IN-SERVICE TESTING OF GENERATOR CURRENT TRANSFORMERS – A PREDICTIVE MAINTENANCE TOOL FOR ELECTRIC GENERATION STATIONS

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Abstract: On September 17, 2000 Kuhlman Electric Corporation (now ABB Kuhlman), with the cooperation of MidAmerican Energy Company, successfully completed the field phase of an In-Service Testing Program at MidAmerican Energy's Neal Energy Center where thirty-nine (39) high ratio generator current transformers (GCTs) on Neal Units 2, 3, and 4 were tested. During the test program these generators, with ratings 300MW, 515MW, and 630MW respectively were operating between 20% and 65% of capacity - providing electrical power to the grid.

Problems were identified with the GCTs and associated monitoring, protection, and control loops on ten (10) of the thirty-nine (39) GCTs tested. The problems addressed were measurement errors, as well as potential plant protection concerns. Although measurement errors on Unit 3 were previously suspected, the potential plant protection problems on Unit 4 were unknown. MidAmerican Energy took steps to use the findings uncovered during the testing to provide repairs as required during the next scheduled outage in April of 2001.

The impact of the findings were significant. First, it was suspected that the measurement errors previously noted on Unit 3 were due to faulty GCTs. The in-service test indicated that the GCTs were providing correct current values to the metering instrumentation thus replacement was not required. For Unit 4 initial findings indicated inadequate voltage applied to the protection system during a simulated fault condition. Consequences would be potential damage to the generator and other equipment in case of an actual fault condition.

This appears to be a “first” in the power generation industry where the condition of GCTs and associated monitoring, and control loops are evaluated on-line and in-service. Traditional measurement techniques simply cannot be performed on-line and in-service. Kuhlman in-service testing techniques (Patent number 6680616) used here have a tremendous potential to become an active part of utility generation plant Predictive Maintenance Programs designed to improve plant performance, and availability.

This paper will discuss details of the testing program, the test technique, findings, as well as corrective actions taken at MidAmerican Energy Company Neal Units 2, 3, and 4.

Key Words: Dielectric performance; generator current transformers; insulation class; in-service testing; metering accuracy; phase angle errors; predictive maintenance programs; ratio correction factor; relay accuracy; secondary excitation characteristics; generator protection.

INTRODUCTION: The primary sensors used in power generation systems are high ratio generator current transformers (GCTs) that are generally designed, manufactured, and tested in accordance with the requirements of national or international standards [IEEE C57.13 (latest edition), IEC 60044-1 (latest edition) or others]. GCTs are rugged, high accuracy devices designed to withstand the environmental and electrical conditions (10,000 to 45,000 Amperes, at up to 26kV) present at the output bushing of the high power generator. These units are built for accuracy and reliability and are normally installed by the generator manufacturers on the bushings. A cutaway view of a generator with installed GCTs is shown in Figure 1 below.

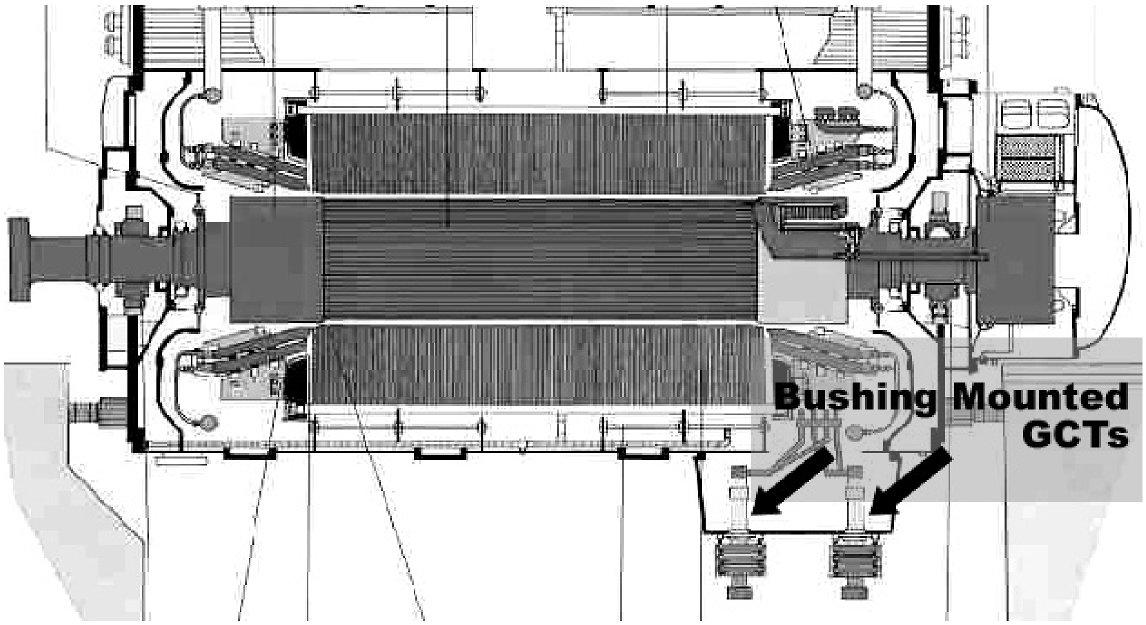

Figure 1 – Cutaway View of Generator Showing Installed Bushing Mounted GCTs

Their outputs are used as inputs to protection and monitoring instrumentation systems on multi-million dollar hydro, fossil-fired, or nuclear generation units. Their importance to plant operation and reliability cannot be over-emphasized. Problems with GCTs and associated monitoring, and control instrumentation can result in very expensive and costly outages – outages that are usually to be avoided at all costs. Un-expected outages are very expensive in terms of lost generation capacity, replacement power costs, and labor and materials. Therefore it is imperative that GCTs be extremely reliable and perform as designed at all times, and that their condition be known throughout their life.

Prior to this new Kuhlman test and analysis method, the evaluation of the GCT condition required extensive scheduled down time with associated costs for testing. Current IEEE Specifications [IEEE C57.13 (1993), and ANSI C57.13.1 (1981)] include only traditional test techniques. These traditional techniques all require the generator to be out of service, and the primary conductor through the GCT be disconnected. Therefore because of the expense involved in dismantling the primary bus structure, GCTs are simply not tested until an operational problem with the generator monitoring and control system dictates that testing be done.

All known failure modes of GCTs can affect metering and relaying accuracy performance. Refer to Figure 2 to define the various failure modes and what they look like on the typical excitation curve view for the GCT.

The failure of a GCT to provide the accuracy required for generator condition monitoring or revenue measurement has a direct major impact on plant heat rate and performance, as well as utility generation revenues. Failure of a GCT to provide protection for the generator during a fault condition can shorten the life of expensive components within the generation system. This may initiate premature replacement of major high cost components during long unscheduled and expensive outages.

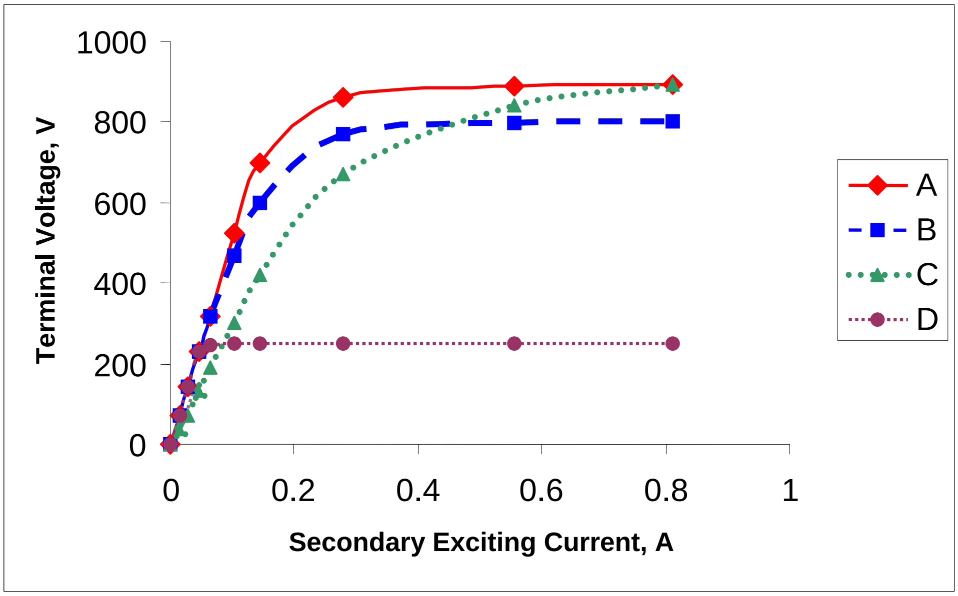

Figure 2. CURRENT TRANSFORMER MODES OF FAILURE

A. Design model of correct current transformer performance
B. Current transformer with turn to turn fault
C. Current transformer with core lamination insulation failure or cores that have experienced mechanical deformation (If return points match Curve A -the core was magnetized)
D. Current transformer with secondary wiring insulation failure

GCT PERFORMANCE REQUIREMENTS: GCTs for thermal power plants are normally indoor (board mounted), or outdoor class (resin cast) units depending upon operating environment and rated for 600 Volt servicewith an impulse withstand rating (BIL) of 10kV. They are normally mounted over the ground sleeve of a high voltage bushing insulated for typically 17kV to 26kV. The electrical insulation is generally rated for 130^0 C for typical 100-450MW units, and up to 155^0 C for some 650-1050MW generators.

With regard to IEEE C57.13 (1993) metering performance, the GCT must provide an accuracy of 0.3% at a burden (effective impedance) of 1.8 Ohms (shown as 0.3B1.8) at 100% of rating, and 0.6% at 10% of rating. With regard to phase angle performance, phase angle errors cannot exceed +/- 15 minutes at 100% of rating, +/- 32 minutes at 10% of rating [Ref. Figure 2, IEEE C57.13 (1993)]. The limiting values for Ratio Correction Factor (RCF), and phase angle for standard accuracy classes are provided in Sub Clause 5.4 of IEEE C57.13 (1993).

With regard to ANSI/IEEE relay accuracy, GCTs are typically rated for C800. The accuracy class C800 is determined by the GCTs ability to deliver a secondary terminal voltage level of 800Volts under a benchmark fault state. This effectively describes the required performance of a relay GCT under a 20 times fault condition (See IEEE Std. C57.13-1993, 6.4.1). The secondary terminal voltage rating is the secondary voltage that the GCT will deliver when it is connected to a standard secondary burden, at 20 times rated secondary current (5 A), without exceeding a 10% ratio error. Furthermore, the ratio correction shall be limited to 10% at any current from 1 to 20 times rated secondary current at the standard burden or any lower standard burden. For example, CT accuracy class C800 means that the ratio error will not exceed 10% at any current from 1 to 20 times rated secondary current with a standard 8.0 Ohm burden (8.0 ohms multiplied by 20 times rated secondary current equals 800 volts). Almost all of the GCTs used for protective relay applications are covered by the C classification. The C classification indicates that the leakage flux is negligible and the **C**alculated excitation characteristic can be used directly to determine overall performance.

A typical secondary excitation characteristic curve becomes the performance "finger print" for any given GCT design as shown in Figure 2 – position A. Any changes to the performance "finger print" for a specific GCT built to the given design over time is an indicator of potential and or existing metering and relay accuracy problems. Given an appropriate GCT design data base, a detailed analysis of the amplitude and shape of the secondary excitation curve for any GCT can reveal typical failure modes common to GCTs and can be used for diagnostics and surveillance in-service as shown in Figure 2 – positions B, C, and D. With regard to the International Standard IEC 60044-1 there are comparable metering and relay protection standards (but not stated necessarily in the same manner) for accuracy.

TRADITIONAL PERFORMANCE TESTING METHODS: Traditional testing methods used for evaluating the accuracy and performance of current transformers (CTs) are described fully in IEEE C57.13 (1993), "IEEE Standard Requirements for Instrument Transformers", Sub Clauses 8.1.5, 8.1.7; and ANSI /IEEE C57.13.1-1981, "American National Standard Guide for Field Testing of Relaying Current Transformers," Sub Clauses 5.0 through 10.0.

All traditional testing methods used to obtain the ratio of an individual GCT, and its associated secondary excitation curve, use special laboratory or field based instrumentation that may or may not be suitable for application on installed GCTs for making metering or relay accuracy measurements. Further, and most important, none of the traditional testing methods can be utilized with the GCT primary in place and fully energized.

For a stack (two to four) of large generator current transformers mounted on each phase of the output bushings of the generator, the primary winding consists of the continuous copper bus structure between the generator output bushing and the iso-phase bus to the generator step up transformer. Typically, work in this area is further complicated by an outer coaxial type case. Removal of a section of the primary bus for testing is extremely expensive and time consuming – the cost of which is primarily due to generator down time required.

IN-SERVICE PERFORMANCE TESTING & ANALYSIS METHOD: The obvious need for a new measurement and analysis technique has been known for decades particularly for high capital cost systems where downtime for any reason must be avoided.

In response to customer needs to be able to assess the existing condition of current transformers on critical high capital cost electric generation, transmission, and distribution systems and using experience gained in the design and production testing of instrument transformers, Kuhlman Electric Corporation developed our patented innovative in-service testing and analysis method to assess the existing performance of installed current transformers.

The test and analysis method developed by Kuhlman Electric Corporation is passive in nature, in that while in normal operation and at a steady state operating condition, the secondary current from the GCT under test is monitored and recorded while the effective burden (seen by the GCT under test) is momentarily changed within a range of pre-determined values. The response of the GCT under test to the burden change is compared off-line to the expected response from a proprietary design model of the same ratio and physical size. Using iterative analysis techniques, the performance of the GCT under test can be determined and predicted within the statistical errors of the measurement and design model. In short - the *as found "true secondary excitation curve"* is then compared against the design typical excitation curve using statistical allowances of the IEEE C57.13 Relay Accuracy Class.

PLANT OPERATIONS & MAINTENANCE ISSUES: Before any new performance test and analysis method can be employed at an operating power generation station, it must be thoroughly investigated to insure its safe application to both the GCT and facility operations. Not only must the method be proven in laboratory and field tests but consideration must also be given to insuring that the testing method does not jeopardize the performance and reliability of the sensor or instrumentation and protection systems tested on generation systems operations.

Laboratory and field testing had been performed by Kuhlman Electric Corporation to validate the test and analysis method but never on an operating power generation station. Previous in-service testing had been successfully performed on substation CTs at San Diego Gas & Electric's Encino and Carlsbad Facilities.

To insure that generation system operations would not be impacted, extra steps were taken to insure that the plant would not be tripped during the performance of the in-service testing program. Steps were also added to insure that the instrument technicians would not be exposed to conditions considered by the industry to be unsafe.

These steps included use of "make before break" connections (to avoid opening the secondary of the GCT with the primary energized), parallel test connections, double checking and monitoring of current loops before and after testing to insure or determine loop conditions before returning the down stream instruments to service.

Detailed written test procedures for use during the test program were prepared by the Kuhlman Staff and MidAmerican Energy Staff from plant instrument diagrams provided by MidAmerican Energy. The written procedures were approved by the MidAmerican Energy Engineering, Operations, & Maintenance Staff after careful review and performance of a dry run of the data acquisition phase had been completed.

TEST INSTRUMENTATION & CONNECTIONS: Prior to connecting to the single GCT under test, the test instrumentation and test connections were pre-tested to insure proper functioning during the test program. Using pre-approved test procedures for each unit, plant instrumentation for a three phase set of GCTs to be tested were bypassed as appropriate such that there was no danger of a plant trip. All GCTs in this set of transformers were individually tested by personnel. Connections were made by MidAmerican maintenance personnel under advisement of Kuhlman Engineering personnel at parallel test terminals, through standard shorting switches, and/or "make before break" connectors so as to avoid the danger of opening any CT secondary. Parallel GCT test terminals had been installed during previous plant outages.

In coordination with MidAmerican Operations Personnel, testing was performed and data was taken for a single GCT under test. Data acquisition took approximately two (2) minutes per CT. Following the acquisition of data, the test instrumentation was disconnected from the GCT under test, and the GCT under test was restored to service without ever opening the GCT secondary circuit. This process was repeated for the balance of the installed GCTs on each unit.

ANALYSIS & REPORTING: Analysis of the data for each GCT tested was performed off-line where secondary excitation curves were generated from the test points taken. Included in Table 1 is a list of GCTs tested at MidAmerican Neal Energy Center from Units 2, 3, and 4 with results.

SUMMARY OF MEASUREMENT RESULTS: On Neal 2, all of the 14,000:5 C800/0.3B1.8 GCTs tested achieved their IEEE Relay Accuracy Class of C800. No magnetization errors were detected, and on each GCT the metering accuracy of 0.3B1.8 was also satisfied.

For Neal 3, the test program confirmed all 20,000:5 C800/0.3B1.8 GCTs tested achieved their IEEE Relay Accuracy Class of C800. No magnetization errors were detected, and on each GCT the metering accuracy of 0.3B1.8 was also satisfied.
An 8% error had been previously reported at Neal 3 from the instrumentation normally connected to two GCTs suspected of having a metering accuracy problem. However; during the test program a normal

secondary excitation curve was generated from each. Thus output currents from the suspect GCTs were compared against the same ratio GCTs on the same bushing and found to be identical within normal statistical measurement errors. Later testing revealed that a portion of the secondary current from the suspect GCTs had been shunted away from the monitoring instrumentation by a parallel current path due to a bad two-element watt transducer. The parallel current path was removed and the GCT was restored to normal service by MidAmerican at its next scheduled outage.

On testing on Neal 4, the test program identified eight (8) of the 20,000:5 C800/0.3B1.8 GCTs tested failed to achieve their IEEE Relay Accuracy Class. In fact, in seven of the eight cases the secondary excitation voltages were found to be less than 35% of their expected relay accuracy value. Wiring and or connector problems were immediately suspected, however there may have been an internal problem with the GCT. This required generator down time for a full investigation as to the cause of the abnormal secondary excitation curves.

Further investigation on the next available outage for Unit 4 found that the readings on these GCTs were impacted by having their secondary wiring run through metallic conduit in extremely high magnetic fields near both the line bushing and neutral bushing. See Figure 3. Heat resulting from the circulating currents in the conduit walls had caused the insulation on the secondary conductors to become brittle, crack, and fall off, thereby exposing the copper wiring. This certainly limited the GCTs ability to deliver rated voltage during a fault to protective relays as clearly demonstrated in Figure 4.

Figure 3. Conduit runs near generator bushing in high magnetic field area

Additional testing and visual inspections of GCTs with associated wiring on Unit 4 revealed burned lead wiring between the GCTs and the local junction box. All eighteen (18) conductors exhibited insulation failure in exactly the same two places in the conduit located 11” away and adjacent to the centerline of phase “A” line and neutral bushings. A photograph showing the problem area is shown in Figure 3.

The suspected cause of insulation failure was localized heating produced by magnetic coupling in the conduit. The excessive heat damaged the insulation qualities of the cable. Thus the cable could no longer withstand the required voltage level produced by the GCT during a fault condition.

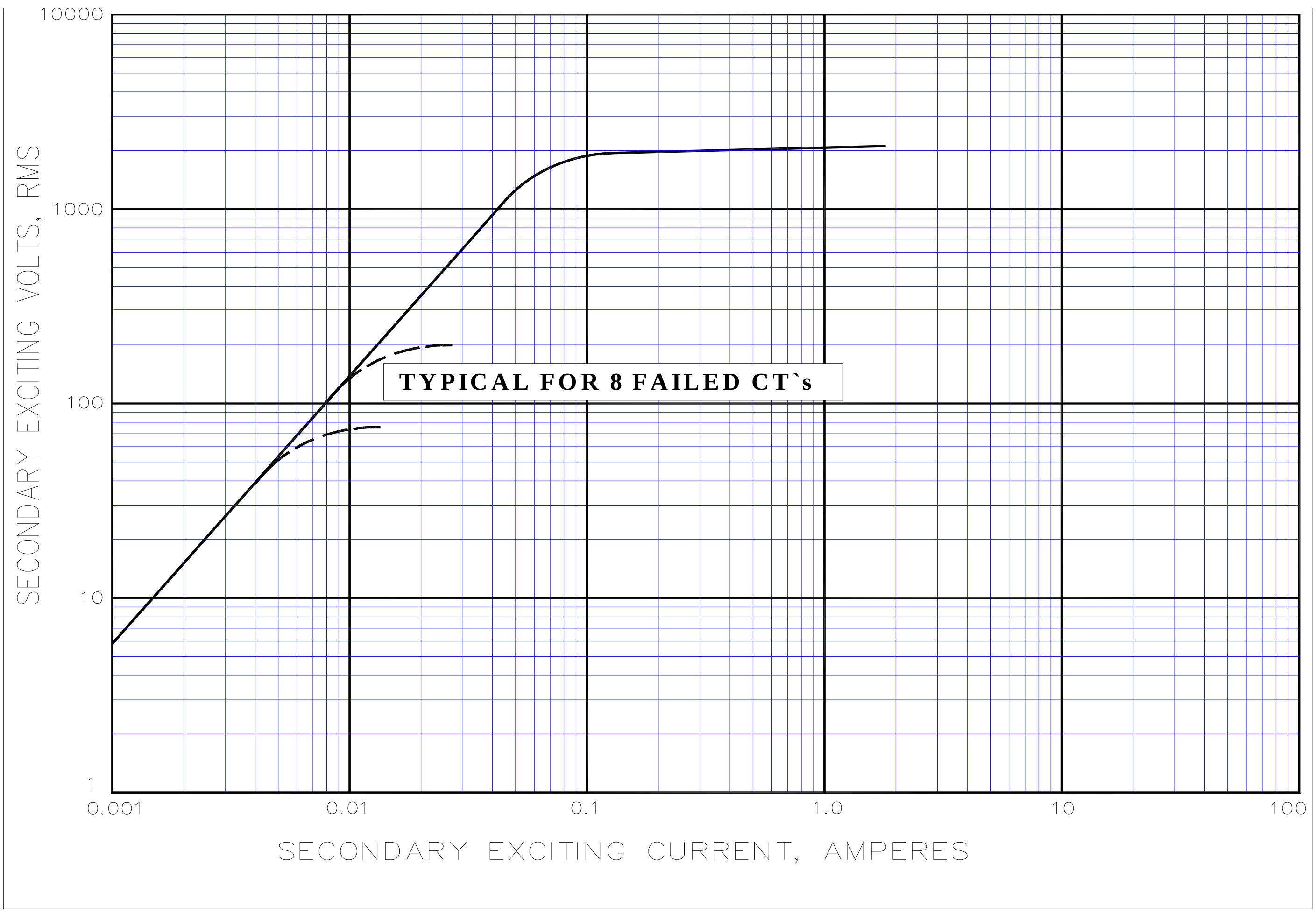

Figure 4. Excitation curve showing expected performance versus abnormal readings on 8 GCTs at Neal 4

This finding confirmed the test results shown in the eight (8) abnormal secondary excitation curves produced during the in-service testing program, and indicates that potentially the Unit 4 generator protection system would not have functioned as designed under a fault condition.

CONCLUSIONS:

Conclusions drawn from the Beta Test Program at MidAmerican Energy’s Neal Energy Center are:

- The In-Service Testing and Analysis Technique applied in the above testing program was able to successfully assess the existing installed condition of all GCTs on-line and in-service without jeopardizing plant, systems operations or personnel.

- The In-Service Testing and Analysis Technique applied in the above testing program is a cost effective method of determining the as-found condition of GCTs <u>and their associated instrumentation loops</u>. Thirty-nine GCTs with associated instrumentation loops were tested on-line within a sixteen hour period.

- Further, the testing and analysis technique provided as-found "dynamic secondary excitation curves" for each GCT which could be used by the plant instrumentation staff in a predictive maintenance data base for use in future periodic plant condition monitoring. In the case of the damaged wiring, MidAmerican not only rerouted the conduit, but replaced the conduit with non-metallic design.

- Additionally, the results seen can be used to schedule future maintenance for correction of any isolated problem in a cost effective planned manner.

- MidAmerican plans to continue and expand this GCT predictive maintenance testing program. Also, deficiencies noted at Neal Unit 4 were checked at other facilities to insure reliability of the GCTs.

Table I – GCTs Tested at MidAmerican Neal Energy Center

<u>Unit No. 2 (300MW): GCTs – All 14,000:5 C800/0.3B1.8 Results</u>

Gen. Cur. Instrumentation – Phase A (Neu. Side-Bottom Set)	Satisfactory(1)
Gen. Cur. Instrumentation – Phase B (Neu. Side-Bottom Set)	Satisfactory
Gen. Cur. Instrumentation – Phase C (Neu. Side-Bottom Set)	Satisfactory
Gen. Cur. Instrumentation – Phase A (Neu. Side-Middle Set)	Satisfactory
Gen. Cur. Instrumentation – Phase B (Neu. Side-Middle Set)	Satisfactory
Gen. Cur. Instrumentation – Phase C (Neu. Side-Middle Set)	Satisfactory

Unit No. 3 (515MW): GCTs – All 20,000:5 C800/0.3B1.8	**Results**
Gen. Protection Relay CT – Phase A (Line Side)	Satisfactory
Gen. Protection Relay CT – Phase B (Line Side)	Satisfactory
Gen. Protection Relay CT – Phase C (Line Side)	Satisfactory
Gen. Differential Relay CT – Phase A (Neu. Side	Satisfactory
Gen. Differential Relay CT – Phase B (Neu. Side)	Satisfactory
Gen. Differential Relay CT – Phase C (Neu. Side)	Satisfactory
Gen. & Main Trans. Diff. Relay CT – Phase A (Neu. Side)	Satisfactory
Gen. & Main Trans. Diff. Relay CT – Phase B (Neu. Side)	Satisfactory
Gen. & Main Trans. Diff. Relay CT – Phase C (Neu. Side)	Satisfactory
Gen. Cur. Instrumentation – Phase A (Line Side)	*Satisfactory*(2)
Gen. Cur. Instrumentation – Phase B (Line Side)	Satisfactory
Gen. Cur. Instrumentation – Phase C (Line Side)	*Satisfactory*(2)
Gen. Cur. Instrumentation – Phase A (Neu. Side)	Satisfactory
Gen. Cur. Instrumentation – Phase B (Neu. Side)	Satisfactory
Gen. Cur. Instrumentation – Phase C (Neu. Side)	Satisfactory

Unit No. 4 (630MW): GCTs – All 20,000:5 C800/0.3B1.8	**Results**
Gen. Differential Relay CT – Phase A (Line Side)	Satisfactory
Gen. Differential Relay CT – Phase B (Line Side)	Satisfactory
Gen. Differential Relay CT – Phase C (Line Side)	***Abnor. Sec. Excit. Crv***.(3)
Gen. Differential Relay CT – Phase A (Neu. Side)	***Abnor. Sec. Excit. Crv.***
Gen. Differential Relay CT – Phase B (Neu. Side)	Satisfactory
Gen. Differential Relay CT – Phase C (Neu. Side)	***Abnor. Sec. Excit. Crv***.
Gen. & Main Trans. Diff. Relay CT – Phase A (Neu. Side)	***Abnor. Sec. Excit. Crv.***
Gen. & Main Trans. Diff. Relay CT – Phase B (Neu. Side)	Satisfactory
Gen. & Main Trans. Diff. Relay CT – Phase C (Neu. Side)	***Abnor. Sec. Excit. Crv.***
Gen. Cur. Instrumentation, CT Set 2, Phase A (Line Side)	Satisfactory
Gen. Cur. Instrumentation, CT Set 2, Phase B (Line Side)	Satisfactory
Gen. Cur. Instrumentation, CT Set 2, Phase C (Line Side)	Satisfactory
Gen. Cur. Instrumentation, CT Set 3, Phase A (Line Side)	***Abnor. Sec. Excit. Crv.***
Gen. Cur. Instrumentation, CT Set 3, Phase B (Line Side)	***Abnor. Sec. Excit. Crv***.
Gen. Cur. Instrumentation, CT Set 3, Phase C (Line Side)	Satisfactory
Gen. Cur. Instrumentation, Phase A (Neutral Side)	Satisfactory
Gen. Cur. Instrumentation, Phase B (Neutral Side)	***Abnor. Sec. Excit. Crv.***
Gen. Cur. Instrumentation, Phase C (Neutral Side)	Satisfactory

Footnote: 1. Satisfactory results indicates GCT produced normal secondary excitation curve for Nameplate IEEE C57.13 Accuracy Class
2. GCTs originally suspected of having metering accuracy problem.
3. Abnormal secondary excitation curve produced indicating potential problem with GCT or plant instrumentation loop