showed that it was practical to demonstrate the design concepts with a smaller short-circuit generator, and to properly test in a laboratory with large short-circuit generators conditions representative of the electric grid from 15 kV up to 230 kV.

Task 3 which acquired and installed the equipment to demonstrate the test circuits and test protocols from Task 1 and Task 2 was completed in the first quarter of 2008. The equipment was temporarily installed in close proximity to an existing, small short-circuit generator to demonstrate the compliance of the equipment to the circuit simulations. The Task 3 Report completed in March 2008 fully documented the equipment specifications and the temporary installation of the equipment for the subsequent demonstration.

Task 4 performed testing according to the test protocols and simulations defined in Task 1 recognizing the impact of the smaller short-circuit generator. The results of that testing completely demonstrate the simulation and modeling, and confirmed that the simulation was adequate to extend the design to larger short-circuit generators. The result of this task was fully documented in the Task 4 Report filed in June of 2008.

Task 5 demonstrated the transmission short-circuit simulation testing using a technique of synthetic testing. This technique utilized the short-circuit current from the short-circuit generator for the high current component of the test combined with high voltage from an auxiliary circuit to properly stress the test object at voltages representative of 230 kV systems. The demonstration test had high voltage equipment operating up to a peak voltage of 460 kV representative of a 230 kV system. The short circuit current was limited by the size of the existing short circuit generator (100 MVA) to 7 kA or less. The testing did demonstrate that the high-current and high-voltage source could be treated independently and therefore sized independently which would allow scaling the results to larger short-circuit generators. The Task 5 Report filed in June 2008 fully documented testing and results.

6.3 Recommendations for Load Simulation Test Circuits

This project developed the equipment specifications and test protocols necessary to perform load current switching tests at 15 kV up to 2000 A, 29 kV up to 2000 A, and 38 kV up to 1200 A. The main load simulation components consists of resistors and inductors of various sizes to adjust the load current, and a short-circuit generator of enough short-circuit capacity to supply the current while maintaining the full test voltage. See Task 1 and Task 4 Reports. The sizing the generator is relatively simple requiring a generator with a short-circuit current and power as shown in the table below:

Test/System Voltage	Load Current	Generator Short-Circuit Current	Generator Short-Circuit Power
15 kV	2000 A	12,000 – 20,000 kA	300 – 500 MVA
29 kV	2000 A	12,000 – 20,000 kA	600 – 1000 MVA
38 kV	1200 A	7,200 – 12,000 kA	500 – 800 MVA

Short-circuit generators of this power rating are available, and when combined with transformers to match the generator voltage to the desired test voltage, can provide direct testing capability for load switching devices for distribution voltage systems. The work to engineer and built a short-circuit generator(s) matching these ratings would be for new project at an estimate budgetary cost of \$30 Million to \$50 Million.

This current project meet its objectives of simulating, engineering, and design test circuits and protocols for simulation of load switching test circuits, and providing the functional requirements for a high power generator to support these test.

6.4 Recommendations for Transmission Short-Circuit Simulation Testing

This project developed the equipment specifications and test protocols necessary to perform testing of transmission voltage short-circuits from 69 kV up to 230 kV. The high-voltage is supplied from a combination of capacitors and inductors that are tuned to provide the peak voltage with the specified rate of rise of recovery voltage to match

conditions found on power systems. The design, rating, and selection of equipment to provide the required voltage transients are specified in the Task 3 and Task 5 report. This project assembled a represented sample of the high voltage equipment to demonstrate the test protocol. Additional equipment will need to be acquired under a separate project to complete the equipment for testing a full range of voltages and currents as noted in the Task 3 and Task 5 Reports.

The high short-circuit current supplied from a short-circuit generator is combined with the high-voltage source through a combination of auxiliary breakers, trigger gaps, trigger vacuum switches driving a “reignition” circuit under the control of a precision measuring and triggering electronics to sequence the voltage source to the appropriate current zero. Again, a represented sample of this equipment was assembled and used to demonstrate the test protocol. Additional equipment will need to be acquired under a future project to develop the test capability for the full range of voltages and currents as noted in the Task 3 and Task 5 Reports.

The high current part of the test protocol is supplied by a short-circuit generator of sufficient short-circuit power to provide the required test current at a generator voltage significantly higher than the arc voltage of the circuit interrupter under test. The generator voltage must be large enough such that the arc voltage of the sample under test does not significantly influence the test current supplied by the generator. A good practice for typical circuit interrupters requires the generator voltage that is 1/10 to 1/20 of the desired system level test voltage – the higher the better. The exact ratio will be determined by the specific device’s arc voltage characteristic which varies with the interrupting technology and needs to be evaluated on the specific device characteristic. The following table documents the generator sizes for the system level test voltage at desire test current shown.

Suggested Generator Sizes (based on a 1/20 – 1/10 voltage ratio)		
69 kV	138 kV	230 kV
For 20 kA short circuit ratings		
120 – 240 MVA	240 – 480 MVA	400 – 800 MVA
For 40 kA short circuit ratings		
240 – 480 MVA	480 – 960 MVA	800 – 1600 MVA

Short-circuit generators of this power rating are available, and when combined with transformers to match the generator voltage to the desired test voltage, can provide the high current source needed for this synthetic testing protocol. The work to engineer, acquire the equipment, and install short-circuit generators matching these ratings would be for a new project at an estimate budgetary cost of \$30 Million to \$50 Million for the high power generators and its ancillary equipment, and an estimated budgetary cost of \$8

Million to \$12 Million for the remaining high voltage components and control equipment needed for the transmission voltage synthetic test equipment.

This current project meet its objectives of simulating, engineering, and design test circuits and protocols for simulation of short circuit current testing at transmission voltage levels, and recommending the design and equipment of a high-power generator and the high-voltage equipment needed to provide the full range of test levels.

6.5 Post-project work from June 2008 through January 2010

Since the completion of this project in June 2008, S&C Electric Company has designed, engineered, constructed, and commissioned the Advance Technology Center at its own expense totaling more than \$35 Million. This project installed two (2) 850 MVA short-circuit generators (1700 MVA total) and the ancillary master breakers, make switches, current limiting inductors, test transformers, bus work, disconnect switches, tuning capacitors and resistors, and test cells to provide the short circuit currents specified by this project for both the load switching test protocols and the transmission short-circuit test protocols. A photo of the installed generators is shown below.

Generators

These generators have been in service providing testing capabilities since January 2010. A full description of the laboratory is show in Appendix A. Page three (3) of that

appendix outlines all of the equipment needed to drive, control, and switch the high power generator and transformer circuits. Appendix B contains photos of most of the equipment.

This subsequent, self-funded project provide capability for load current switching as stated in the objectives of the DOE project utilizing the equipment developed during that project. Load current testing capability includes 15 kV up to 2000 A, 29 kV up to 2000 A, and 38 kV up to 1200 A. Below is a photo of the load current resistors and inductors developed under the DOE project now installed to provide this testing capability.

② Load resistors and inductors

Load Room

In addition, the generators and the ancillary equipment can also test short-circuit currents by direct test methods from 15 kV up to 38 kV at a variety of test currents depending upon the testing protocols. The generators can also be used for testing short circuit withstand capability of switches, circuit breakers, grounding devices, etc. and for testing the ability of equipment to withstand and contain the hazards that may develop from arcing faults within the equipment. A summary of the testing capabilities is shown on the following summary sheet.

Advanced Technology Center 50/60-Hz Testing Capabilities^①

Circuit Breaker and Recloser Three-Phase Tests

Rated/Test Voltage, kV	Maximum Current, kA
15	31.5
17	25
27	25
38	15

Circuit Breaker Single-Phase Tests

Rated Voltage, kV	Test Voltage, kV	Maximum Current, kA
15.5	13.4	63
29	23.5	31.5
38	32.9	25

Disconnect Switch Three-Phase Tests

Ten-Cycle Duration Three-Phase Momentary/Peak Withstand Maximum Current, kA		
Constant Fault Current	Peak Current Mitigated By Switched Inductors	Current Droops to 80%
40	80	100
Short-Time Withstand Maximum Current, kA		
Two-Second Duration	Three-Second Duration	
100	80	

Loadbreak Switch Three-Phase Tests

Load Switching		
Rated/Test Voltage, kV		Maximum Current, A
15.5		2000
29		2000
38		1200
Fault Closing		
Rated Voltage, kV	Test Voltage②, kV	Maximum Current③, kA
15	9	63/80/100
15.5/27	15.5	40/50/63
27	27	25/31/40
38	22	25/31.5/40
38	38	12.5/16/20

Fuse Single-Phase Tests

Rated/Test Voltage, kV	Maximum Current, kA
15.5	50
29	31.5
38	20

Arcing Fault Three-Phase, 0.5-Second Tests

Rated Voltage, kV	Test Voltage ^② , kV	Maximum Current ^③ , kA
15	15	40
15	7.9	63
27	27	25
27	15.5	40
38	38	12.5
38	27	25

① All current ratings are symmetrical. In each instance, the first peak asymmetrical current is 2.7 times the symmetrical current unless the current is controlled by additional circuit resistors or switch peak-current-limiting inductors.

② Single-phase testing at phase-to-ground voltage is permissible for single-phase switches.

③ Multiple current capability varies with standard requirements X/Y/Z, where:

X = Constant fault current;

Y = Peak current mitigated by switched inductors;

Z = Current droops to 80% at 10 cycles.

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S&C is still planning on completing the short circuit testing capability for transmission voltage short circuits utilizing the testing protocols and equipment developed under DOE project being reported in this Task 6 Report. Progress on completing this testing capability depends upon obtaining funding of \$8 Million to \$12 Million to complete the purchase of voltage and control equipment per the synthetic test protocol, and the engineering and construction of a permanent installation for that equipment. The funding for the next phase is uncertain making the plans for completion of the next phase uncertain.

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Appendix A—ATC Descriptive Bulletin 115

S&C Electric Company's

Advanced Technology Center

S&C Electric Company's Advanced Technology Center

Generator Room.

S&C Electric Company—one of Chicago's leading manufacturers—is investing in the future with a striking new addition to the area's high-tech scene . . . the company's unique Advanced Technology Center ("ATC").

The recently completed facility will enable S&C to accelerate development and delivery of innovative electrical switching and protection products in the United States, including the highly-sophisticated automatic service restoration, energy storage, and power quality equipment needed for the Smart Grid.

The testing laboratory at the heart of the ATC includes two 850-megawatt electrical short-circuit test generators that can test up to 100 kA and up to 230,000 volts. The laboratory will allow S&C to perform quality control and other testing at the Chicago industrial campus, instead of relying on costly, time-consuming visits to test labs in Europe.

In addition to the world-class high-power testing laboratory, the ATC houses S&C's R&D offices, plus

expanded molding operations. S&C is the largest manufacturer of high-voltage cycloaliphatic epoxy insulators in the U.S. These insulators are superior to porcelain insulators for many reasons—including their ability to integrate intelligent voltage and current sensing, as well as control, diagnostic, and automation components. Such components are essential to equipment for the Smart Grid.

The ATC is one of the most environmentally-friendly facilities of its kind in the world. The 43,000-square-foot structure minimizes environmental impact through numerous energy-efficient and sustainable design features, including an 8,000-square-foot green roof, use of recycled content and locally-produced building materials, and other innovative measures. The ATC holds LEED "Gold Certification" rating per the U.S. Green Building Council. It's one of the first industrial buildings in the Chicago metropolitan area to hold such a rating.

Advanced Technology Center Single-Line Diagram

- ① **Short-circuit-rated generators** are two-pole, synchronous machines rated 850 MVA, based on open-circuit voltage and short-circuit current. The two 4-kV windings per phase can be connected in series or parallel, in delta or wye, and produce 4 to 13.75 kV. The laboratory has a maximum short-circuit test capability of 100 kA symmetrical, 270 kA peak.
- ② **Super-excitors** provide normal field excitation using a power-electronic-rectified dc source, supplying 500 A to the field windings. During short-circuit testing, the field current jumps to 5,000 A. The excitors can deliver up to 5 MW as “super-excitors,” to maintain high field current and produce steady short-circuit current.
- ③ **4.5-MVA variable-frequency drive** starts each generator individually, then synchronizes them in parallel. The machines “idle” at 35 to 40 Hz and are accelerated to 50 or 60 Hz just before the test operation, when the drive is disconnected. The low machine speed reduces power consumption and heating losses inside the generators, which have very limited cooling capacity.

Power for the testing is supplied by the stored energy of the rotors. Each generator stores 150 megajoules (150 MW-seconds) in its 20-ton (18,000-kg) rotor. This energy is used to supply the losses during short-circuit, load-circuit, or arcing-fault tests. Short-circuit tests from 3 to 10 cycles result in a small droop in machine speed—from 60 to 58 Hz, while one-second arcing-fault tests result in a speed droop from 60 Hz to 48 Hz.
- ④ **80-kA air-blast main breakers** provide redundant backup to the auxiliary breakers.
- ⑤ **63-kA auxiliary breakers** “back up” the device under test and protect against inadvertent short-circuits. Each breaker has two series-connected vacuum interrupters per phase, with resistor snubbers to control switching transients. These breakers operate with every test operation; contact wear is minimized by means of synchronous interrupting control.
- ⑥ **Controlled-closing make switch** rated 100 kA symmetrical, 270 kA peak closes “point-on-wave” within 0.5 millisecond, to control asymmetrical current peak on a per-pole basis.
- ⑦ **Current control inductors** reduce the short-circuit test current from the maximum of 100 kA to less than 1 kA.
- ⑧ **Peak current control inductors and resistors** reduce the first asymmetrical current peak if the X/R of the generators exceeds their rating. The inductors and resistors are bypassed after a few cycles to reduce heating.
- ⑨ **220-MVA short-circuit-rated transformers** (six single-phase units) can be connected three-phase or single-phase, to step up generator voltage to the required test voltage. The four secondary windings, nominally rated 15 kV, 5 kA short-circuit current, can be connected in parallel or series. Output voltage range is 5 to 104 kV three-phase, and up to 240 kV single-phase.
- ⑩ **High-frequency inductors** provide high transient recovery voltage frequencies for the 10%, 30%, and 60% test duties of circuit breakers and reclosers.
- ⑪ **Transient recovery voltage control** comprised of capacitors, resistors, and inductors “tune” the natural frequency of the test circuit to match transient recovery voltage specifications.
- ⑫ **Device under test**
- ⑬ **Load resistors, inductors, and capacitors** for load switching and capacitor, line-, and cable-switching tests.
- ⑭ **Distribution line simulator** uses very-high-frequency inductors, resistors, and capacitors to create transient recovery voltages representative of overhead line faults.

Advanced Technology Center 50/60-Hz Testing Capabilities^①

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Rated/Test Voltage, kV	Maximum Current, kA
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27	25
38	15

Circuit Breaker Single-Phase Tests

Rated Voltage, kV	Test Voltage, kV	Maximum Current, kA
15.5	13.4	63
29	23.5	31.5
38	32.9	25

Disconnect Switch Three-Phase Tests

Ten-Cycle Duration Three-Phase Momentary/Peak Withstand Maximum Current, kA		
Constant Fault Current	Peak Current Mitigated By Switched Inductors	Current Droops to 80%
40	80	100
Short-Time Withstand Maximum Current, kA		
Two-Second Duration	Three-Second Duration	
100	80	

Loadbreak Switch Three-Phase Tests

Load Switching		
Rated/Test Voltage, kV		Maximum Current, A
15.5		2000
29		2000
38		1200
Fault Closing		
Rated Voltage, kV	Test Voltage②, kV	Maximum Current③, kA
15	9	63/80/100
15.5/27	15.5	40/50/63
27	27	25/31/40
38	22	25/31.5/40
38	38	12.5/16/20

Fuse Single-Phase Tests

Rated/Test Voltage, kV	Maximum Current, kA
15.5	50
29	31.5
38	20

Arcing Fault Three-Phase, 0.5-Second Tests

Rated Voltage, kV	Test Voltage ^② , kV	Maximum Current ^③ , kA
15	15	40
15	7.9	63
27	27	25
27	15.5	40
38	38	12.5
38	27	25

① All current ratings are symmetrical. In each instance, the first peak asymmetrical current is 2.7 times the symmetrical current unless the current is controlled by additional circuit resistors or switch peak-current-limiting inductors.

② Single-phase testing at phase-to-ground voltage is permissible for single-phase switches.

③ Multiple current capability varies with standard requirements X/Y/Z, where:

X = Constant fault current;

Y = Peak current mitigated by switched inductors;

Z = Current droops to 80% at 10 cycles.

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Appendix B –Photos of the ATC Equipment

⑥ Air-blast main circuit breaker

⑦ Delta/wye-connection switch

- ⑧ Auxiliary circuit breaker
- ⑨ Resistor snubber
- ⑩ Resistor snubber circuit breaker
- ⑪ Controlled-closing make switch

⑫ Current control inductors

⑬ Peak current control inductors and resistors
⑭ Bypass circuit breaker

⑮ Bushings of short-circuit-rated test transformers
⑯ Bushing interconnecting disconnect switches
⑰ High-voltage bus output disconnect switches

- ⑱ Very-high-frequency inductors
- ⑲ Transient recovery voltage control
- ⑳ Device under test