Modern Protective Relay Enables Generator Operating at Wide Range of Frequencies and Different Phase Rotation

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***Abstract*— This paper presents application and performance of microprocessor-based protective relay when applied to a bi-directional generator. The two-shaft gas turbine drives the generator to deliver energy to local load or to the grid. This generator is unconventional in design and operation with the capability of delivering power at a wide range of frequency as low as 10Hz and different phase rotation. Traditional generator protection when applied to such generator application faces several challenges, such as:**

- **Performance limitation of instrument transformers at low-frequency operation**
- **Frequency impact on the phasor estimation**
- **Reduction in the output capability of the generator with respect to frequency – impacting power-based protection functions**
- **Change in the generator output voltage with respect to frequency to maintain the V/Hz ratio**
- **Improper operation of unbalance protection due to change in phase rotation**
- **Varying load flow level and direction results in the improper operation of protection functions like out-of-step, loss of excitation, reactive power, power factor, distance protection, etc.**
- **Ability to switch phase rotation for pumped storage applications.**

Keywords— Generator protection, off-nominal frequencies, load-bank, phasor estimation, test bench

I. Introduction

Nova LT16 GT is a two-shaft gas turbine designed for mechanical drive and power generation applications. The turbine delivers 16.5 MW shaft output power. It is ideally suited for pipeline compression – with direct coupling to the latest PCL pipeline compressors featuring high performance stages. As part of the R&D process the turbine needs to be tested and validated throughout the widest possible range of loads and frequencies.

The gas turbine is connected to a generator that delivers energy to a resistor load bank or the national grid. To speedup R&D cycle, two twin turbines are connected to a bidirectional generator, see Fig. 1. Only one turbine runs at a time. The unavailability of one turbine, or the results analysis of one turbine does not avoid keeping on testing with the remaining one.

A generator connected to a set of load-bank packs or the national grid will provide the resistance torque to the turbine.

The generator is a GE Power Conversion synchronous 4 poles machine with a rated output of 22 MVA and rated voltage of 10.5 or 13. 8kV with a static excitation system. The generator is cooled by water.

Generator voltage regulation along with the number of resistance packs will provide the required load for each test. Load steps can be easily provided adjusting generator voltage to the required load or adding or removing resistor packs depending on the type of load steps needed for the test.

Generator will be connected to the grid for the endurance tests. This will allow to sell the electricity generated to the grid and reduce test costs. For the dynamic tests or other specific tests, the generator will be connected to the resistor bank.

Generator protection relay is used to prevent the generator from electrical failure or if not possible, the mitigation of that electrical failure.

There are IEEE Standards covering generator protection which provide guidance material on generator protective relaying. For this application, main references used include [1], [2] and [3].

Modern protection relay not only provides protection against the short circuit conditions but also provides a control protection and monitoring solution. Generator protection devices provides:

- Primary protective elements

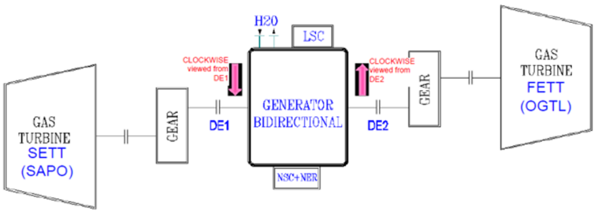

Fig. 1. Test bench layout

- Protection against generator abnormal operating conditions
- Back-up protection

Primary protection elements are those primarily provided to protect against in-zone faults of any type.

Second main group are those related to an abnormal machine operation. These operating conditions can be the result of internal issues (strictly related to the generator), related to the control systems of the turbo generator or purely an external issue.

Back-up protection elements provide back-up to the primary protection elements, the AVR, the turbine governor and the system being distance protection (ANSI 21) or phase overcurrent with voltage restraint (ANSI 51V) the most common of the system back-up protections.

This paper is reviewing the challenges and capability of the generator protection relay and its performance when applied to the non-conventional system as some of the system parameters (voltage ratios, frequency and phase rotation) will vary over the operation [4], [5] and [6].

Challenges that may arise when applying the protection relay to non-conventional generator-turbine systems.

- Impact of the forward to/from reverse phase rotation on protection functionality and measurements like power, sequence components and directionality.
- Performance limitation of instrument transformers at low-frequency operation
- Frequency impact on the phasor estimation
- Reduction in the output capability of the generator with respect to frequency – impacting power-based protection functions
- Change in the generator output voltage with respect to frequency to maintain the V/Hz ratio
- Improper operation of unbalance protection due to change in phase rotation
- Varying load flow level and direction results in the improper operation of protection functions like out-of-step, loss of excitation, reactive power, power factor, distance protection, etc.
- Ability to switch phase rotation for pumped storage applications.

Protection IED is aided by an external control system to properly enable the corresponding protection parameters. The system at higher levels is able to validate the actual settings against the expected settings based on actual measurement values. If the testing mode does not correspond with the frequency, rotation system or voltage range expected for the test based on voltage and currents coming from different instruments, the system will raise an alarm avoiding proceeding further with the test.

Section II discusses various test modes under which generator protection relay performance is checked. Section III reviews the protection, control and monitoring functions available in a typical modern protection relay. Section IV discusses various challenges followed by the conclusions.

II. TESTING MODES

The generator will go through five different testing modes:

- “K-SET 1”. Resistor Load Bank. LOAD (FETT-OGTL).
- “K-SET 2”. Grid Operation. GRID OPERATION (FETTOGTL).
- “K-SET 3”. Resistor Load Bank. LOAD (SETT-SAPO).
- “K-SET 4”. Resistor Load Bank. LOAD (SETT-SAPO).
- “K-SET 1*”. Motoring test. LOAD (FETT-OGTL).

Voltage ranges, frequency ranges, rotation system along with prime mover are described below:

1) “K-SET 1”. Resistor Load Bank. (FETT-OGTL)

The turbo-generator is directly connected to a Resistor Load. It will operate throughout the following conditions

Voltage test range: 0 – 10.5 kV
Frequency test range: 25 to 65 Hz
Generator Phase rotation system: Counter Clock Wise ACB
Generator moved by: Turbine Nova LT16 FETT at OGTL

2) “K-SET 2”. Grid operation. (FETT-OGTL)

The turbo-generator is connected to the national grid. It will operate throughout the following conditions

Voltage test range: 10.5 kV
Frequency test range: 50 Hz
Generator Phase rotation system: Counter Clock Wise ACB
Generator moved by: Turbine Nova LT16 FETT at OGTL

This test mode will be primarily used for the endurance tests.

3) “K-SET 3”. Resistor Load Bank. (SETT-SAPO)

The turbo-generator is directly connected to a Resistor Load. It will operate throughout the following conditions

Voltage test range: 0 – 13.8 kV
Frequency test range: 25 to 65 Hz
Generator Phase rotation system: Clock Wise ABC
Generator moved by: Turbine Nova LT16 SETT at SAPO

4) “K-SET 4”. Resistor Load Bank. (SETT-SAPO)

The turbo-generator is directly connected to a Resistor Load.

It will operate throughout the following conditions

Voltage test range: 0 – 10.5 kV
Frequency test range: 25 to 65 Hz
Generator Phase rotation system: Clock Wise ABC
Generator moved by: Turbine Nova LT16 SETT at SAPO

5) “K-SET 1”. Motoring test. (FETT-OGTL)*

The turbo-generator is directly connected to a Resistor Load. It will operate throughout the following conditions

Voltage test range: 0 – 2.2 kV
Frequency test range: 10 Hz
Generator Phase rotation system: Counter Clock Wise ACB

The scope of the test is to check if the turbine can operate at 10 Hz delivering and approximate output of 300 kW for an hour. The idea is to verify if it is feasible to eliminate the need of a turning gear. This will reduce initial capital expenditure (Capex) and subsequent operation and maintenance costs.

To simulate above condition not only the turbine will explore marginal operation but the generator and the protection control unit as well.

III. A Typical Modern Generator Protection Relay

Fig. 2 shows a typical state-of-the-art modern generator protection system with various protection functions. 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.

It can be inferred from the above tables that today's modern generator protection system facilitates multiple protection, control, and automation functionalities with diagnosis and self-test features.

IV. Discussion on the Protection Challenges

A. *Off-nominal frequency operation*

There are two special concerns when off-nominal frequencies are addressed from a strict protection perspective: low frequencies, high frequencies and frequency rate of change. Higher frequencies in the test was set-up to 65 Hz according to the maximum allowable over-frequency setting so this posed no major threat. Frequency rate of change did not pose great risks as the tests did not require great rates of change. On the other hand, low frequencies posed several challenges.

The first impact that must be assessed is the performance of CTs, specially at low frequencies that is the case of some of the tests.

Conventional voltage transformers as well as current transformers are not indicated for frequencies of 10 Hz. As per

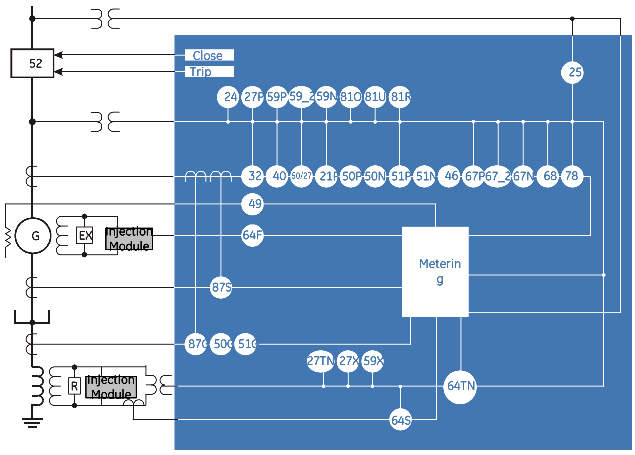

Fig. 2. A typical multifunctional generator protection system

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)

tests at laboratory with an injection test set, greater errors than those of the instrument specifications are expected and will need to be assessed if acceptable for the test as the generator will be operating off-limits from operation, protection and control point of view [8]. Additionally, error not only from the generator protection units are expected but from the current transformers as well.

The current transformer knee point voltage is reduced as frequency is reduced [7] and [8]. According to the Faraday's law, law, the rate of change of flux linkage is equal to induced electromotive force.

$$E = N\frac{d\Phi}{dt} \tag{1}$$

For a sinusoidal voltage, flux is also sinusoidal

$$\Phi = \Phi_{max}\sin(2\pi f t) \tag{2}$$

$$E = N\frac{d\Phi_{max}\sin(2\pi f t)}{dt} \tag{3}$$

$$E = 2\pi f N \Phi_{max}\cos(2\pi f t) \tag{4}$$

The e.m.f. is proportional to the frequency so the voltage required to produce the same flux density given the same current transformer for a frequency f_2 is:

$$E_{f1}f_2 = E_{f2}f_1 \tag{5}$$

$$E_{f2} = \frac{E_{f1}f_2}{f_1} \tag{6}$$

If we consider f_1 the nominal frequency of 60 Hz and f_2 the testing frequency of 10 Hz we get that the voltage is reduced to 1/5th when compared to the nominal, shown in Fig. 3. So, CT capability to withstand saturation at such low frequencies is reduced significantly.

Moreover, magnetics used in the relay as current transducers are also current transformers. Therefore, performance of relay current transducers at low operating frequencies is important to analyze before addressing the impact of low operating frequency at relay protection functions.

Ref [8] shows that at very low frequency (2Hz) operation, relay current transducers can saturate, as shown in Fig. 4. Though such a low frequency operation is not possible in generator application, but it is important to properly analyze the relay transducer performance at the lowest frequency possible.

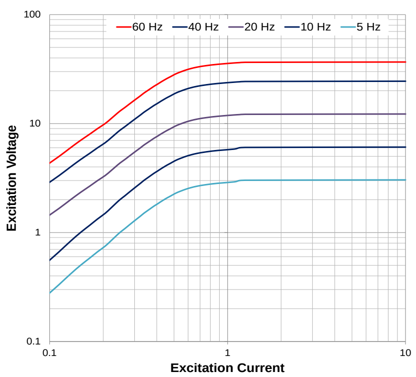

Fig. 3. Measured V-I characteristic for 60, 40, 20, 10 and 5 Hz motor operating frequencies [8]

However, the impact of low frequency is not just limited to CT saturation but also impacts phasor measurements, metering and monitoring elements. This has a direct impact on the performance of the protection functions and settings.

The second impact we must assess is the frequency response of phasor estimator at the IED level. A typical digital Fourier transform (DFT) phasor estimator under off-nominal frequency looks as follows:

Oscillation will increase according to the difference between the actual frequency and the "nominal" frequency set-up in the IED. However, if IED includes the frequency tracking feature it can accommodate actual frequency to the phasor estimator and eliminate phasor estimation oscillation. Even if frequency tracking feature is enabled there will be an unavoidable transient that will occur during the adapting time (few cycles) so frequency change rate is also a factor to consider.

These both factors have been considered so that:

1. Special attention has been applied to protection functions using phasor estimation.
2. Settings have been adapted for the low frequency operation. Pick-up levels and delay times have been reduced according to the new scenario

It can be easily inferred that saturation issue because of de-rated CT capability at low frequencies as well as operation times because of saturation and 10 Hz wave period deviates from standard settings and so these factors have been included in the pick-up levels and time delays.

Considering above circumstances the pick-up levels and delay times were set conservative and bordering the "control" or specific test operational ranges enhancing dependability.

Typically, RMS- or DFT-type estimators are used to calculate phasors for the current based short circuit protection functions in the modern generator relays. Current based short circuit protection elements that use DFT-type phasors to detect the presence of higher levels of fault currents will be affected. This issue can be solved by using the RMS-type estimator complemented with a peak sample detector to detect the maximum fault current level, but such estimator accuracy will not be great.

For example, over-current protection typically uses fundamental currents (DFT-type) to detect short circuit. Performance of the overcurrent protection can be impacted at the low frequency operation. Fig. 5 shows that when CT is properly selected considering low frequency operation,

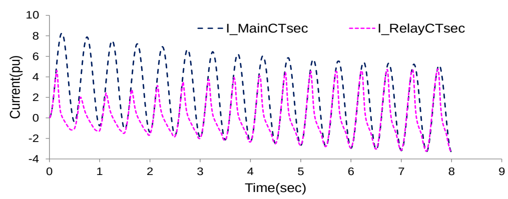

Fig. 4. Testing of the internal current transformer of the relay when (a) input signal is transient and undistorted, (b) input signal is transient and distorted [8]

overcurrent correctly operates as soon as the primary current reaches the pickup level. However, in case of CT saturation, secondary current doesn't replicate the primary current and reaches the pickup level after 33msec, resulting in the delayed operation of the overcurrent, which can result in the delayed operation of the overcurrent in short circuit conditions.
This problem can be solved by (1) proper selection of current transformer (2) lower setting of the overcurrent pickup level.

Differential protection performance during an external fault: Single- or dual-slope characteristic and higher pickup are typically used to prevent mal-operation of the differential protection in the event of an external fault with CT saturation. However, it won't impact the differential operation because both ends CTs see the same low frequency currents resulting in zero or very small false differential current measurement.

Many of the today's digital relays provide multi setpoint groups; when required protection, settings can be switched to different settings for a different operating condition [1]. In varying system parameters (voltage, frequency, angle) conditions, adjustment to the protection settings can be achieved by automatic switching between groups at different system parameters levels.

B. Tailoring the protection scheme for each test mode

A single protection IED is used to protect the generator on the 4 possible configurations.

"K-SET2" test mode does not differ from a standard generator protection scheme.

"K-SET1", "K-SET3" and "K-SET4" protection schemes differ from standard ones as those provided by IEEE C37.102 [2]. There is no relevant effect on application of IEEE C37.101 [1].

Under this configuration there is no possibility of:

- Importing active power
- Importing reactive power
- Power Swing
- Accidental Energization

Loss of excitation, reverse power, accidental energization and phase under voltage remain disabled for "K-SET1", "KS

The "K-SET1*" mode also known as motoring test is the most challenging one due to the off-nominal frequency impact on protection measurements.

All the sets are managed by 5 Grouped Elements which are activated by digital inputs hardwire coming from turbine control panel depending on the testing mode.

A logic to reverse phase sequence rotation is done when relay receives the activation of K-SET1 and K-SET 2. This allows proper functionality of generator unbalance protection, which uses negative sequence currents and proper functionality of several protections which implement positive and negative sequence supervision elements. For example, internal VT Fuse Failure algorithm depends on current positive sequence detection and voltage positive and negative sequences. Distance protection also uses voltage and current supervision elements for voltage memorization for polarization. Similar supervision elements based on phase sequences apply to power swing protection, loss of excitation and 100 % stator ground protection with third harmonic comparison.

Phase distance is active as system backup in K-SET2 when connected to the grid. Backup protection for K-SET 1, KSET3 and K-SET 4 is performed through an instantaneous overcurrent.

Stator differential protection, generator unbalance and 100 % stator ground protection share the same settings.

Neutral overvoltage, phase overvoltage, overexcitation protection and frequency protection elements are set depending on each voltage and frequency ranges at each group.ET3" and "K-SET4".

V. Conclusions

The Generator protection system has faced several

challenges:

- Protection accuracy and reliability at low frequencies
- Phase rotation systems among the different configuration groups
- Four settings groups with complete different settings. The possibility of an error when issuing the group setting command from the DCS is not negligible

Generator protection was able to adequately measure currents and voltages through the 5-65 Hz range. Providing degraded but acceptable protection at low frequency for Research and Phase rotation and settings group validation checks were available at higher control levels, this allowed extra security as expected operation mode was checked against actual operation mode parameters.

Additionally, the tests were used to perform voting techniques for the analog measurements. These techniques, commonly used with control devices, provided enhanced security to the operation at protection level.

VI. References

[1] C37.101 IEEE Guide for Generator Ground Protection

[2] C37.102 IEEE Guide for AC Generator Protection

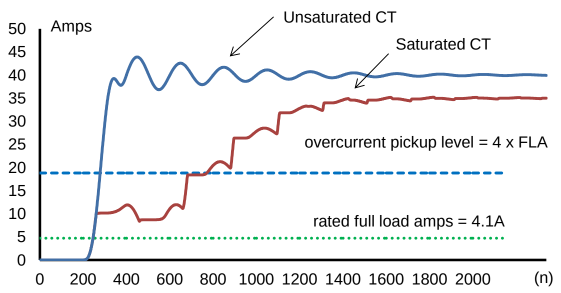

Fig. 5. Sinusoidal and RMS Measurement of the Steady State Short Circuit Secondary Current

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