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Dynamic Testing of Generator Protection Using a Model Generator Platform

DYNAMIC TESTING OF GENERATOR PROTECTION USING A MODEL GENERATOR PLATFORM

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1. Introduction

Modern, microprocessor-based generator protection relays integrate many functions into a single package. Each protection element is designed to detect a specific abnormal condition in the system and to initiate a particular tripping sequence. Static testing of individual functions in many cases will not validate the ability of the entire package to respond correctly to different system conditions. This is particularly true for generator protection.

EMTP-type simulators may not allow comprehensive dynamic testing due to limitations in the models (simulation of true internal faults in machines and transformers, generation of natural third harmonics by a generator, etc.). Therefore in some cases such as ungrounded distribution networks, generator, motor and transformer protection, physical made-to-scale models of the protected equipment, and actual field recordings are exceptionally useful.

This paper will demonstrate the advantages, methodology and sample results of dynamic relay testing using a scaled model generator platform. Some of the of abnormal conditions applied to the relay include:

- Internal faults (true turn faults)
- External faults with CT saturation
- Loss of prime mover
- Over/under excitation
- Stable/unstable power swings
- Inadvertent energization
- Low frequency operation (static starting)
- Loss of excitation

A new generator relay is tested on our unique physical model and state-of-the-art digital simulator. Particular attention is paid to new algorithms, such as stator differential with extra immunity to CT saturation conditions.

Sample test results are included.

2. Simulation and Testing Tools: Analog versus Digital

2.1. Generator Testing Needs

The model for in-depth testing of a modern generator protective relay should consist of the following components:

- A synchronous generator with electrical parameters consistent with those of a typical high-voltage generator. The generator should produce a third harmonic component with a voltage distribution that is typical of a high-voltage generator.
- A prime mover with a control system capable of constant speed and/or constant real power control and with matching gains and time constants.
- An excitation system with a control system capable of constant voltage and/or constant reactive power control. System gains and time constants should match the real world equivalents.

- A high-voltage-interconnect system consisting of a generator grounding system, unit transformer, circuit breaker, transmission line model, and equivalent grid system. The transmission line model should allow for the simulation of both strong and weak systems.

The model should be capable of off-line and on-line operating modes. In on-line mode the model should be capable of transferring real and reactive power to an equivalent grid system.

The model should allow for the application of phase-to-phase and phase-to-ground electrical faults at the following points:

- The neutral of the machine.
- At various points on the stator winding.
- At the machine terminals within the zone formed by the generator Current Transformers (CTs).
- At the machine terminals outside the zone formed by the generator CTs.
- At various points on the transmission line model.

The model should allow for the application of the following abnormal conditions:

- A loss of prime mover.
- A loss of excitation.
- Over/under-excitation.
- Over/under-voltage.
- Over/under-frequency.
- An open phase or phase unbalance.
- Accidental energization.
- Generation rejection.

The model should permit for both wye and open delta relay Voltage Transformer (VT) connections. In addition the model should allow for the simulation of a failure of one or more VT fuses.

The Circuit Breaker (CB) should be controllable from the protective relay and the CB position should be available as a status input to the relay under test.

2.2. Internal Faults

This is probably the single most important reason for building and using analog simulators. In the case of rotating machines and power transformers, internal short circuits can occur between different points of the same winding, between different windings, or between a winding and a core, all within the complex magnetic core of the apparatus. In the case of rotating machinery, the situation is even more complicated as part of the apparatus rotates.

Because modeling of such true “inner” faults is a complex task, testing for internal faults is typically limited to faults at the machine/transformer terminals within the differential zone of protection as outlined by the main CTs.

In the case of power transformers, several attempts have been made recently to model true internal faults [1]. Some of the solutions have been incorporated into commercially available simulation packages or as pre-processors to standard simulation tools such at ATP/EMTP.

Some attempts at modeling true internal faults in rotating machines, generators in particular, have been made as well, but the industry is far from seeing the models validated and incorporated in standard simulation packages.

Analog simulation using made-to-scale machines solves the problem to a great extent. Typically an appropriate machine is selected (or build) and hand-wound. A number of artificial terminals are created along the windings and brought out so that short-circuits involving those terminals can be created.

The major problem with this approach is that the magnetic structure of the machine is altered when making extra external connections to the taps along the windings. Arcing faults or faults that truly evolve cannot be accurately modeled. With all the limitations, however, analog models are the most realistic and accurate way to simulate internal faults in machines and transformers. Such simulators, though, are quite expensive and are rarely available.

2.3. External Faults

Saturation of main and relay CTs and switch-off transients are the main concerns when testing the stator differential protection.

Particular attention must be paid to long-lasting external faults of small current magnitude but very long d.c. time constant. Small magnitude currents create small restraints. This, in turn, places an operating point on a dual-slope differential characteristic in the region of lower slope, where the relay is very vulnerable to misoperation. If a given generator relay is based on percent differential characteristic alone, it may misoperate on external faults of low current magnitude and long d.c. time constant.

Switch-off transients associated with clearing an external fault is yet another test condition to be considered. An external fault saturating a CT to the extent of bringing the differential-restraining point close to the operate / no-operate boundary needs to be simulated. Next, the fault has to be cleared. As the algorithm filtered magnitudes ramp-down, an unfavorable transient may be generated within the relay causing misoperation.

Given the testing requirements and the data / physical models available, the tester must choose the most appropriate tool (digital or analog simulator) to meet the requirements.

2.4. Stator Ground Faults and Third Harmonic Methods

The amount of third harmonic and proportions between the third harmonic in the neutral voltage and zero-sequence terminal voltage, as well as fundamental frequency components and exported power during stator ground faults and normal conditions are described by quite complex relations. In addition rotor asymmetry and natural noise in the signals may play significant role for stator ground protection methods based on the third harmonic.

Because of the above reasons analog models are much more suitable for overall testing of stator ground fault protection relays and algorithms.

Testing at off-nominal frequencies using an analog model may create a problem, though. Keeping the third harmonic content in proportion requires fine-tuning – depending on actual frequency – of a grounding resistor of the made-to-scale machine. At the same time, the response of the relay shall be tested at ramping-up or down frequencies (in order to simulate ground faults during machine start up).

In general every method that is based on harmonics should be tested at off-nominal and ramping frequencies in order to validate performance of the frequency tracking system of the relay. If the frequency tracking does not work correctly, a certain amount of the fundamental frequency signals “leaks” into measurements of the other harmonics and may cause misoperation.

2.5. Power Swings

Digital tools can be used for testing out of step tripping and power swing blocking functions., and a digital simulator can handle a variety of system configurations and fault conditions. However, when a response to internal faults under power swings and off-nominal frequencies is considered, analog models are more capable because they can handle true internal faults in machines.

2.6. Loss of Excitation

An analog model with actual field winding and associated d.c. source, controls, and decay time constant proved to be a better way of testing the loss of field protection. This is particularly true if one considers short circuits in the field winding as a potential source of loss of excitation.

An analog model interfaces better with actual sources of excitation and real controllers. However, as long as short-circuits and similar abnormalities are left out of testing, digital closed-loop simulators can be used for this purpose. However, the interdependency of the other machine functions are only as accurate as the digital model.

2.7. Overexcitation

Overexcitation protection can be tested using both analog and digital models. An analog model is typically limited to one particular magnetizing characteristic but most detection methods are based on a volts-per-hertz measurement, which is independent from the magnetic core that is being protected.

An interaction between generator controls must be taken into account when testing the overexcitation protection.

Attention must also be paid to the operating principle of the V/Hz element. The core being protected from overheating may be one piece of iron (machine alone) or more (machine plus transformer). The relay, though, measures and responds to three phase-to-ground or phase-to-phase voltages. Different vendors treat the three-phase voltages differently. Phase-A voltage, average, or maximum voltage can be used. A “global” thermal history, or three per-phase “thermal counters” may be implemented. With three counters, the average may be derived, or the first one to reach the operate threshold would operate. Significantly different results can be obtained when testing V/Hz relays under unbalanced conditions.

Response time of the V/Hz element should be approached with care as well. While the voltage (numerator) can increase abruptly causing a step change of the V/Hz ratio, the frequency (denominator) cannot. Some relays apply certain amount of post-filtering to measured frequency in order to bring more security while still covering the fastest possible frequency ramp (say 10Hz/sec). With post-filtering the relay would smooth out any step changes in frequency if such changes are applied in laboratory conditions. If this is the case, the “start mark” for the testing timer becomes fuzzy. Generally, the frequency shall be assumed constant: for any given frequency and required V/Hz ratio, a corresponding voltage shall be calculated. When applying the calculated voltage, a well-defined start mark is created allowing for precise measurement of the response time of the V/Hz element under test.

2.8. Overall Dynamic Testing

Overall dynamic testing should be the last step for building an appropriate comfort level for new relay designs protecting a-few-hundred-MW generators. In the case of a rotating machine there are many complex interactions between the electromagnetic and mechanical portions of the system as well as between the machine, its excitation system and all the relevant control systems. These interactions becomes even more complex once problems with the equipment itself, either the generator, its controls, or the excitation system, are to be tested.

A microprocessor-based relay itself is a complex device as well. The relay would track frequency, respond in a certain way to low-frequency currents and voltages (response of the input magnetics), etc. This calls for a number of test scenarios that involve overlapping events that need to be considered (stator ground fault following a VT fuse fail, during a ramping frequency, for example). Typically, scenarios like that can be tested only on a complete made-to-scale analog model.

3. Analog Generator Model

A power generator, being a rotating piece of equipment, has complex dynamic interactions between the prime mover, generator controls, and the power system over a wide range of operating conditions. For completeness, dynamic testing of generator relays requires an accurate model on which to exercise the relay over the ensemble of possible operating conditions.

Physical scale models of two 907MVA and a 144MVA cross compound generator and interfacing transformer and line model were developed in the early 1970's in a joint venture between the MIT Electric Power Systems Engineering Laboratory and the Laboratory and the American Electric Power Service Corporation [2]. The models were originally built due to concerns over lack of field data in this area as well as a need to verify computer models used in large system studies. The system has demonstrable characteristics and controls that are similar to actual field systems. The 1444MVA model was acquired for the purposes of dynamic testing.

The 1444 MVA model was built to one-millionth scale and as such, each half of the cross compound unit is rated for about 700VA with a 221V output rating. On a scaled basis, the model is "electrically correct" – carefully modeling the per-unit reactance, actual machine time constants, and rotor inertia. Included in the overall control system are operational amplifier models of a supercritical generator with three time constants and appropriate transfer functions and gains to simulate governor dynamics and droop.

The machine is hand-wound and gives access to all stator terminals as well as access to intermediate points on the stator windings. For synchronized operation, the unit can be paralleled with the local utility. As the design is physically robust, it can be subjected to a wide range of faults and system operating scenarios with relative impunity. Various fault types, fault locations, and fault initiation angles can be effected and consistently repeated. Since the full load currents are about 1.8 A 2.5:5 current transformer were installed to bring the steady state current closer to typical field conditions. Figure 1 shows a one line diagram of the test system as implemented.

The system can test for virtually any generator abnormality, for example, Stator Differential, Stator Ground, Loss of Excitation, Overexcitation, Over/Under Frequency, Reverse Power, etc.

One of the more uniquely modeled aspects of the systems is the excitation system and field winding. On an actual generator, the L/R ratio of the field winding is quite large yielding a time constant on the order of several seconds on Loss of Excitation. As the rotor of the models electrically falls short of this number, equivalent time constants are achieved by electronically providing a "negative resistance" in the field supply. In the actual implementation, the time constant is adjustable over a wide range of times. As such, Loss of Field protection performance can accurately be tested for a range of machine time constants.

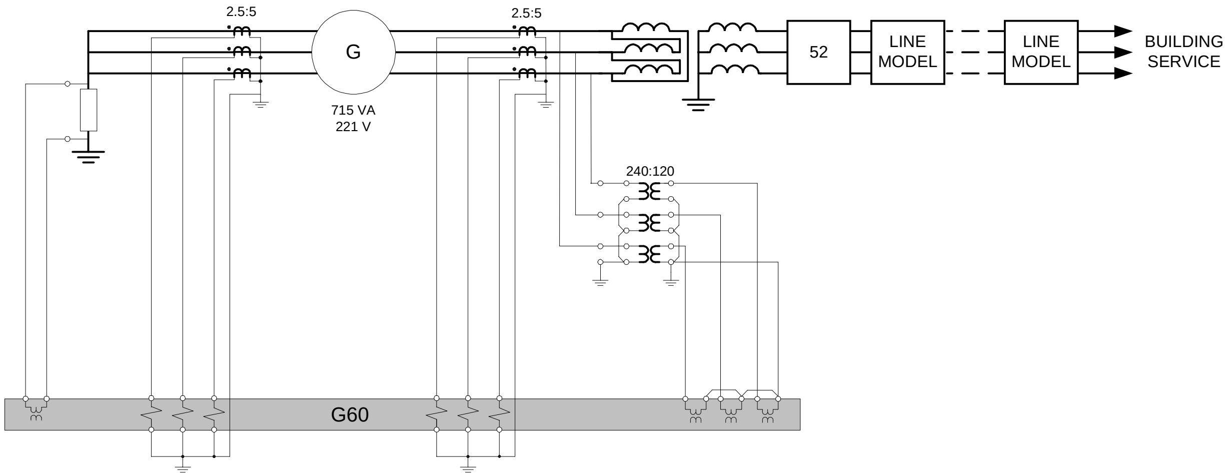

Figure 1. Diagram of the analog generator model.

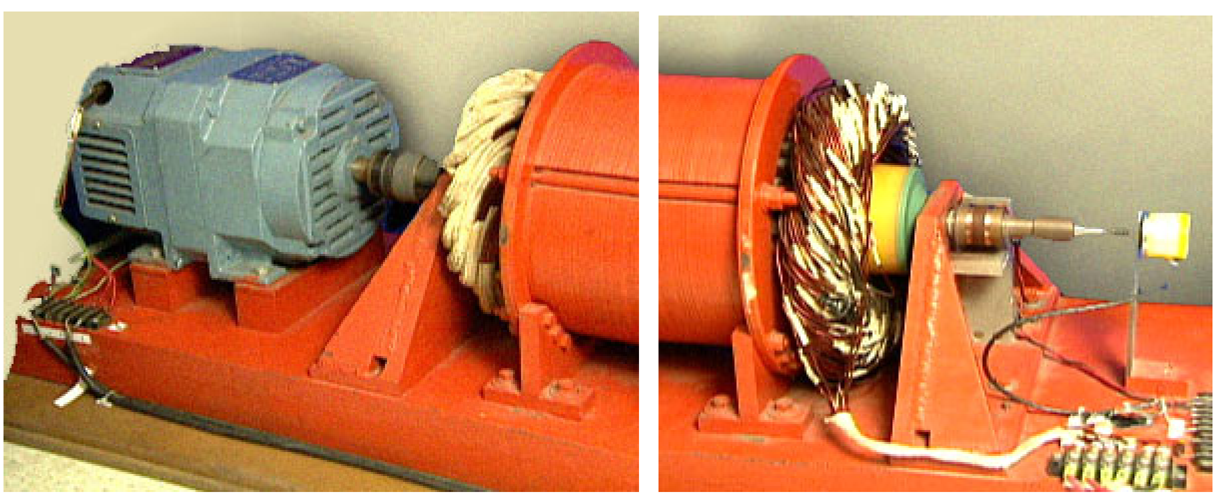

Figure 2. D.C. motor (left) acting as a prime mover for the generator (right). Hand-wound generator brings out taps along the windings for short-circuit tests.

4. Digital Generator Model

The Real Time Digital Simulator (RTDS) [3] has become a de-facto standard for closed-loop testing of protection and control equipment.

Figure 3 presents configuration of the simulator used for relay testing, while Figure 4 shows photos of the physical equipment. Three sets of amplifiers are available for testing three-terminal line applications. For generator testing, two sets are actually required in order to feed the relay under test with neutral and terminal-side currents. The third set may sometimes be needed if an overall generator-transformer differential protection is to be tested.

The main disadvantage of any off-the-shelf simulation package is lack of ability to simulate true internal faults in electrical apparatus such as motors, generators or transformers as described in section 2.

The RTDS is a general-purpose high-accuracy simulation system. As such it suits better certain generator testing needs. For example, the simulator is a better source of external fault currents as compared with analog simulator because it more easily allows different system configurations, different parameters of CTs, and it is more repeatable (establishing residual magnetism in the CT cores, for example), etc.

Some other tests, however, must be performed on a physical model. Stator ground fault protection is a good example. While the RTDS can be used as a very accurate and stable source of the third harmonic for testing accuracy of the relay and quality of filtering, the physical model needs to be used to test the overall performance of the protection system.

5. Generator Relay Under Test

5.1. Hardware Overview

The new protective relay [4] is built on a Universal Relay platform [5]. The platform allows for modular hardware that can be ordered and configured to suit variety of application needs. In particular, the relay can be configured with three sets of current inputs allowing applications that involve current-based functions on the third set of currents, such as step-up transformer tertiary winding monitoring or protection.

The user-selectable a.c. inputs are configured using the mechanism of sources. The relay may be ordered with different combinations of CT and VT inputs. These inputs are configured individually (ratios, rated secondary values, connection, etc.). “Sources” are next combined from available phase and auxiliary voltages, and phase and ground currents. Protection and control elements are subsequently configured to respond to selected “sources”. This mechanism is equivalent to “virtual a.c. wiring” and becomes a very powerful configuration tool. In particular it allows configuring, Time Overcurrent (TOC) protection or Distance Backup functions to respond to neutral- or terminal-side currents as per user preferences. Moreover, the source setting for each protection or control element is under multiple setting group control: a given TOC or other element can be dynamically switched from terminal- to neutral-side set of currents depending on user-programmable conditions.

Current and voltage signals are sampled at 64 samples per cycle. Second order Butterworth filter is used for antialiasing.

Transducer modules are available that could be configured to respond to dcmA or resistive temperature sensors for thermal protection and other protection and/or control functions.

Digital Inputs and Output Contacts are provided on a modular basis as well allowing configuring hardware components (a.c. inputs, digital inputs, contact outputs, transducers) per requirements of a given application.

The relay supports multiple protocols over an Ethernet port and TCP/IP including TFTP, MMS / UCA 2.0, etc. as well as an embedded web server. This allows cost-effective applications for distributed generation [6].

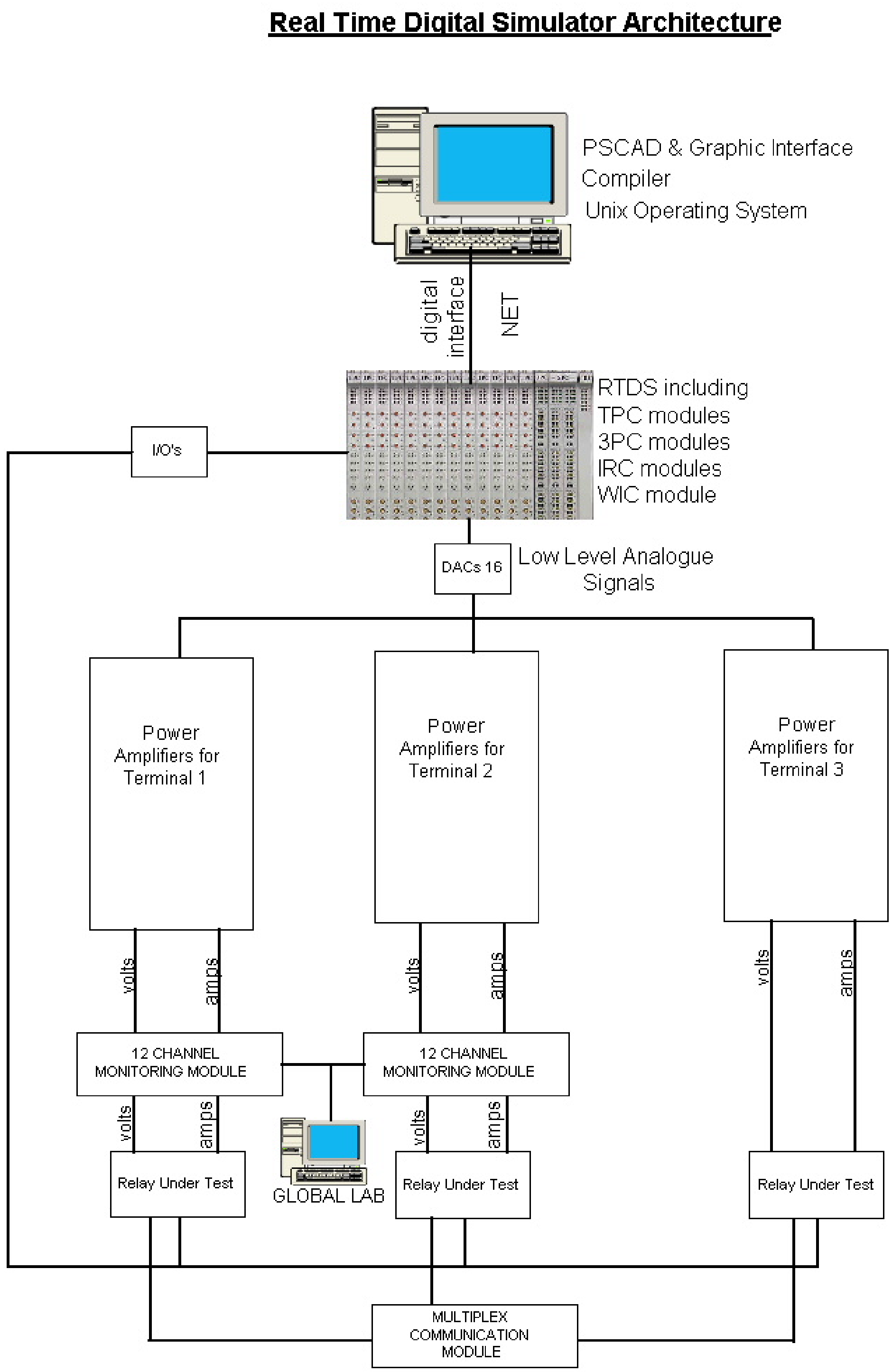

Figure 3. Architecture of the digital simulator.

Figure 4. Digital simulator used in testing.

5.2. Phasor Estimation and Frequency Tracking

The relay samples currents and voltages at 64 s/c. Current signals are pre-filtered using an optimized MIMIC filter for rejection of d.c. components as well as off-nominal frequency oscillatory signal distortions. The filter outperforms classical numerical MIMIC filters in terms of filtering quality. A different pre-filter optimized for voltages and their distortions is applied to voltages.

Current and voltage phasors (magnitudes and angles) are filtered using full- and half-cycle Fourier filters, respectively. Third harmonic in the voltages – required for stator ground fault protection – is estimated using the full-cycle Fourier working on raw voltage samples.

Frequency tracking algorithm is based on zero-crossing detection of a composite voltage signal. The selected signal is a Clarke transform equivalent to the positive-sequence voltage. Owing to the Clarke transformation, the frequency is tracked correctly during VT fuse fail conditions and other abnormal situations. The relay starts tracking frequency from 3 Hz using the voltage signal as low as 3V secondary. The frequency tracking and metering algorithms are fast enough to keep with a 10Hz/sec ramp in frequency. At the same time a robust post-filtering is applied that guards the relay from frequency tracking errors resulting from phase shifts and other abnormalities.

True RMS values are also calculated based on raw samples and can be used as effective inputs to certain thermal protection elements. Symmetrical components, power and energy metering and many other functions are incorporated.

5.3. Stator Differential Protection

Stator differential protection is based on a dual-slope dual break-point differential characteristic. In addition, the element incorporates CT saturation detection. The saturation detector responds to any external fault even without actual CT saturation. The detector will not trigger on any internal fault even if the CTs saturate. When saturation is declared, the relay would check phase relation between the neutral- and terminal-side currents: if both currents are significant, the angle between them must be less than 90 degrees to issue permission to trip. If only one current is significant, permission is granted without checking the angle. This solution is based on bus differential protection [7] and ensures superior performance on external faults saturating the main (or relay's) CTs.

The response time to internal faults is between half and full power system cycle.

5.4. Stator Ground Protection

Third harmonic neutral undervoltage, or differential third harmonic elements provide stator ground fault protection. The latter compares third harmonic components in the neutral of the machine and in the zero-sequence voltage at the terminals of the machine. Power supervision (window) is incorporated allowing sensitive settings on machines that have their third harmonic content varying significantly as the exported power changes.

5.5. Other Function

A standard set of generator protection features has been implemented. This includes accidental energization, loss of excitation, current unbalance, overexcitation, etc. These functions have been tested as described below.

6. Sample Test Results

6.1. Stator Phase Faults

The model generator is placed on-line. An internal phase-to-phase fault is applied at various locations on the stator. The machine load is also varied. The operating time of the relay is measured. The location of the fault is specified from the neutral of the machine and is recorded as a percentage of the total stator impedance (i.e. in test A: 14% of winding A to 6% of winding B).

Table 1. Sample Test Results for Stator Phase Fault Protection.

Test	Faulted Phases	Location	Load (W)	Operate Time (ms)
A	a-b	14%-6%	300	8
B	b-c	6%-29%	400	11
C	c-a	29%-14%	500	9
D	a-b	50%-50%	500	9
E	b-c	50%-50%	400	9
F	c-a	50%-50%	300	11
G	a-b	100%-100%	300	9

H	b-c	100%-100%	300	9
I	c-a	100%-100%	300	10

Figure 5 presents an internal fault example showing a sub-cycle operating time of the stator differential protection element.

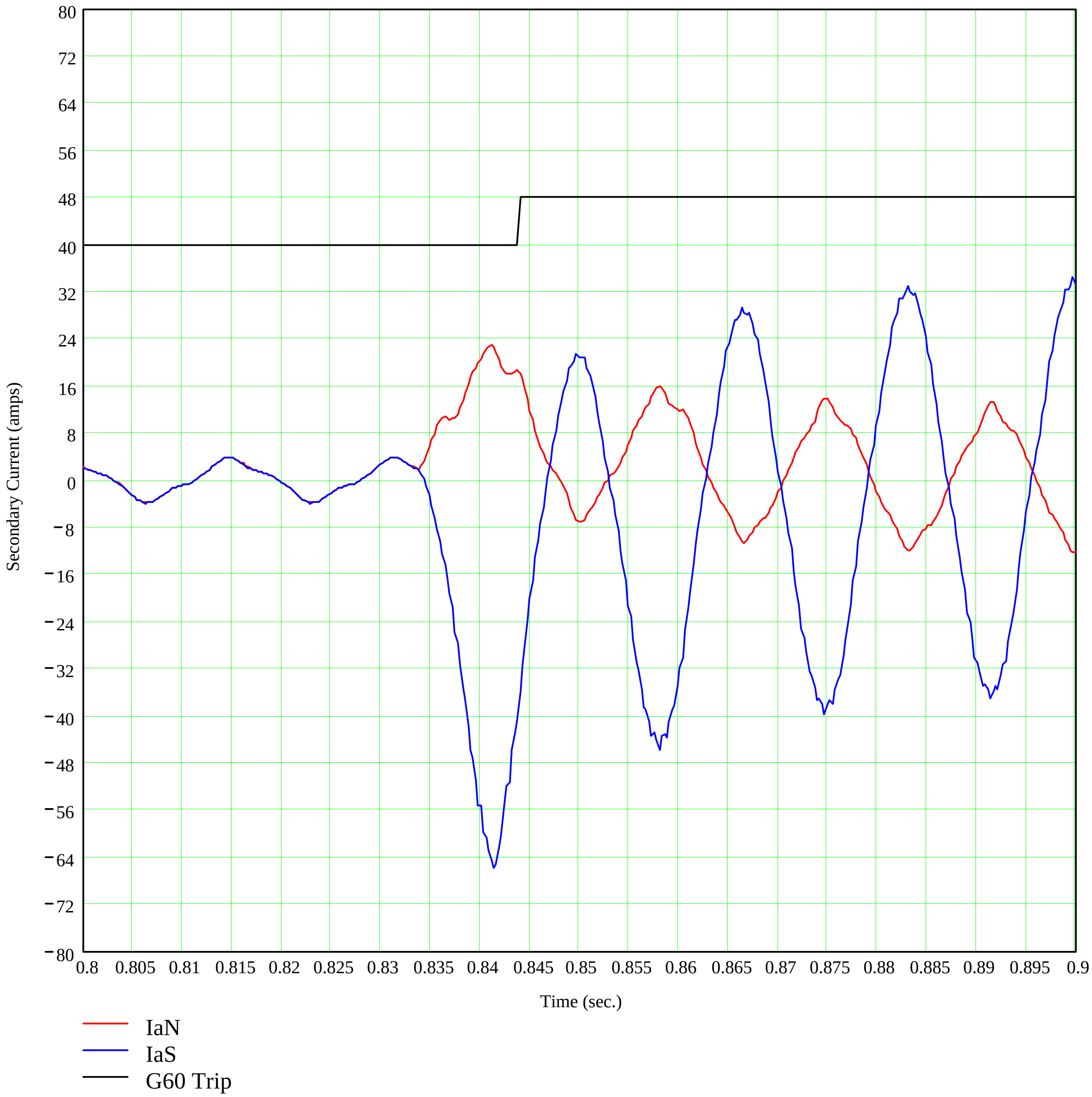

Figure 5. Sample stator phase fault.

6.2. Stator Ground Faults

In this test, the model generator is placed on-line. A ground fault is applied at various points on the stator of the machine. The operation of the fundamental overvoltage (59N) and third harmonic undervoltage (27TN) elements are verified.

Table 2. Relay Response to Stator Ground Faults.

Test	Faulted Phase	Location	Operate Time (s)	Elements Operated
A	A	14%	1.0	59N, 27TN
B	B	6.4%	1.0	59N, 27TN,
C	C	29%	1.0	59N

The model generator is placed on-line. A fault is applied at the neutral point (100% stator ground) at various levels of power. Pickup is set just below the available 3rd harmonic voltage. The power-blocking window is set at 140-210 watts.

Table 3. Sample Test Results for Stator Ground Fault Protection.

Test	Pickup	Power (W)	Operate Time(s)	Elements Operated
A	0.09	75	5.0	27TN
B	0.09	175	NA	None
C	0.09	245	5.0	27TN

6.3. Loss of Excitation

The model generator is placed on-line. In tests A-E, the excitation is switched off. The loading of the machine will determine the path of the impedance locus into the relay characteristic resulting in a zone 1 or zone 2 operation (see Figure 6 for an example). In test F, the AVR is switched to manual and the excitation is reduced until an operation occurs.

Table 4. Sample Test Results for Loss of Excitation Protection.

Test	Generator Load	Zone	Operate Time (s)
A	100	2	14.121
B	200	2	8.41
C	300	2	6.577
D	400	1	4.934
E	500	1	3.673
F	300	2	17.59

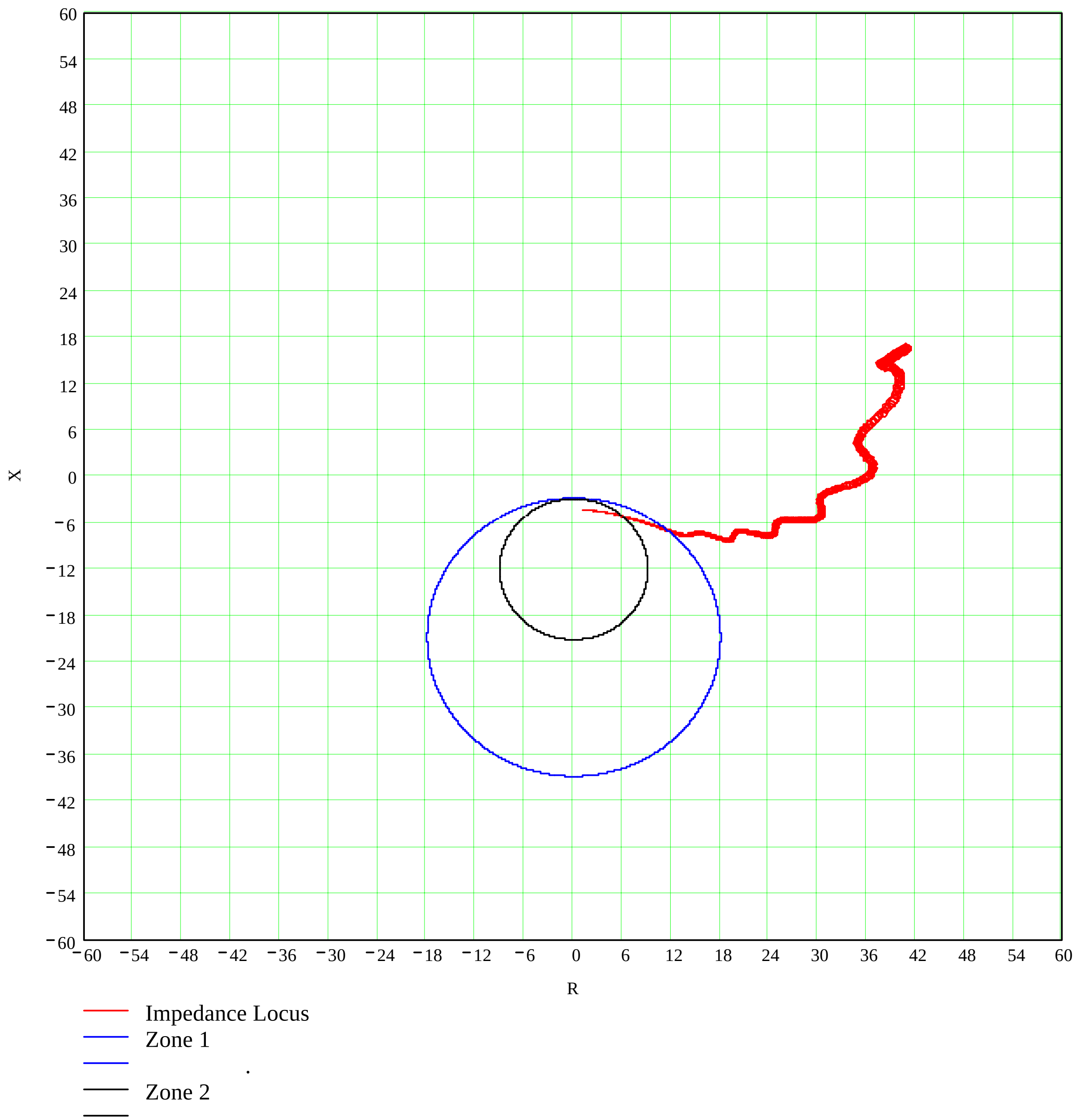

Figure 6. Sample impedance locus during loss of excitation conditions.

6.4. Current Unbalance

In this test the model generator is placed online. Placing an open-phase at a point between the generator and the system creates an unbalance. As the open phase is moved closer to the generator the percentage of the negative-sequence current (I_2) increases accordingly. The reset column specifies the time elapsed from the previous fault. For reset times less than 240 seconds, the element will maintain thermal memory and the tripping time will be reduced accordingly.

Table 5. Sample Test Results for Current Unbalance Protection.

Test	I_2 (pu)	Reset	Pickup	TDM	Operate Time (s)
A	0.1	240.0	0.068	21.63	984.0
B	0.08	240.0	0.068	2.163	150.0
C	0.08	58.0	0.068	2.163	35.8
D	0.04	240.0	0.025	15.38	678.0
E	0.04	123.0	0.025	15.38	345.0
F	0.138	240.0	0.025	15.38	56.0
G	0.138	178.0	0.025	15.38	42.0

6.5. Over-excitation

In this test the model generator was placed off-line. Alternately increasing the system voltage or decreasing the system frequency creates an over-excitation condition. The reset column specifies the time elapsed from the previous fault. For reset times less than 30 seconds, the element will maintain thermal memory and the tripping time will be reduced accordingly.

Table 6. Sample Test Results for Over-Excitation Protection.

Test	Voltage	Frequency	Reset	Operate Time (s)
A	70	40	30	13.2
B	70	30	15	13.8
C	80	60	30	114
D	90	60	7.5	5.4
E	100	60	30	10.3

6.6. Abnormal Frequency

The model generator is placed off-line and the frequency is alternately increased and decreased from nominal.

Table 7. Sample Test Results for Abnormal Frequency Protection.

Test	Frequency (Hz)	Operate Time (s)
A	56	0.115
B	57	0.50
C	58	10.0
D	59	50.0
E	61	50.0
F	62	10.0

G	63	0.50
H	64	0.110

6.7. Abnormal Voltage

The model generator is placed off-line and the voltage is alternately increased and decreased from nominal. The overvoltage element has a definite time characteristic. The undervoltage element has an inverse time characteristic. Correct operation of these elements is verified.

Table 8. Sample Test Results for Abnormal Voltage Protection.

Test	Voltage (V)	Operate Time (s)
A	85	30.1
B	50	105
C	45	53.6
D	40	36.2
E	35	27.3
F	30	21.8
G	25	18.2

6.8. External Faults with CT Saturation

Immunity of stator differential protection with respect to CT saturation and switch-off transients, as well as the combination of the two, was tested.

The relay performed exceptionally well due to its dedicated CT saturation and directional principles. Figure 7 illustrates a typical sequence of events under deep CT saturation: an external fault is detected first and signaled by setting the STATOR DIFF SAT flag; directions of the neutral and terminal currents are sensed as opposite and the directional principle resets its permission to trip by resetting the STATOR DIFF DIR flag; when the CTs start to saturate, differential current appears jeopardizing security of the relay (the STATOR DIFF PKP flag is set meaning the operating characteristic is entered). A typical differential protection (without any dedicated countermeasures) would misoperate at this point. The relay under test does not misoperate owing to its operating logic (**OPERATE** = **PKP** AND (**DIR** OR NOT(**SAT**)).

7. Conclusions

Generator protective relays are one of the most critical protection applications. A relay that could inadvertently reject, say 800MW generation, can cause a lot of damage to the power system. Criticality of generator protection could be only compared to protection of very critical lines, EHV busbars, and large step-up transformers.

At the same time a generator relay includes a number of protection functions. These protection elements can be tested individually using a 50/60Hz injection from a test set.

It is important, however, to validate new relay designs by testing complete relaying application dynamically either on an analog made-to-scale machine or a digital simulator. Only in this way complex interactions within the machine and its control system, and within the protective relay could be fully tested in a variety of operating conditions.

Comprehensive dynamic testing is also the best environment for comparative testing between legacy devices and alternatives from various vendors.

This paper discusses major test requirements for generator relay testing and presents sample test results for a new generator protective relay. The new solution has been tested using both a unique analog simulator and state-of-the-art digital simulator.

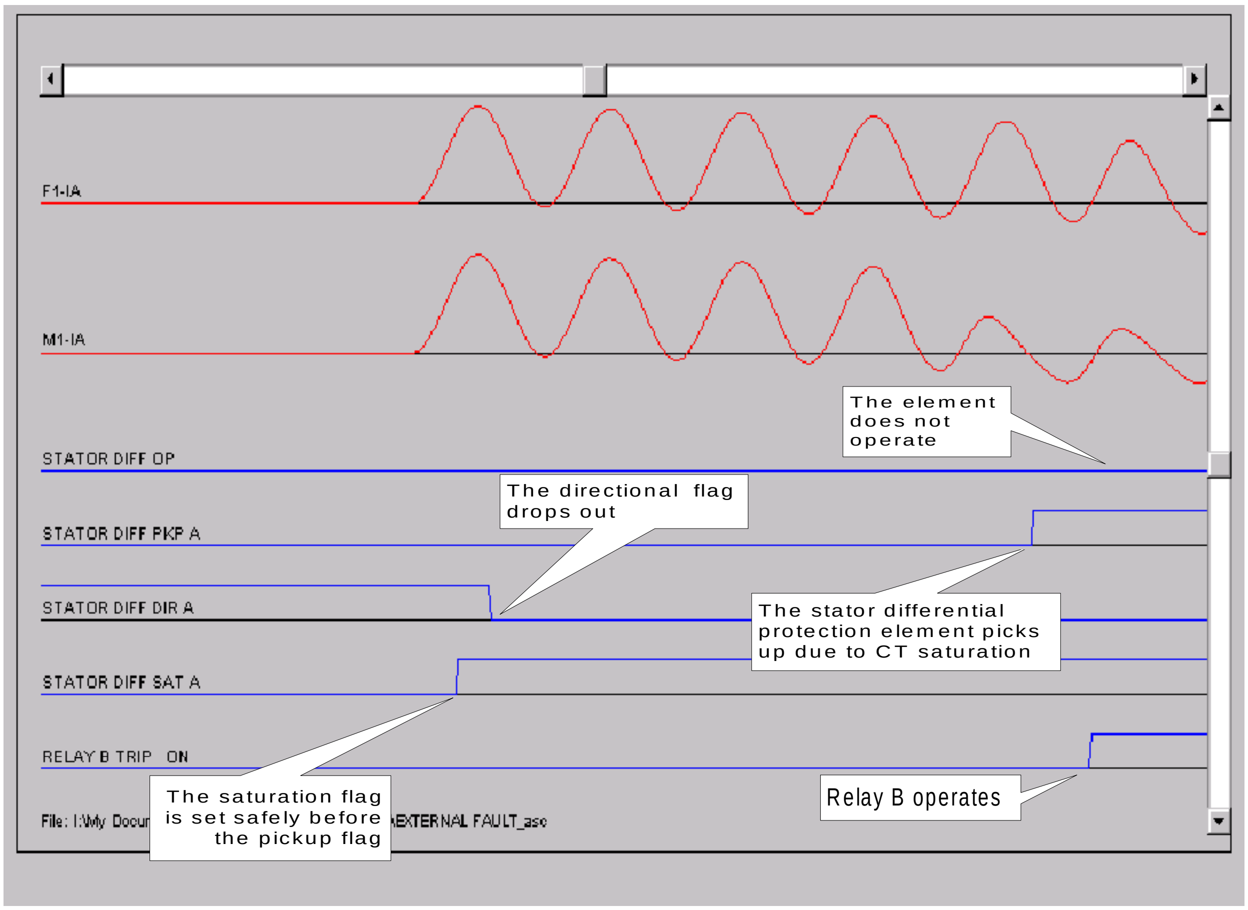

Figure 7. Sample external fault case with CT saturation caused by extremely long d.c. time constant. The relay under test is secure (STATOR DIFF OP flag). Typical protection tested in parallel misoperates (RELAY B TRIP ON flag).

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