Comprehensive Testing of Generator Protection Systems

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***Abstract*—This paper focuses on considerations and field experiences while testing a typical multifunctional generator protection IED. The comprehensive generator testing is classified in four major stages: 1) certification/functional/type testing; 2) commissioning; 3) periodic maintenance; and 4) troubleshooting. First of all, the paper presents different aspects of the certification/ functional testing, and demonstrates example of transient simulation based protection element testing using Real Time Digital Simulator (RTDS). Further, the important attributes of commissioning testing, in order to verify the deployed generator protection scheme is working as designed after field installation, are discussed with field examples. The regulatory, technical and economic considerations for periodic-maintenance testing are further described in this paper. Finally, the troubleshooting is discussed with field examples by utilizing state-of-the-art diagnosis tools available from today's modern multifunctional generator protection IEDs.**

***Index Terms*— Generator protection, protection testing, commissioning, maintenance, troubleshooting.**

I. Introduction

GENERATORS are the one of the most expensive components of the power system, as well as, important components for stable and reliable operation of a power system. Functionality, settings and equipment defects undetected by protective relays may lead to outages of generators that impose unnecessary costs to power utilities, and stress the power system network for no reason. Therefore, the generator protection system needs to be tested carefully considering dependability, reliability (operate reliably and fast during internal faults) and security (does not mis-operate for external faults) aspects of the protective relaying system. Literature categorizes the types of protection tests as follows:

1. Certification/Functional/Type tests
2. Commissioning
3. Periodic maintenance
4. Troubleshooting

In addition to above tests, some literature has further sub-categorized these tests or used different terminologies, e.g. application tests, performance tests, acceptance tests, conformance tests, upgrade tests, etc. The following section highlights various functions available in a typical multifunctional generator protection system.

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II. A Typical Multifunctional Generator Protection

Fig. 1 shows a typical state-of-the-art multifunctional generator protection system with encircled codes of various protection functions. In addition to protection IED, injection modules can also be included for sub-harmonic (20 Hz) based 100% stator ground (64S), as well as to detect and locate field ground fault (64F) by low frequency injection (0.1-3 Hz). The protection functions with respective codes in the figure are listed in Table I. In addition to protection functions, modern multifunctional generator protection system also facilitates other functionalities for control, communication, metering, monitoring, diagnosis, etc. are tabulated in Table II.

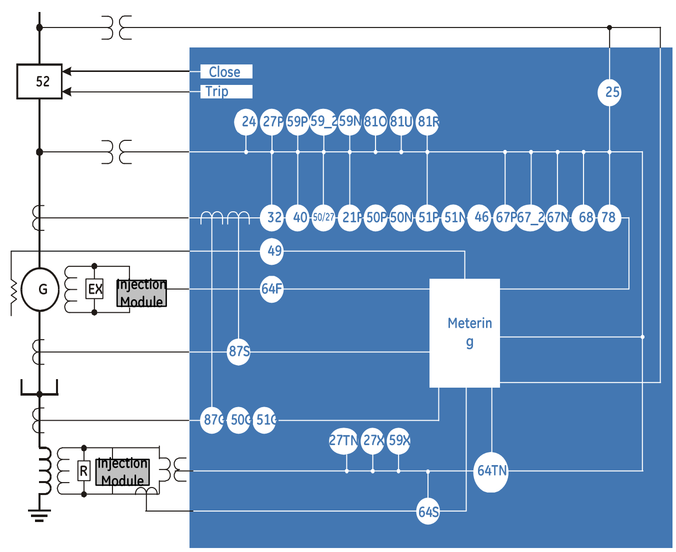

Fig. 1 A typical multifunctional generator protection system.

Table I List of protection functions available in a typical multifunctional generator protection IED

Codes of generator protection elements	Description of protection elements in a typical generator protection IED
21P	Phase distance backup
24	Volts per hertz
25	Synchro-check
27P	Phase under-voltage
27TN	Third harmonic neutral under-voltage
27X	Auxiliary under-voltage
32	Sensitive directional power
40	Loss of excitation
46	Generator unbalance
49	Thermal overload (RTD)
50G	Ground instantaneous overcurrent
50N	Neutral instantaneous overcurrent

50P	Phase instantaneous overcurrent
50SP	Split phase protection
50/27	Accidental energization
51G	Ground time overcurrent
51P	Phase time overcurrent
59N	Neutral overvoltage
59P	Phase overvoltage
59X	Auxiliary overvoltage
59_2	Negative-sequence overvoltage
64F	Field ground protection (low-freq. injection based)
64S	Sub-harmonic injection - 100% stator ground
64TN	100% stator ground third harmonic neutral voltage
67_2	Negative-sequence directional overcurrent
67N	Neutral directional overcurrent
67P	Phase directional overcurrent
68/78	Power swing detection
81A	Frequency out-of-band accumulation
81O	Over-frequency
81R	Rate of change of frequency
81U	Under-frequency
87G (RGF)	Restricted ground fault protection
87S	Stator differential

Table II Additional functionalities of a typical generator protection IED

Additional functions
Breaker control
VT fuse failure
In-built Phasor Measurement Unit (IEEE C37.118)
Communications (IEC 61850, DNP3.0, IEC 60870-5-104, Modbus) with advanced cyber security features
Event recorder
Data logger
Oscillography
Metering
Contact I/Os
Analog/Transducer I/Os (DCMA, RTD, etc.)
Flexible/Programmable Logic schemes
Flexibility of user-defined protection & control schemes/ elements
Self-testing and setting Targets/Flags
Trip circuit monitoring
Multiple groups of protection functions (user-defined protection group transition)

It can be inferred from the above two tables that today's modern generator protection system facilitates multiple protection, control, and automation functionalities with diagnosis and self-test features. Following sections present testing aspects related to generator protection system at different stages.

III. Certification/ Functional/Type Tests of Generator Protection

This section describes the important aspects of certification/functional/type testing of a generator protection system, with relevant examples.

A. Why Certification/Functional/Type Testing?

The purpose of these tests is to validate the entire design of the protection system/device(s), as well as the performance of the developed protection & control elements in various power system scenarios. Typically, the functional testing is carried out by relay manufactures using real-time system simulated platforms or made-to-scale (small) generator-motor machines, while considering full range of all expected operating conditions [1].

B. Considerations for Certification/Functional/Type Testing

Further sub-categories under Certification/Type Testing

a. Functional and system type tests
    i. Steady state functional test
    ii. Transient/dynamic performance tests
b. Physical and electrical environment tests
c. Pilot project tests

Rigorous functional and system testing of any product protection system is performed by manufacturer's product validation department before releasing any product revision. Few examples of this testing include: i) each specified product feature, e.g. protection functions, control, monitoring, metering, communication, etc. is performing as expected; ii) various system conditions, and check for any interdependencies within the same group of protection systems; iii) compatibility tests among system revisions (firmware, hardware, configuration tool, etc.), as well as other product devices (e.g. stator or rotor injection modules with main protection IEDs); iv) Processing performance/stress tests (confirm capability of all processors while most of the functions/features are running at its maximum usage; v) communication protocol conformance and performance; vi) cyber security compliance; vii) product configuration tool testing; viii) normal run time for longer period (days or months), and checking functionalities after several times power-up the device; ix) destructive system testing to understand product's behavior in case of any hardware/firmware failures, etc. at the same time check self-test indicators. The functional and system tests are also performed for any minor change to make sure there is no any other function/feature affected due to this change.

In addition to above product validation testing, transient and dynamic testing is also performed by simulating power system components in real-time environment. With close-loop testing, various transient conditions can be simulated to verify the performance parameters, such as dependability, security, speed, selectivity, etc. of the generator protection & control elements.

The physical and electrical environmental testing is a performed as per specified environmental standards. These environmental compliance standards may vary from geographical regions, for example IEC 60255-x, EN 61000-x, IEEE/ANSI C37.90.x [2], UL 508, etc. Normally, a product manual lists of all compliance standards.

After gaining confidence from exhaustive functional/type as well as transient/dynamic simulation testing, manufactures may further carry-out pilot installation and testing at generating sites.

Following tests may be performed by power utility alone or also in collaboration with manufacturers.

i. Application functionality tests
ii. Product pre-qualification tests

Certification/functional/type tests are "objective" and carried out by manufacturers to validate the product for wide range of power utilities. Whereas, application and product pre-qualification tests are "subjective" and these are conducted using utility/system-specific parameters or requirements, where generator protection is applied to [3].

As an example of transient simulation testing using real-time tool is demonstrated in following sub-section.

C. Example-Transient Simulation Testing

Latest development in digital simulators facilitates complex transient models in real time, which allow study of several applicable generating station fault scenarios. A simulated 500 MVA, 22 kV synchronous generator model is connected to a power grid through a 22/230 kV GSU transformer. The model allows different types of fault events to test the various generator protection elements. The examples of few generator protection functions testing using RTDS are discussed in this section.

1) Differential protection testing:

Fig. 2 shows the generator stator differential operating characteristic while a stator ground fault was applied at 50% of the stator A-phase winding on the real time digital simulation based generator model. The stator differential element picked-up instantaneously, and operated within a cycle. Various scenarios can be tested to verify the behavior of the element, and percentage of the stator winding protected.

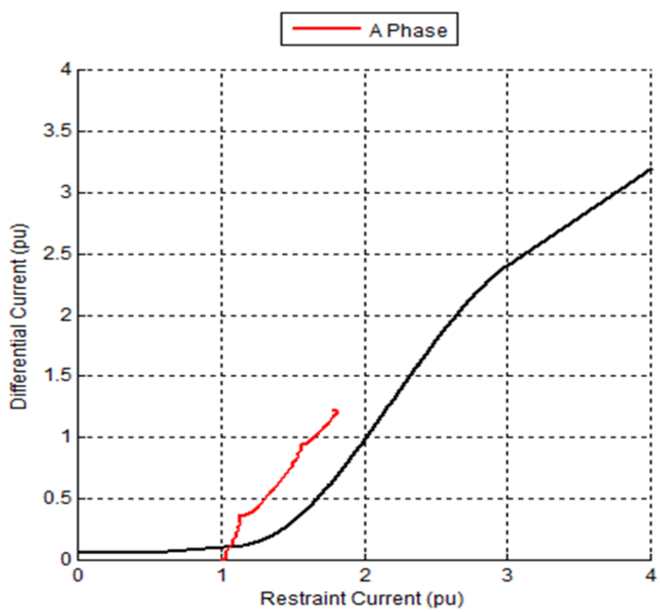

Fig. 2 Differential protection element during stator ground fault at 50% of the A-phase winding.

2) Inter-turn testing:

Fig. 3 illustrates the locus of differential element for inter-turn fault created on A-phase winding of the generator stator. It can be verified from the figure that 3-phase differential elements cannot protect generator stator for inter-turn fault. On the other hand, the inter-turn fault can be detected by utilizing negative sequence component as a part of generator unbalance protection element.

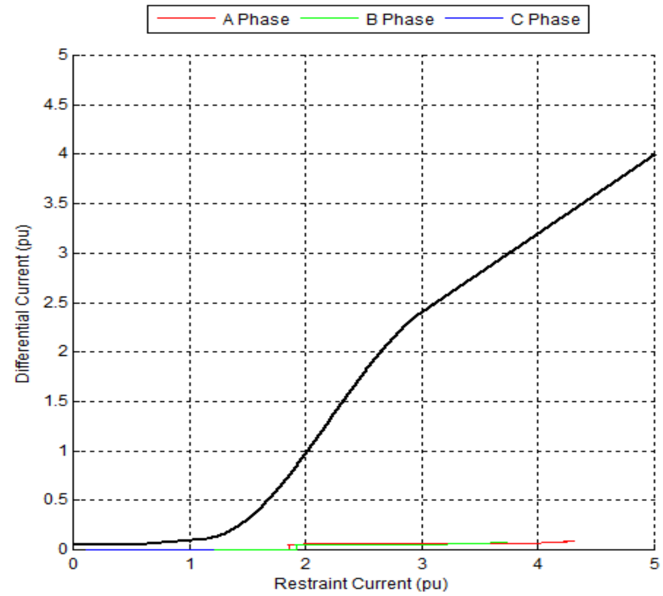

Fig. 3 Three-phase differential protection elements for inter-turn fault in A-phase winding.

The oscillography of generator currents on terminal side phase currents, as well as calculated positive and negative sequence components are illustrated in Fig. 4. It can be observed from Fig. 5 that stator differential did not operate, whereas, negative sequence based generator unbalanced element operated to clear the fault.

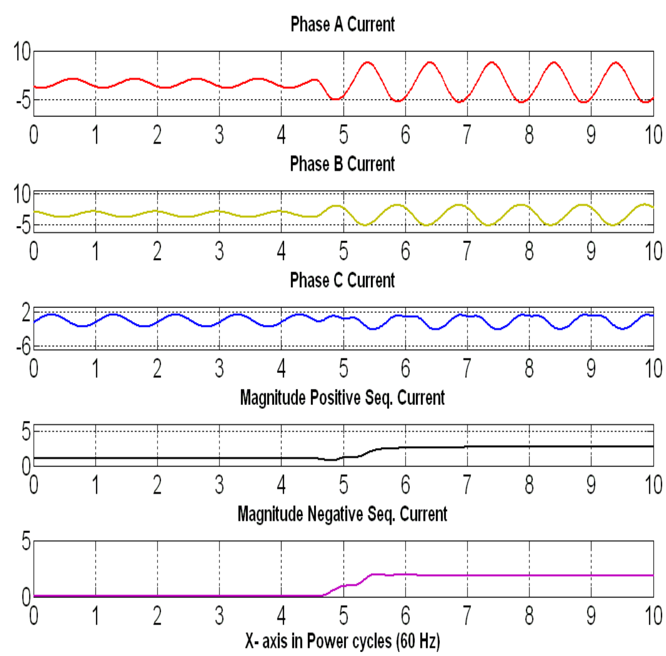

Fig. 4 Plot of generator terminal side currents and sequence components.

Fig. 5 Captured oscillography from an IED for inter-turn fault.

3) Loss of prime-mover element:

A sensitive directional power protection was used to protect generator for loss of prime-mover in this case here. As shown in Fig. 6, the multifunctional generator protection IED detected the reversal in active power, and tripped the generator circuit breaker within certain allowed delay.

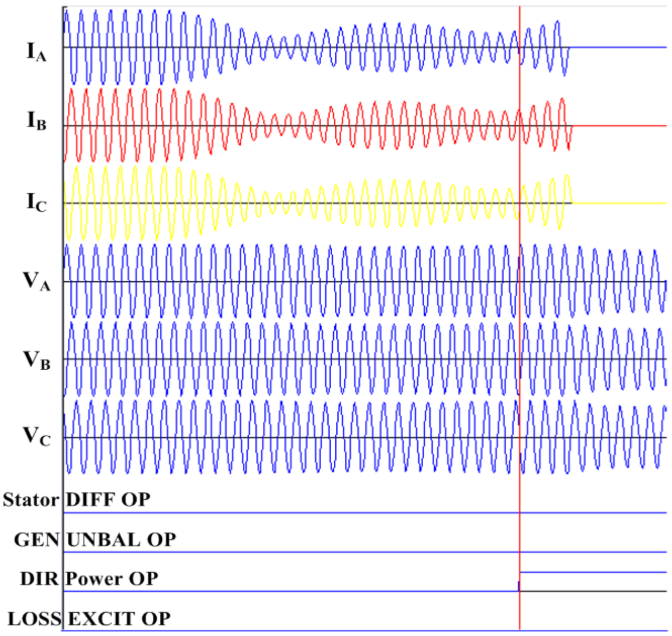

Fig. 6 Captured oscillography from an IED for loss of prime-mover fault

D. Dynamic Testing using Analog Model Generator

For certain generator test cases, EMTP-type simulation may not provide comprehensive dynamic behavior of a generator, e.g. simulation of true internal faults, natural third harmonic generated by a generator, etc. In such limited cases, a physical made-to-scale generator machine model can be utilized. An example of such generator model testing can be referred from the reference [4]. Small scale generator model may also facilitate to create various fault scenarios (in a controlled environment) to validate the protection functions.

E. Example – Pilot Installation & Testing

The pilot installation and testing of injection based stator and rotor ground fault projection modules was carried out at 35 MVA, 13.8kV, natural gas based generating station owned by Eastern Power in Ontario, Canada. The stator and rotor ground resistance were measured at various conditions. The waveforms captured at the site demonstrated stable measurements of these ground resistances during normal operation.

Fig. 7 demonstrates the pilot installation at the site. The field injection module was connected across the field winding, which acted as low frequency (0.1 to 3 Hz) voltage source, and the measured ground resistance was transmitted to the main generator protection IED via the communication cable. Stator ground module was connected across 13.8kV/240V NGT to provide 100% stator ground protection (64S).

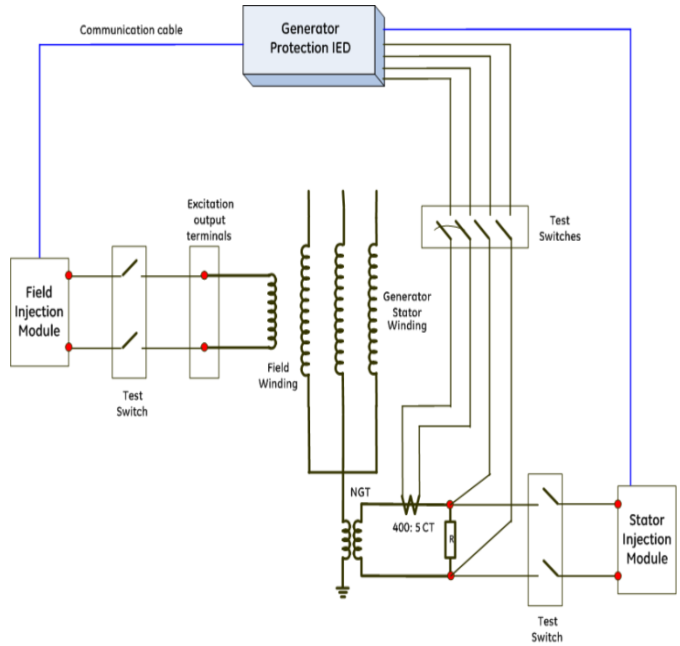

Fig. 7 Functional testing setup at Eastern Power, Canada.

IV. Commissioning Tests of Generator Protection

This section presents considerations and field experiences of generator protection commissioning.

A. Why Commissioning Testing?

Typically, the commissioning testing is carried out at installation site by power utility. Followings are the objective of the commissioning tests:

1. Check if received protection systems is intact after shipping
2. Verify the installation and proper wiring/connections
3. Confirm protection functions selection in multifunctional devices, and their setting groups
4. Check interconnection with other system devices/equipment at the site

The commissioning tests should be performed for any new installation or significant modification to an existing system [1].

B. Considerations for Commissioning Testing

1) Verification of wiring/circuit

Some generation utilities include visual-verification of wiring to check the complete agreement with the elementary diagrams prior to start device testing. Although, the wiring errors can be detected from directly performing primary/secondary injection based testing, it involves risk of incorrect operation or safety due to wrong wiring. The three-line, elementary, or schematic diagrams should be used for the purpose of checking the connection [5].

2) Secondary injection testing – including protection setting & setting groups

After selecting a specific manufacturer's protection device, a P&C engineer derives settings of all desired protection & control functions based on the system specific parameters of generating station. Make sure that derived settings are within the accuracy ranges specified by the manufacturers.

The testing of each enabled/configured protection element is carried out using a secondary injection module (to inject all required three phase voltage and current signals). Test switches can be utilized for this test to isolate the IED from rest of the circuit, and also short CT secondary.

Further, multifunctional IEDs have capability to configure multiple setting groups, and also allow switching among these setting groups adaptively. If implemented, the generator protection IED should also be tested considering these setting group changing conditions.

Some power generation utilities also involve co-ordination of generator capability limits with the corresponding protection settings, e.g. loss of field, unbalance current, reverse power flow, etc.

3) Primary injection based testing

Some power utilities also perform primary injection test while generator is not in service [5]. The intention of primary injection is to verify: 1) polarity of CTs from both ends for differential element; 2) polarity of CT/VT, especially for polarized/directional related elements; 3) consistency in secondary circuit connections. The challenge for such testing is the availability of high-voltage source to inject in primary circuit. If allowed, the primary injection can also be performed during generator short-circuit testing (which eliminates need of any external primary injection source), while limiting currents to nominal/rated value. Since, this is only polarity/connection testing, there is no need to inject high current/voltage to operate any element, but only sufficient to verify polarities.

4) Logic scheme testing

Advanced multifunctional digital IEDs have PLC (Programmable Logic Controller) functionalities to significantly reduce complexity of hardwiring for different protection & control logics. Using which, various logical protection and control schemes can be implemented as a part of one or more IEDs (e.g. generator protection IED, breaker control IED). Major logic schemes include multiplexing of multiple protection element operation driving to CB contacts, interlocking schemes, LOR (Lock-Out-Relay) scheme, breaker-failure schemes, etc.

In addition, generator protection system has different tripping modes associated with different protection element operations [6]. Therefore, it is recommended that generator tripping mode is also included in the logic scheme testing.

Furthermore, large generators are also part of System Integrity Protection Scheme (SIPS), generator dispatching/scheduling, or Wide Area Situation Awareness (WASA) schemes. And hence, the logic schemes involving generator protection system schemes should also be tested as well at this stage.

5) Trip circuit testing

The close circuit integrity should be tested between generator protection relay tripping contacts and respective breaker(s) trip coils. Since generator plant is shut-down, actual OPEN/CLOSE operation of CBs can be verified from operation of relay output contacts, as well as, the status of the CB can be monitored/confirmed in the device. Tripping initiated by LOR should also be included as a part of this testing.

6) Monitoring & metering on first time running

Monitoring and metering of various analog/digital values of a generator protection IED is performed while generator is start-up first time. The tools provided by IED manufacturers can also be used, for example oscillography, event logger, data recorder, etc.

C. Field Example- Site Commissioning

1) 125 MW Hydro Generating Station, Spain

Rotor ground injection module as a part of a generator protection system was tested on 125 MW hydro generating station. It can be observed from Fig. 8 that the field injection module was connected across the static exciter, and the field ground fault was created by connecting 5 kOhm fault resistance on negative side of the exciter with respect to ground bar in the exciter panel. Fig. 9 shows stable measurement in rotor ground resistance while ramping up field voltage.

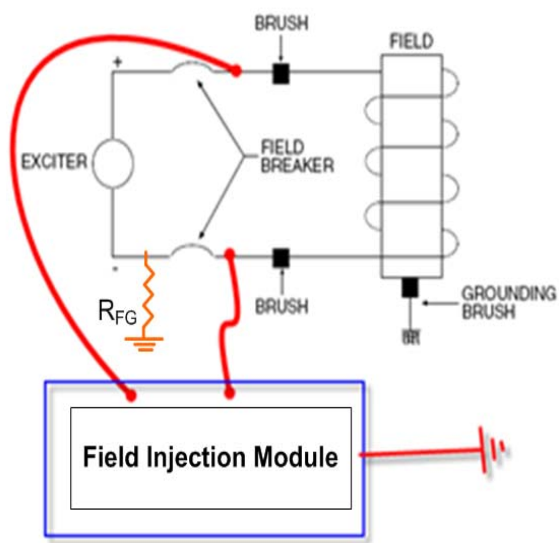

Fig. 8 Field testing setup at site.

2) 224 MVA Generator, JEA, USA

Commissioning of sub-harmonic injection based 100% stator ground protection was carried out at JEA (previously known as Jacksonville Electric Authority) located in Jacksonville, FL, USA. The generator protection system was commissioned on two simple cycle gas turbine/generator units, protecting 224MVA, 18 kV generators. Fig. 10 shows the data logged during generator start-up, with magnitude of sub-harmonic injected voltage, current, as well as measured stator ground resistance. The stable stator ground resistance can be observed throughout the generator loading in Fig. 10.

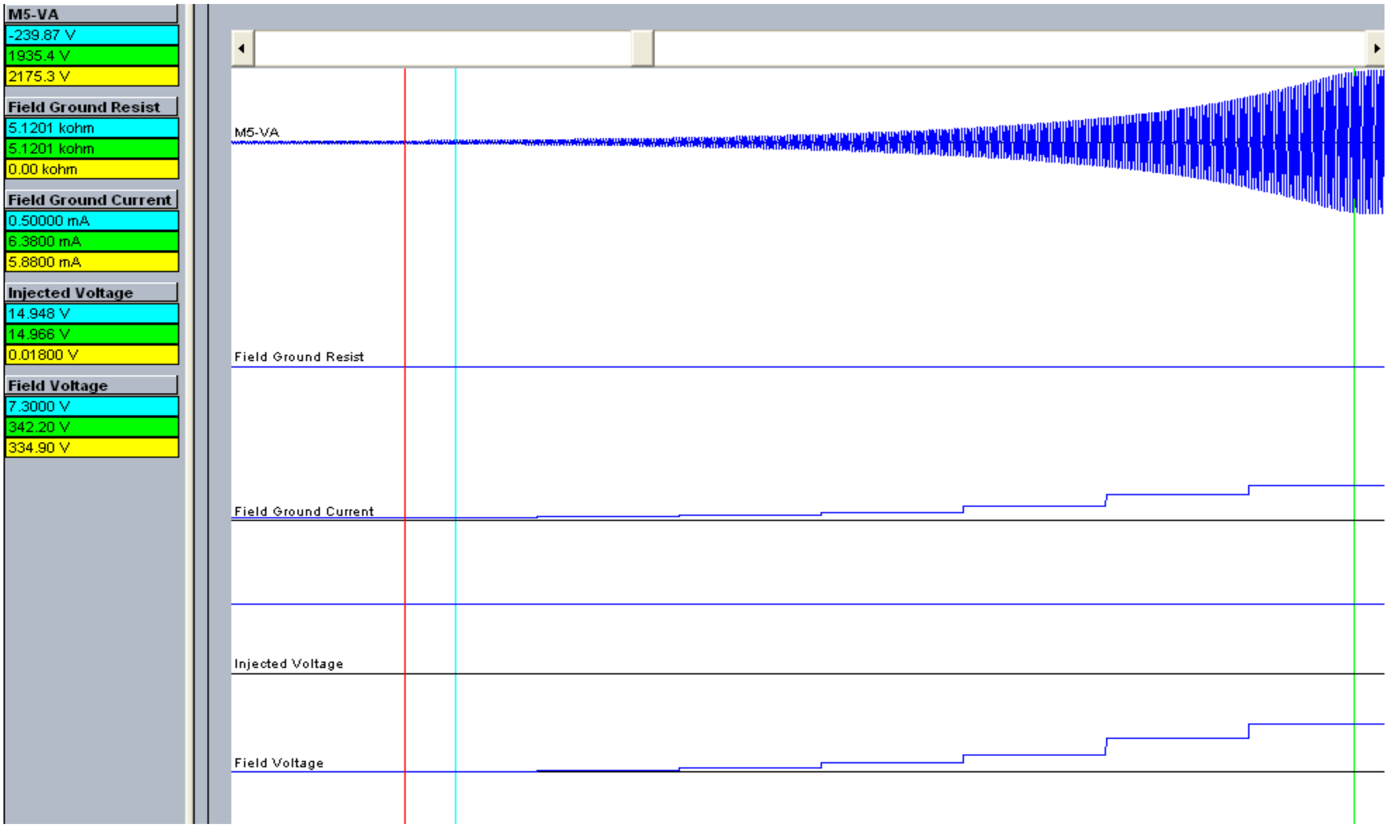

Fig. 9 Data captured for injection module based 100% stator ground protection module.

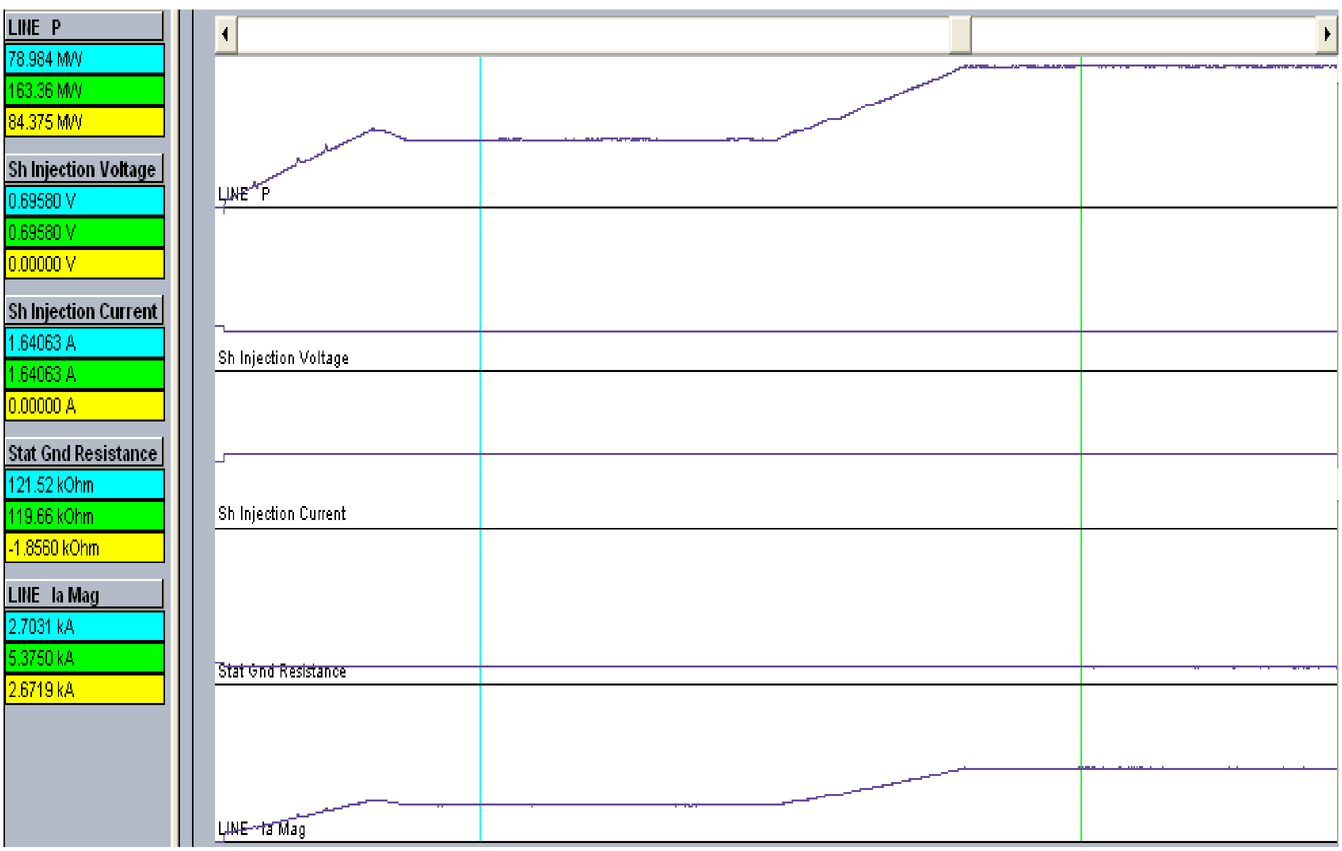

Fig. 10 Data captured for injection module based 100% stator ground protection module at JEA site

V. Periodic Maintenance Tests of Generator Protection

This section describes important considerations and examples of period maintenance of generator protection.

A. Why Periodic Maintenance Testing?

The objective of periodic maintenance testing is to validate the generator protection system is working as expected, and detect if there is any failed components in generator protection system. In addition to protective device, other important testing includes wiring, interfaces, communications, etc. [1]. If only generator protection (e.g. system-A) maintenance needs to be carried out, it is desirable to isolate one of the redundant protection device (using test switches) without affecting common portion of a redundant generator protection system-B.

B. Considerations for Periodic Maintenance Testing

The important items to be considered for periodic maintenance testing of generator protection systems are as follows:

1) Regulatory Requirements

Proper operation of protection and control system ensures the reliability of the electric power system. And hence, it is important to follow effective maintenance program by the asset owner (power utility) which can uncover any hidden failures in the circuit. Many regions have regulatory body which setup guidelines/regulations to carryout maintenance testing of the generator protection systems. An example of regulatory agency for North America is NERC (North American Electric Reliability Corporation), which has established certain requirements for maintenance of transmission and generation protection systems [7].

2) Period/Interval for Maintenance Testing

Normally, the generator protection systems maintenance is co-ordinated to the possible extent with scheduled shutdown of the unit maintenance or minor replacements. Nevertheless, actual period/interval of the generator protection system maintenance can be derived from one of the following methods discussed in the literature [1], [3]:

a. Time-based maintenance interval
b. Performance-based maintenance interval
c. Cost-based maintenance interval
d. Condition-based maintenance interval

The maintenance interval derived using time-based technique is fixed, and may be in the range of months/years. Normally, reliability studies can be performed to obtain the optimum interval of the generator protection systems [3], [8]. Performance based maintenance interval is derived based on analytical results or historical experience related to the occurrence of in-service failures of the protection systems [1]. On the other hand, cost-based maintenance interval involves deriving Break-Even-Point (BEP) between two cost functions: 1) cost for testing generator protection systems; 2) power supply interruption costs incurred due to mis-operation of protection caused by lack of periodic maintenance [3]. The condition-based maintenance interval method basically utilizes parameters derived from experience of maintenance engineer, history of problems related to system components, application data, frequency of faults, etc.

In any case, the maintenance testing interval should be in compliance with the respective regulatory requirements mentioned earlier.

3) Periodic Monitoring

Due to economic reason or coordination issue in generator shut-down schedule, it may not be possible to carry out comprehensive (secondary injection based) period maintenance test whenever required, and need to be delayed. In this scenario, it is advantageous to perform at least periodic monitoring by visual verification using diagnosis tools provided by multifunctional IEDs, e.g. event recorder, oscillography, data logger, etc. More details of these tools will be provided in following subsections. Although, this does not provide 100% check of protection functionalities, this method can delay the necessity for periodic maintenance [3].

During periodic monitoring, the generator plant as well as protection system can remain in-service. And, visual verification of the analog values integrity such as voltage, current, power (in comparison to other devices on the corresponding system) can be conducted. Further checking of status of device using IED setup tool, active alarms, relay display messages/event log in the relay, LED indications should be performed. Visual inspection of any damage, corrosion, dust or loose wires should be carried out as well. Even recorder file can be downloaded to re-verify any major or minor events related to protection system or generating system.

Periodic monitoring may not provide required level of confidence, and hence it cannot completely replace the need for regular periodic maintenance tests.

VI. Troubleshooting Tests of Generator Protection

This section describes troubleshooting testing tools available in a typical modern protection IED, and field experience utilizing them.

A. Why Troubleshooting Testing?

This test is normally performed after correct or incorrect operation of the protection systems by utility protection engineer in collaboration with manufacturers. For any disturbance/fault in the generator station, it is recommended to collect status and data from all protection devices. Using this information, the reliability of protection system can be evaluated using two parameters: 1) “security” parameter (protection system not operated when not required); 2) “dependability” (protection system operated when required).

Troubleshooting involves effectively utilization of troubleshooting tools, good engineering practices, and experience to identify the causes of operating problems.

B. Troubleshooting using Diagnosis Tools of Multifunctional IEDs

In addition to Digital Fault Recorders (DFRs), the diagnosis tools provided by modern digital protective relays can also be utilized, the list of such tools are as follows:

1. **Event recorder for SoE (Sequence of Events)**: Modern multifunctional IEDs can store list of more than 1000 events. Generally, each event record shows the event identifier/sequence number, cause/trigger, and accurate date/time stamp (time of event occurred). In addition to log event for protection element operation, the advancement in technology allows detailed self-testing of trip circuit monitoring, hardware, analog and digital I/Os, software/firmware, maintenance alerts, etc. The SoE within the multifunctional IED can be downloaded using manufacturer's device setup tool.
2. **Oscillography:** It captures waveforms at the high sampling rate as well as other analog and digital data at the point of trigger. The oscillography triggers can be defined by the users or based on pick-up or operation of any protection group elements. Normally, IED can store pre-fault, during fault, and post-fault data in the standard format, e.g. COMTRADE [9]. The oscillography data can be used to diagnose behavior of the device during system transients.
3. **Data logger**: the data loggers can store measured and calculated values for even longer duration than oscillography at lower sampling rate. Some IEDs offer non-volatile memory based storage to retain the logged data even if power of an IED is lost.
4. **Vector diagram representation:** The vector diagram representation tool allows user to view and compare various input signals to the device capture by oscillography. The entire captured oscillography can be played back in vector diagram to diagnosis the signal behavior during an event. In addition, the vector representation provides visual verification of angular relationship among the signals.
5. **User-programmable fault reports**: Advanced multifunctional IEDs can provide user-configurable multiple fault reports. This allows user to select pre-fault and fault triggers to generate such reports storing various information, such as, relay name, firmware revision, time of trigger, and specification of triggers, and measured values for the complete duration of event.

C. Field Example- Event Logger

Fig. 11 and Fig. 12 show typical diagnosis tools (event logger and vector viewer) of a multifunctional IED, which helped a P&C engineer at Ontario Power Generation's (OPG) to quickly troubleshoot a nuclear power Standby Generator (SG) tripped on start-up. When the SG was synchronized with the station bus, and the SG began to rise in power per the commissioning work plan, the protective relay tripped the SG on differential protection.

Event Number	Date/Time	
10	Dec 03 2009 10:22:28.426431	94-R11TRIP Off
9	Dec 03 2009 10:22:27.424963	STATOR DIFF DPO C
8	Dec 03 2009 10:22:27.424963	STATOR DIFF DPO A
7	Dec 03 2009 10:22:27.335471	94-R11TRIP On
6	Dec 03 2009 10:22:27.335471	OSCILLOGRAPHY TRIG'D
5	Dec 03 2009 10:22:27.335471	STATOR DIFF OP C
4	Dec 03 2009 10:22:27.335471	STATOR DIFF PKP C
3	Dec 03 2009 10:22:27.335471	STATOR DIFF OP A
2	Dec 03 2009 10:22:27.335471	STATOR DIFF PKP A
1	Dec 02 2009 15:05:38.694117	EVENTS CLEARED

Fig. 11 Event recorder captured at OPG nuclear power plant.

It was quickly determined through captured oscillography/vector representation obtained from the protection IED that the mis-operation was due to the incorrect wiring. The tool saved lots of diagnosis time for re-checking wiring and protection settings.

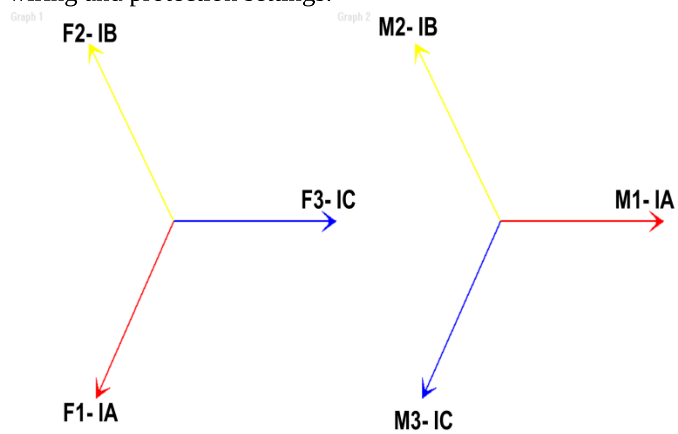

Fig. 12 Event recorder captured at OPG nuclear power plant.

D. Field Example- Differential mal-operation

Combustion turbine-generation unit, 109 kVA, 13.8 kV was on scheduled outage for testing generator and transformers at one of the major US utilities. Generator differential relay keep operating every time generator load approached to 20 MW. The oscillography from the generator protection IED (the waveforms of generator of both sides current signal), as well as the status of protection elements are captured for this event (as shown in Fig. 13). Generator neutral side CTs were tested for ratio, saturation, and insulation resistance. All CT tests were acceptable. Further, it was also confirmed that signal processing module of the digital generator protection relay was normal as well. Thereafter, the digital protection device was replaced, however, the neutral side current signals were still distorted, and 87G continued to mis-operate while loading generator to 20 MW. By analyzing the logged COMTRADE data obtained from device using MATLAB, the even order harmonics were observed at the generator neutral side current signals. The secondary circuit cables were running with batter-charger (power electronic converter) cables. While tracing secondary circuits (CT wiring) connected to the relay, the wrong as well as loose connections in secondary circuit were found and fixed, and harmonics disappeared.

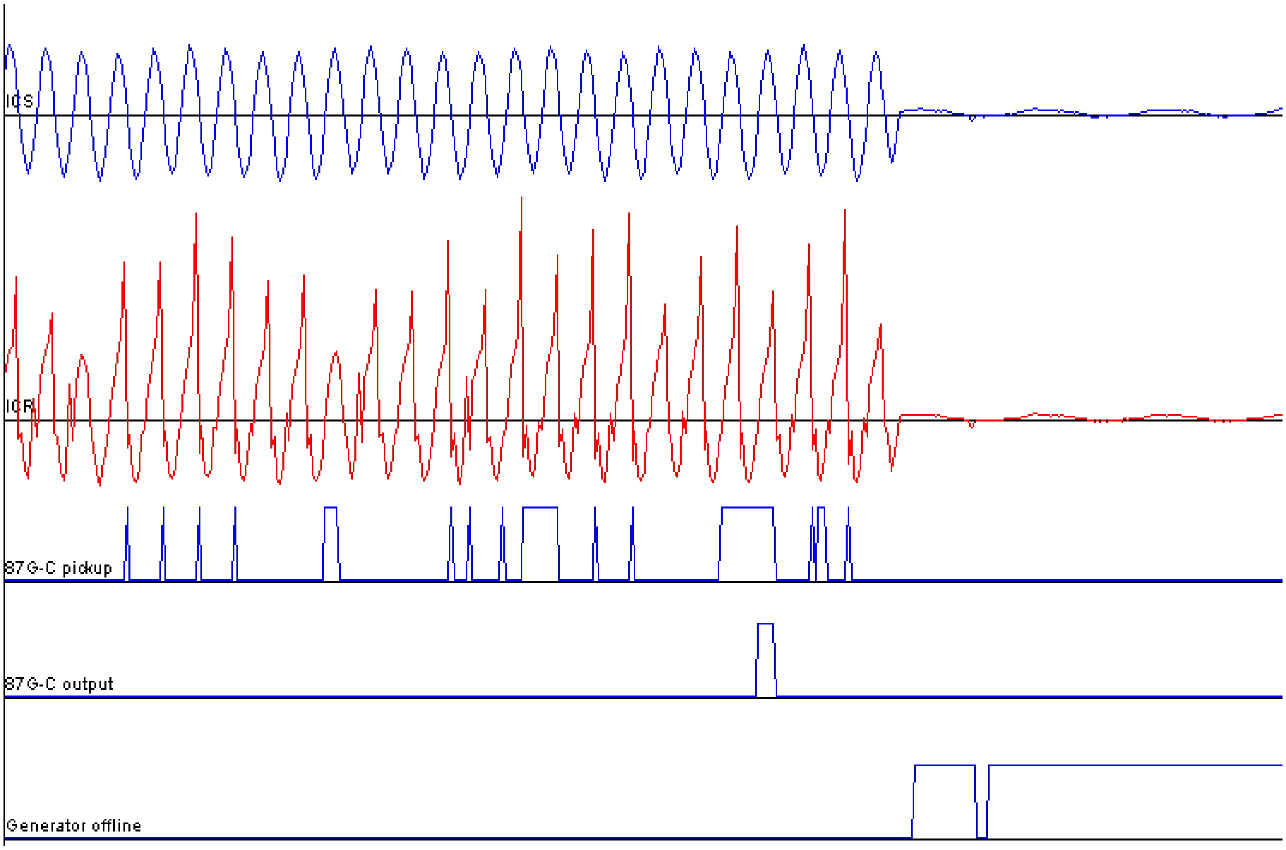

Fig. 13 Data captured for 87G digital generator protection relay.

VII. Summary

This paper presents important aspects of generator protection system testing at different stages, such as: i) functional/type/certification testing by manufacturer in order to validate the developed functionalities/features of the product; ii) commissioning testing by power generating site engineers to verify that the installed generator protection system working as expected; 3) periodic maintenance to check healthiness of entire protection system and circuit, at a regular interval; 4) troubleshooting to understand the protection response in case of any power system event occurrence. Utilizing IED tools (i.e. oscillography, event recorder, data logger, metering/actual values, exporting all required information) at the time of commissioning, maintenance, and troubleshooting is explained with examples. The important considerations while commissioning, e.g. secondary/primary injection, logic/schemes, trip circuit, etc. are discussed. The regulatory requirements, and various methods to derive optimum interval for periodic maintenance are described briefly. Troubleshooting tools from digital generator protection IED and field example of tracing root cause of false-trip are presented.

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