Injection-Based Generator Stator Ground Protection Advancements

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Abstract—**Generators are critical production assets responsible for reliable power system operation. Generator faults are very costly and may require months of repair time before a generator goes back online. Compared to the potential loss of revenue and the cost of generator component repairs, protection system costs are hardly detectable on the same scale. It is therefore no surprise that generators are protected using the absolute best technology available at any given time.**

This paper takes an in-depth look at the injection-based stator ground protection principle, reviews state-of-the-art techniques, and reports on a novel standalone injection-based relay capable of offering 64S 100 percent stator ground protection all of the time. The paper then presents the field experience of this 64S relay on a 50 Hz system at Generación Riojana S.A., Argentina.

I. INTRODUCTION

Large generators are critical power system resources capable of influencing the stability of an entire geographic region. Given the fault energies involved, the potential asset damage, and the costs associated with generator repair, generator protection is seen as a key ingredient for ensuring reliable power system operation. Generator protection functions normally include stator ground (64S), field ground (64F), current differential (87G), loss of field (40), thermal overload (49), synchronism check (25), out of step (78), and others [1]. Relay misoperation (false trip or failure to trip) is highly undesirable and leads to extended outage times, expensive shutdown, costly repairs, loss of generation capacity, lost revenue, and potentially compromised network security.

One hundred percent stator ground protection represents an important part of the generator protection package. The injection-based method provides better coverage than the third-harmonic-based approach in applications lacking third-harmonic content. Injection-based systems are capable of detecting stator faults at rest, while idled on a turning gear, or at full speed, and they are applicable to a wide range of high-impedance grounded generator configurations.

This paper starts with a summary of generator grounding. It reviews stator ground protection methods and summarizes the most popular injection-based solutions in the field. It then looks at injection signal requirements and documents field experiences with a new injection-based protection system having improved fault coverage during generator startup, dual-redundant injection capability (Main 1 and Main 2), and improved measurement accuracy.

II. GENERATOR GROUNDING METHODS

The primary objective of generator grounding is to limit and control transient overvoltage, minimize damage for stator ground faults, and limit generator contribution to a phase-to-ground fault.

Multiple grounding methods are used in practice. Reference [2] lists the following:

- High-resistance grounding:
  - High-voltage neutral grounding resistor.
  - Distribution transformer with low-voltage neutral grounding resistor on the secondary side.
  - Grounding transformer at the generator terminals with low-voltage grounding resistor on the secondary side.
- Medium-resistance grounding with three-phase grounding transformer (delta-ground-wye).
- Low-resistance grounding (neutral grounding resistor).
- Low-reactance grounding (neutral grounding reactor).
- Hybrid grounding (low-resistance to high-resistance switching).
- Resonant grounding.
- Ungrounded.
- Effectively grounded.

Grounding resistor calculations can be found in [3] and [4]. Fig. 1 shows the tradeoff between the grounding resistor value and the maximum transient overvoltage stress that will be imposed on the stator winding. While the ultimate decision is left to the designer, the most common solution is to make the grounding resistance equal to the total capacitive reactance to ground. This approach results in conservative but well-accepted calculations (Xcg = Rg).

The terms in Fig. 1 are defined as follows:

Rg = grounding resistance (total).

$\mathrm{Xcg} = 1/\left(2\pi f_{\mathrm{nom}} \mathrm{Cg}\right)$.

Cg = total capacitance to ground (all three phases).

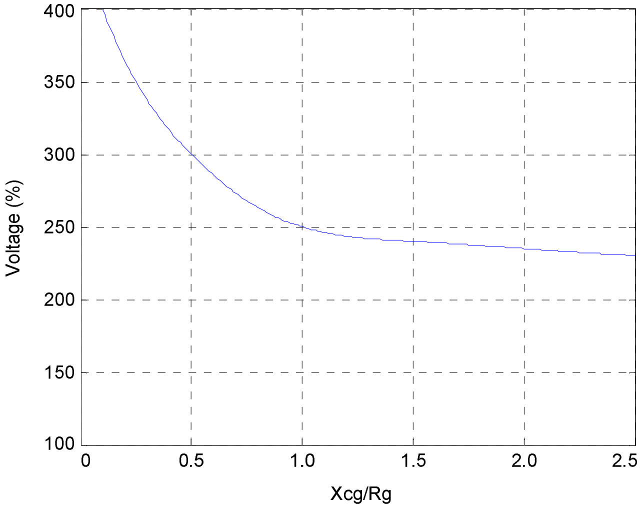

Fig. 1. Transient overvoltage as a function of grounding resistance [3]

III. STATOR GROUND FAULT PROTECTION

The need for stator ground protection was identified very early, back in the days of directly connected low-voltage machines [5]. Initial protection schemes were combined with the grounding resistor and included nonlinear resistors created using light bulbs, ground overcurrent relays, and wattmeter-based designs. Injection-based systems gained popularity with the advent of higher-voltage generators connected to a unit transformer [6] [7]. Additional protection methods in use today include the neutral overvoltage element (59GN), the third-harmonic undervoltage element (27TN), and the third-harmonic differential element (59THD).

Fig. 2 shows the coverage of various protection schemes. The neutral grounding resistor (NGR) overvoltage scheme (59GN) is simplest and provides reliable coverage for ground faults in the upper 90 to 95 percent of the winding. Faults close to the neutral terminal unfortunately generate insufficient voltage and need to be detected using other methods.

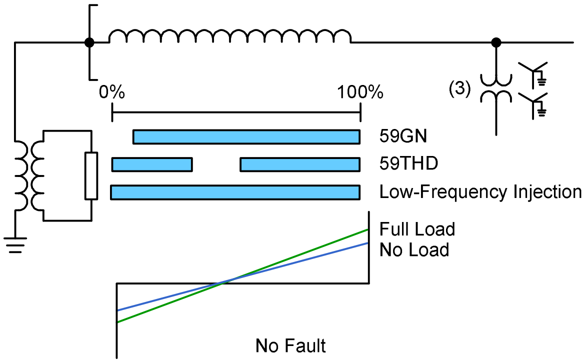

Fig. 2. Comparison of stator ground protection methods

Because the ground fault impedance can vary widely, coverage for 100 percent of the winding is accomplished by combining a 59GN element with a third-harmonic-based or injection-based scheme.

Most modern microprocessor-based relays include third-harmonic-based elements (27TN and 59THD), making them very cost-effective compared with injection-based schemes. However, as the description implies, they do rely on the third-harmonic voltage for reliable performance. Factors influencing the available third-harmonic voltage include the generator design, load and terminal voltage, potential transformer (PT) connection, neutral ground impedance, and distributed capacitance to ground [8] [9].

Injection-based schemes do not rely on third-harmonic voltage and have the additional advantage of being able to operate at a standstill or while the generator is on the turning gear. This allows for continuous supervision and reliable detection of stator winding insulation failure before the generator is put online.

Due to its ability to minimize winding damage, high-impedance grounding is by far the most popular method for grounding large generators. Injection-based 100 percent stator ground protection can be used only with high-resistance grounding methods (such as those listed in Section II).

Fig. 3, Fig. 4, and Fig. 5 show typical high-impedance generator grounding methods and the associated injection current source (I_SRC) attachment methods.

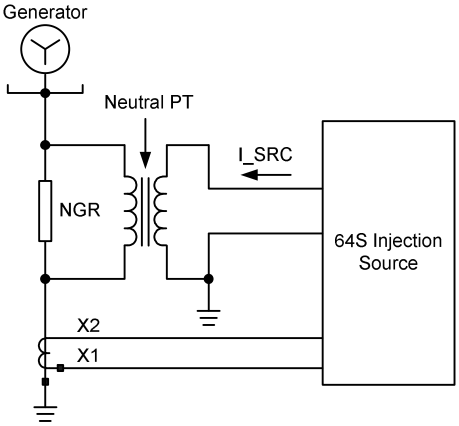

Fig. 3. High-voltage grounding resistor with PT-based injection (I_SRC)

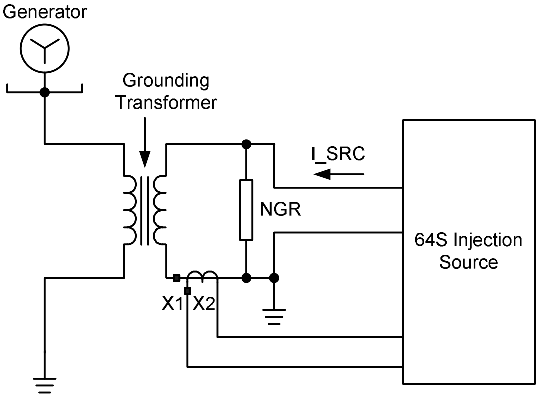

Fig. 4. Low-voltage grounding resistor on the grounding transformer low-voltage side

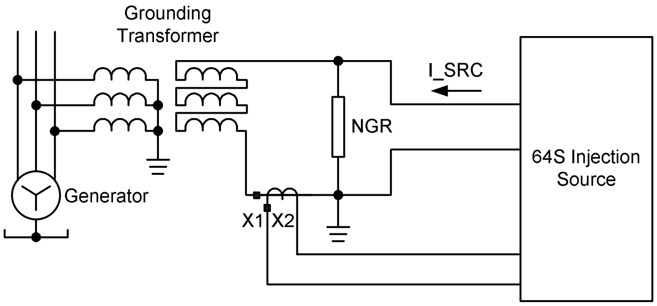

Fig. 5. Grounding transformer at the generator high-voltage terminals

For operator safety, the source injection voltage reflected on generator winding terminals is typically kept below 50 V. This prevents accidental injury in cases when the generator is de-energized and at a standstill while the injection source is still active. Regardless of the low voltage level, appropriate lockout/tagout procedures are required and must be followed with all injection-based systems.

IV. PRINCIPLES OF INJECTION-BASED STATOR GROUND

A. *Problem Definition*

Injection-based stator protection is in essence an impedance measurement method that must operate in the presence of power system harmonics, interharmonics, and power system faults. Because the measurements are needed at generator standstill, the source must inject its own power (active method) and be immune to variable-frequency swept sine disturbances such as those present during generator ramp-up. Measurements are made more difficult by the stator winding capacitance, which makes it advantageous to use low-frequency signals (10 to 120 Hz) because high-frequency signals would be effectively shorted to ground. In addition, the injection source should not interfere with normal generator operation and must be capable of riding through and surviving generator faults. Generator ground faults above 5 percent of the stator winding are in effect attempting to backfeed the injection source, making it necessary to devise additional methods to prevent injection source damage. Backfeed voltage can be as high as 240 Vrms with the fault at the generator terminals.

Fig. 3, Fig. 4, and Fig. 5 illustrate the additional difficulties faced by injection-based stator ground systems, namely the presence of a grounding resistor. The grounding resistor is connected in parallel with the generator winding leakage impedance to ground, which needs to be measured. The grounding resistor dissipates most of the injected power. Several designs in the past have used alternate attachment methods with the injection source connected in series with the generator grounding system. Although advantageous in terms of the required injection source power, the introduction of additional components in the generator grounding circuit is seen as an unnecessary complication or deviation from standard design practice and has been abandoned over time. Modern injection sources are therefore expected to work with standard high-impedance grounding arrangements.

Injection source requirements can be summarized as follows:

- No dc component (transformer coupling requirement).
- Immunity to electric noise and outside disturbances.
- Ability to operate with highly capacitive load.
- Ability to drive the grounding resistor.
- High power output (50 to 100 VA, continuous).
- High efficiency.
- Long design life.
- Overload protection (backfeed, open and short circuits).
- 2,500 V isolation.
- Electromagnetic compatibility compliance (low susceptibility and emissions).

B. *State-of-the-Art Injection Systems*

Modern injection systems [8] [10] [11] use low-frequency signals, typically in the vicinity of 20 to 25 Hz, with power electronics used to produce square wave outputs. A series resonant circuit tuned to the injection source frequency may further be used to turn the square wave into a sinusoid and prevent power system frequency backfeed from damaging the source. High-power resistors connected in series may also be used to help with this task. One design uses a coded square wave with a quiet period between coded bursts that helps separate the stator ground impedance measurements from the background noise present in all real-world applications. Another recent design [10] moves the injection frequency higher—to 87 Hz in a 50 Hz power system—further improving the system ability to operate during generator startup.

Most commercially available designs to date use a dedicated injection source, have single injection frequency, and rely on a simple square waveshape. The stator ground protection function (64S element) is delegated to the generator protection relay.

Although initially appealing, the lack of injection signal standardization among different manufacturers has created unnecessary relay specialization, resulting in the generator relays from one manufacturer being unable to operate with an injection source from a different manufacturer.

New power electronics technologies made available over the past decade make it possible to reinvestigate some of the basic premises of injection-based stator ground protection and take a fresh look at the best way to accomplish the task. Injection source efficiency can be significantly improved by using the latest Class D pulse width modulated (PWM) high-frequency switching amplifiers. Switching amplifier technology enables the use of arbitrary injection waveform shapes, making it possible to improve overall system performance.

C. *Injection Signal Design*

The stator winding leakage impedance can be measured by using a large number of injected signal waveshapes. The transformer coupling shown in Fig. 3, Fig. 4, and Fig. 5 makes it necessary to build a precise ac ohmmeter. From an application standpoint, it is also desirable to measure both resistive and capacitive components of the leakage impedance, meaning we need a vector measurement device. Assuming we can precisely measure the injection source current, the grounding resistor voltage, and the portion of the injected current circulating through the stator winding capacitance, the Fourier transform can be used to separate the real and imaginary components of the leakage current.

The most popular injection signal choices used for in-circuit system identification include the following [12]:

- Step signal, impulse.
- Band-limited noise.
- Pseudo random binary sequence (PRBS).
- Swept sine (frequency sweep).
- Multisine.

Typical waveshapes and their associated spectral contents are shown in Fig. 6. The figure starts with the band-limited noise signal, followed by the pseudo random binary sequence signal and the popular swept sine signal, which is often used to measure linear system frequency response.

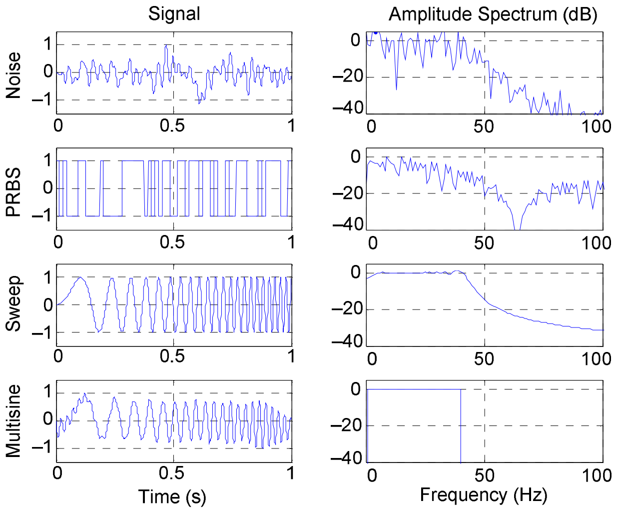

Fig. 6. Most popular excitation signals with their spectral properties [12]

While relatively simple to generate, swept sine signal-based measurements tend to be more complicated, resulting in an unnecessary algorithmic burden. Pseudo random binary sequence is very easy to generate, but has significant high-frequency content and would make it difficult to measure the winding capacitance. A similar problem occurs with white band-limited and gated noise signals.

Fig. 6 purposefully omits the step and impulse signals because their low signal-to-noise ratio limits their use primarily to theoretical analysis. The last signal on our list, multisine, offers an interesting set of properties. It is very similar to (even looks like) swept sine, but instead contains a set of discrete, equidistant frequencies that are amenable to Fourier transform-based processing. Multisine is widely used in spread-spectrum communications and forms the basis of orthogonal frequency-division multiplexing (OFDM). Multisine offers an exceptionally high signal-to-noise ratio and can be tailored to the application. Similar to code division multiple access (CDMA) spread-spectrum radio signals, multisine is very resilient to single-frequency interference. This property makes it a natural choice for systems that must be immune to swept sine interference seen during large generator startup.

D. Schroeder Multisine

A special class of multisine signals is Schroeder multisine, which can be constructed by using the following set of equations.

$$X(t)=\sum\nolimits_{k=1}^{F} A\cos\left(2\pi f_k t+\phi_k\right) \qquad (1)$$

where:

$f_k = k \bullet f_0 =$ component frequencies. (2)

$\phi_k = -k\left(k-1\right)\pi/F =$ individual phase. (3)

$f_0 =$ frequency step (resolution).

$1/f_0 =$ signal period (sequence length).

$F =$ maximum frequency index.

A spectral representation of this signal is shown in Fig. 7, containing a set of equidistant frequency components starting at f_{min} and progressing to f_{max}. All components have the same magnitude, with the individual component phase derived according to (3).

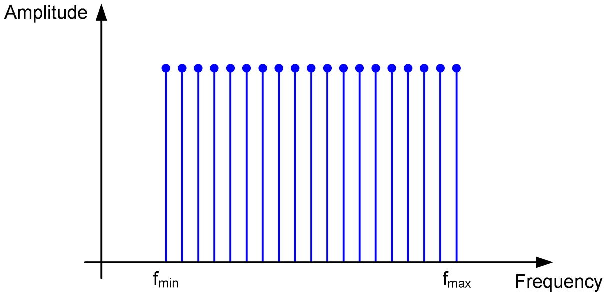

Fig. 7. Spectral view of the Schroeder multisine

The resulting signal has a very favorable peak-to-rms ratio, making it very desirable for robust system identification measurements. Failing to observe (3) results in high amplitude peaks and suboptimal use of the excitation source capabilities.

The resulting signal shown in Fig. 6 looks similar to the frequency sweep. It is repetitive, with a repetition period equal to the minimum spacing between individual frequency components. In practical terms, this means that a multisine signal with a repetition period equal to 0.2 seconds contains sinusoidal frequencies starting with 5 Hz and its multiples thereafter, as shown in Fig. 7.

Another interesting property of the multisine signal is that the number of discrete frequencies it uses can be custom tailored to the application at hand. As the number of frequencies gets lower, the Schroeder phase expression (3) will not offer the optimal peak-to-rms ratio, but can often be used as a good starting point for the subsequent optimization process.

In the case of the 64S injection application, the desire is to create an excitation signal that has good interference rejection without causing an excessive computation burden during the impedance calculation process. The Class D amplifier bandwidth is sufficiently wide to allow arbitrary waveshape injection with any number of components between 5 and 200 Hz.

After investigating the performance of this method for the 64S application, we settled on a set of four frequencies. The multisine repetition period was set to twenty nominal power frequency cycles, with injection frequencies set to 18, 24, 36, and 48 Hz for 60 Hz systems and 15, 20, 30, and 40 Hz for 50 Hz systems. The resulting four-frequency waveform is shown in Fig. 8.

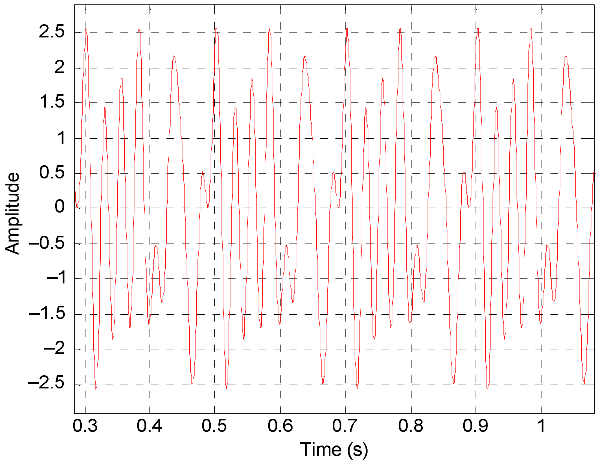

Fig. 8. Four-frequency multisine waveshape

Being set on a uniform frequency grid, the multisine signal frequency components are very well suited for Fourier transform processing. Individual frequency components are orthogonal to each other, ensuring that each frequency can be used to perform an independent impedance measurement. Multiple frequencies mean that multiple measurements can be conveniently combined to minimize external interference.

In the case of injection-based stator ground protection systems, the worst-case interference signal is the swept sine disturbance created while the generator is being brought online with excitation applied. This scenario is common with large cross-compound machines and needs to be addressed in order to prevent 64S element misoperation.

The Fourier transform ability to reject interfering signals is influenced by the type of windowing function used for the data input. Although it is the most popular, a rectangular (uniform) window does not provide adequate protection against a slowly sweeping narrow-band interference. This makes it necessary to use higher-order windows. The proposed design uses the Hann window function characterized by fast side lobe attenuation, ensuring no more than two measurement frequencies are affected at any given time. The quality of the individual frequency measurements is continuously supervised, allowing affected measurements to be discarded ahead of the 64S protection element.

V. LEAKAGE IMPEDANCE MEASUREMENT

Fig. 9 shows a block diagram of the new multisine signal injection source.

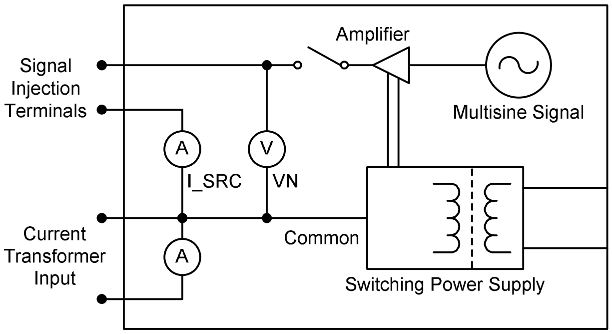

Fig. 9. New injection source block diagram

In order to accurately measure stator insulation resistance, it is important to account for various impedances in the path of the injected current. The majority of these impedances are shown in Fig. 10, including the 64S source wiring impedance (Z_WIRE), neutral grounding transformer impedance (Z_NGT), stator winding capacitance (INS_CAP), and stator winding leakage resistance (INS_RES). It can be seen that the leakage current (I_LKG) is typically a very small fraction of I_SRC. This requires a direct measurement of neutral current (IN) to accurately measure the leakage impedance.

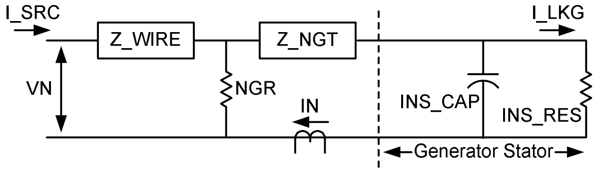

Fig. 10. Equivalent diagram of injected current circuit path

The voltage (VN) and currents (I_SRC and IN) are directly measured. However, other parameters must be measured and saved as part of the field commissioning and calibration process. Fig. 11 shows a signal processing diagram depicting discrete Fourier transform (DFT) and a measurement block used to calculate various impedances and the stator winding insulation resistance.

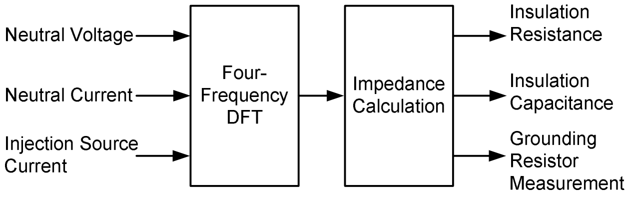

Fig. 11. Signal processing block diagram

The four-frequency multisine signal does not depend on one frequency for reliable performance and allows for computation of the insulation resistance, even during a generator start with field applied.

The Class D amplifier is configured to act as a current source, which enables injection source paralleling. Multiple injection frequencies make it possible to divide the workload among multiple injection devices. The features outlined are used to provide fully redundant stator ground protection, as shown in Fig. 12. In the redundant configuration, each device is assigned a two-frequency subset (18 and 36 Hz, and 24 and 48 Hz for the 60 Hz system example).

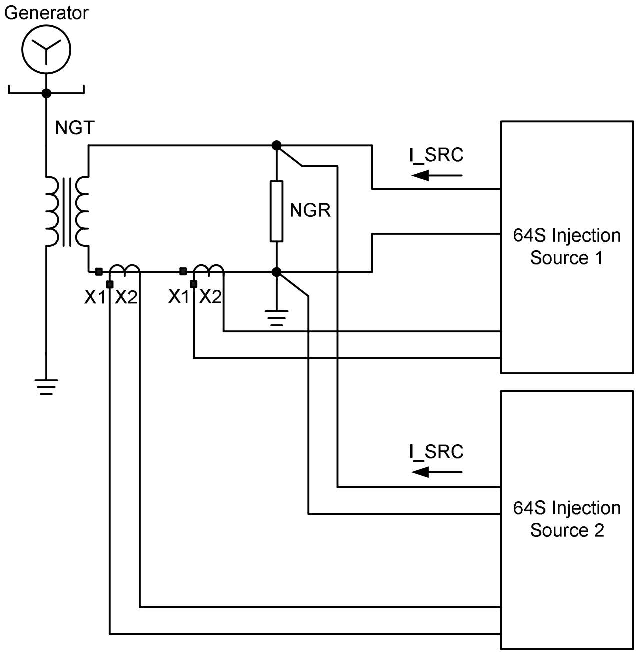

Fig. 12. Fully redundant 64S stator ground protection

VI. BACKFEED PROTECTION

The injection source must be able to survive significant backfeed voltage present during stator faults. Backfeed voltage is determined by the grounding transformer ratio (secondary voltage rating) and can easily reach 240 V for faults at the generator terminals. Some of the solutions in the field use external tuned filters, high-power resistors, and overcurrent relays to temporarily isolate the injection source.

Class D amplifier technology offers an interesting way to accomplish this task. Because the amplifier already operates with high switching frequency (100 to 300 kHz), it is relatively easy to integrate a fast (< 20 microseconds) voltage-controlled disconnect device. With this approach, the injection amplifier is immediately disconnected and shut down as soon as the output terminal voltage exceeds the high power amplifier supply rails. The disconnect switch position is carefully selected such that the switch does not interfere with the neutral voltage measurements. The disconnect switch position is shown in Fig. 9.

VII. SYSTEM INTEGRATION

As explained in Section IV, virtually all injection-based stator ground protection systems that have been built to date attempt to minimize hardware costs by using a very simple, dedicated injection source and by concentrating all measurement functions in the generator protection relay. This has multiple disadvantages, including the inability to precisely control the injected signal, the inability to measure all the desired parameters, the inability to support injection sources from different manufacturers, and the signal degradation associated with bridging the large physical distance between the protection panel and the generator grounding cubicle.

Recent technology advancements and the significantly lower cost of modern electronic hardware allow us to reevaluate this practice and enhance the 64S injection source by equipping it with a modern microprocessor-based relay. This creates a self-contained 64S protection system optimized for mounting in the machine space (in the immediate vicinity of the grounding resistor subsystem).

The resulting stator ground protection system is equipped with built-in tripping contacts and the latest communications protocols, including redundant fiber-optic-based Ethernet, IEC 61850 Generic Object-Oriented Substation Event (GOOSE) capability, Modbus®, File Transfer Protocol (FTP), Telnet, and DNP3.

Integrated protection functions include a 64S injection-based stator ground, 59N ground overvoltage element, 59N rms high-set overvoltage element, and communications link to an optional field ground measurement module (64F protection function). A standalone relay approach allows for easy integration with existing generator protection systems.

VIII. FIELD EXPERIENCE

This section presents field testing results obtained on a 17 MW gas/diesel turbine base generating station. Fig. 13 shows an internal view of a decommissioned prime mover similar to the one used in the tests. The tested unit is housed inside a building with fully protected intake and exhaust manifolds.

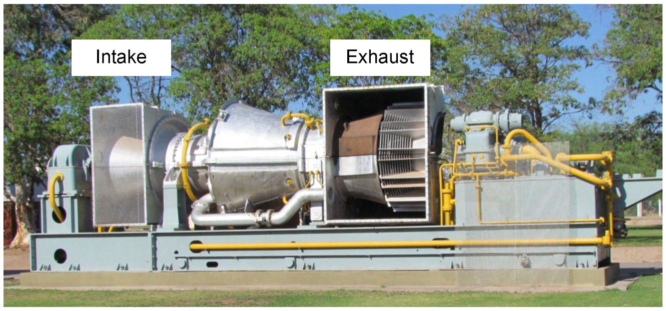

Fig. 13. 17 MW gas/diesel turbine used by Generación Riojana

Fig. 14 shows the 64S protection system installed in the generator exciter cabinet with the grounding resistor and transformer located in the neighboring cubicle.

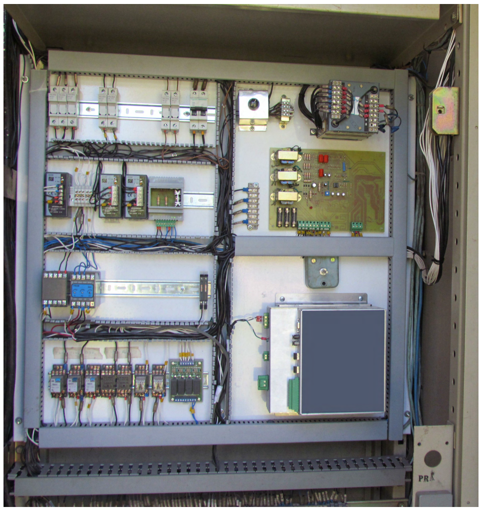

Fig. 14. Control panel cabinet

Tests included the field commissioning and calibration process, staged stator ground faults with the generator offline, generator startup shown in Fig. 15, and normal operations.

During a normal generator startup, the stator ground capacitance measurement and the voltage measurements change as different events take place. As shown in Fig. 15, there is a clear jump in the stator capacitance to ground after the breaker is closed between the generator and the generator step-up transformer. Fig. 15 also shows the voltages at the grounding resistor terminals as measured by the 64S protection system. We see a fundamental component, a third-harmonic component, and the total rms measurement, which includes the 64S injection signal voltage. The stator leakage resistance measurement stays above 99.99 kΩ throughout the test, which is the highest (open circuit) value reported by the protection system.

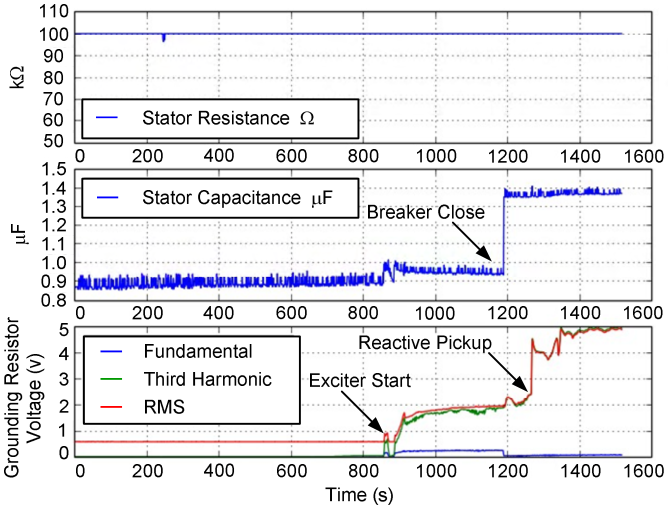

Fig. 15. Generator startup measurements

Fig. 16 shows the frequency spectrum of current and voltage magnitudes recorded at the grounding resistor while the generator is online. This figure puts in perspective the relative magnitudes of the injected signals with respect to the 50 Hz fundamental and third-harmonic components.

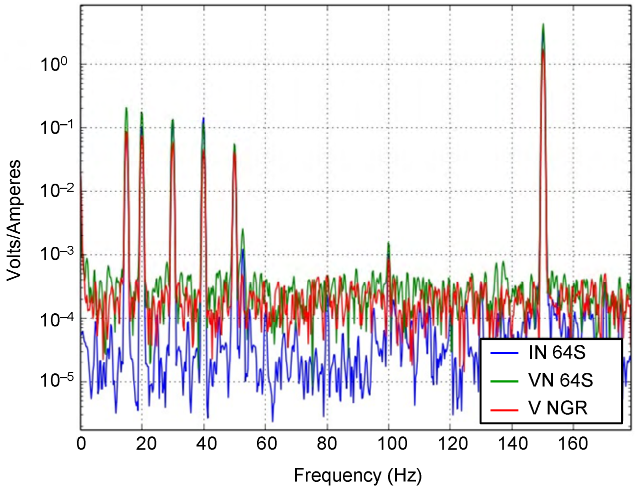

Fig. 16. Frequency spectrum of the current and voltage measured by the 64S protection system and a generator relay

IX. CONCLUSION

Injection-based 100 percent stator ground protection offers the ability to detect stator winding insulation faults regardless of the generator speed or excitation status. This includes detection of faults while at a standstill, on the turning gear, or in full operation. The most recent injection-based systems can also monitor winding capacitance and continuously supervise the grounding system health parameters. New electronic technologies made available over the past decade have made such systems affordable, reliable, and capable of surviving in harsh generator environments.

The authors believe that integrated functionality, improved accuracy, reduced cost, robustness, and the ability to provide fully redundant protection contribute substantially to the safe, reliable, and economical operation of large generator assets.

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XI. BIOGRAPHIES

Pablo Soñez received his BSEE from Universidad Nacional de Córdoba, Argentina in 2007. His areas of expertise include strategic planning, development of preventive, predictive, and corrective maintenance, and generator protection. He began his career at E-LINX S.R.L., designing electronic circuits and programming low-level microprocessor and microcontroller applications. He is currently employed with Generación Mediterránea S.A., a subsidiary of the Albanesi Group, where he commissions thermoelectric power plants.

Fabian Vicentini received his industrial maintenance degree from Universidad Nacional de San Luis at Villa Mercedes, Argentina in 2000 and his electronic technician degree from the Instituto de Enseñanza Superior Leonardo Da Vinci at Río Cuarto, Argentina in 1996. He began his career with Procter & Gamble in 1996, where he worked as a process and maintenance engineer. Fabian currently works with Generación Riojana S.A., a subsidiary of the Albanesi Group, where he oversees the operations and maintenance of generating plants.

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