New Methods for Monitoring Neutral Grounding Resistors

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Abstract — Electrical power systems control arcing current and electrical shock hazard by proper neutral grounding such as high resistance grounding. The high resistance neutral grounding resistors fail due to vibration, intermittent arcs, corrosion, etc. and cause the risk of the system being ungrounded, or solidly grounded. In this paper, two efficient solutions are introduced that provide continuous monitoring of such resistors installed at neutral of two most common configurations of the unit-connected generators. The first proposed method relies on the third harmonic of neutral and residual voltages, and the second technique employs the sub-harmonic injection based generator stator ground protection. The proposed methods show satisfying performance under different conditions of the resistor and generator, observed through comprehensive software analysis and further hardware validations. The first proposed monitoring method has been retrofitted to an industrial generator protection relay which no longer maloperates due to failed-short neutral grounding resistor. Proposed techniques can be incorporated into digital protective relays, which will monitor and alarm in case of the failed grounding resistor.

Index Terms — Neutral Grounding Resistor, Unit-Connected Generator, Signal Injection.

I. Introduction

Neutral Grounding Resistors (NGR) protect power system generators and transformers by controlling the ground overcurrent and transient overvoltages [1]. Integrity and intactness of these apparatuses are necessary to prevent the system from being ungrounded or solidly grounded [2], [3]. As such, the NGRs should be continuously monitored to avoid the false sense of safety, as mandated by Canadian Electric Code (CEC) and National Electric Code (NEC).

The various existing NGR monitoring methods are classified into three categories called passive, active, and passive-active methods. The passive methods utilize the inherent voltage and/or current of the grounding system. The active methods employ signal injection. Lastly, the passive-active methods combine both the passive and active concepts, which results in a very comprehensive solution. There are six different passive approaches under the passive class that are briefly explained:

- **Method P1** — Preventive maintenance is the traditional approach to inspect and ensure the intactness of the NGRs. This method is not known as continuous monitoring since it cannot provide the online status of the NGR and is functional only during the planned inspection [3].
- **Method P2** — The second passive approach relies on the negligible current that appears in neutral system due to inherent asymmetry of the power system. It supervises the presence of

this current and detects the disconnected NGR in the case of absence of the current [2]. This technique cannot identify the partially failed NGR condition.

- **Method P3 —** The resistance of the NGR has been targeted by the third passive approach using the neutral voltage and current obtained by neutral PT and CT, respectively. This method is also not a continuous monitoring since the mentioned measurement instruments cannot measure the very low voltage and current of the neutral system in normal operation condition of the power system where there is no ground fault [2].
- **Method P4 —** The fourth passive approach is, indeed, an enhanced version of the third technique since it uses the residual voltage, obtained by three-phase PTs that are wye-broken-delta connected, instead of neutral voltage. However, it faces the same limitations in the absence of ground faults [4].
- **Method P5 —** As may be known, the continuity of service of the NGRs is mostly necessary during normal operation condition, where the ground faults are yet to happen, to prepare the power system for catastrophic situations such as ground faults. Hence, a well-designed NGR monitoring approach should be able to measure the neutral voltage and current in the absence of the ground faults. The fifth passive method fulfills this requirement using a Sensing Resistor (SR), and a sensitive CT to measure the neutral voltage and current, respectively [2], [5]. As such, the resistance of the NGR becomes available in the absence of the ground faults. Any noticeable drift in NGR resistance is reported as NGR failure. This method is highly of interest. However, it fails to provide NGR monitoring in the presence of the ground faults. Monitoring the status of the NGR during the ground fault is very important in applications that do not de-energize the power network upon occurrence of the first ground fault, which is single-phase-to-ground fault. Such applications limit the ground current using high impedance grounding and locate the ground fault to benefit from the uninterrupted operation. The continuity of service of the NGR, which is still in service, during the first ground fault is critical since the continuity of operation relies on it. The connection diagram of measurement instruments used in this method is shown in Fig. 1(a). When the neutral voltage is very low, the TVS is open and the neutral voltage is directly delivered to voltage measurement points. If a ground fault happens, the neutral voltage increases, and the TVS clamps the voltage across the measurement points to protect the monitoring equipment.
- **Method P6 —** Another sort of the well-designed passive monitoring methods utilizes the Resistive Potential Divider (RPD) for measuring the neutral voltage instead of SR. In addition, the neutral current is measured by a sensitive and a conventional CT. The obtained resistance is certainly valid during the ground faults. In normal operation condition, sufficient voltage at neutral is needed to provide the accurate resistance of the NGR [6]. The measurement points of this method are demonstrated in Fig. 1(b), as well. The measured voltage is scaled-up to obtain the neutral voltage using a scaling factor that is equal to $(R_1 + R_2)/R_2$.

It should be added that the passive methods number 3-6 employ the neutral current supervision logic where the resistance of the NGR is not available. This logic reports failed-short or failed-open NGR conditions when the current becomes sufficiently greater than the neutral let through current (I_{let}),

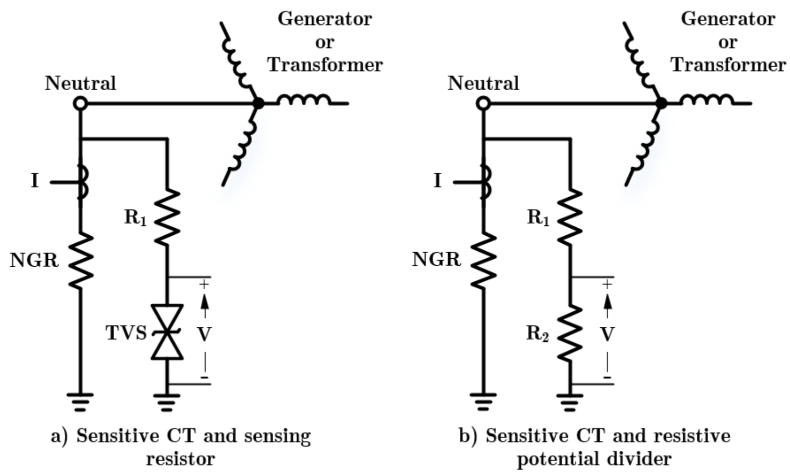

Fig. 1. Connection diagram of the fifth and sixth passive methods [5], [6].

or absent, respectively.

The second category, active methods, includes two approaches as follows:

- **Method A1 —** In the first approach, DC and/or AC signals are injected to the neutral node, and NGR status is monitored by supervising the neutral current level [8]. This method only alarms on failed-open or failed-short NGR conditions since current variations alone cannot imply partial failure of the NGR. The neutral injection system of a wye-connected generator or transformer is shown in Fig. 2. The injected and monitored current is equal to E/r where r is called logic resistor that is used to convert the injected current to a voltage that can be measured by the monitoring relay.
- **Method A2 —** The enhanced version of the previous technique relies on the resistance of the NGR obtained using the injected signals [7]. Any drift in NGR resistance is identified reliably resulting in an interesting solution. In this case, the NGR resistance is equal to rV/E. It should

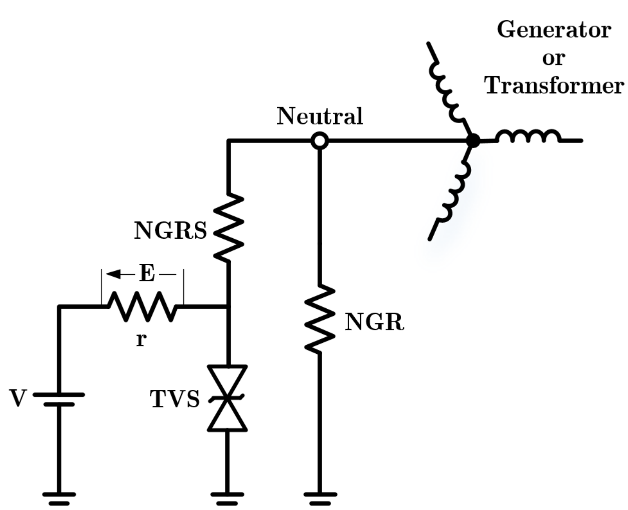

Fig. 2. Connection diagram of the active methods [7].

be noted that if multiple AC and DC signals are injected, the resistance at different frequencies becomes available that support different applications such as monitoring the NGR continuity during the start-up procedure or de-energized condition.

The issues associated with the active methods are: 1) they cannot monitor in the presence of the ground faults since the protection means of the injection system decouple the monitoring relay from the neutral node for safety issues, and 2) the injection circuit can fail itself resulting in malfunction and complexity, i.e., the need for monitoring the monitor.

As elaborated, the active methods operate reliable in the absence of the ground faults while the passive methods function properly in the presence of the ground faults. Therefore, any feasible combination of the passive and active methods, hereafter called passive-active methods, will result in the best performance. For example, the combination of the sixth passive method with the second active method results in a monitor that operates reliably in both normal and faulted conditions. This category of NGR monitoring methods are expected to emerge in near future.

The existing and anticipated NGR monitoring methods are represented in Fig. 3. This figure shows the evolution of the art of NGR monitoring, as well.

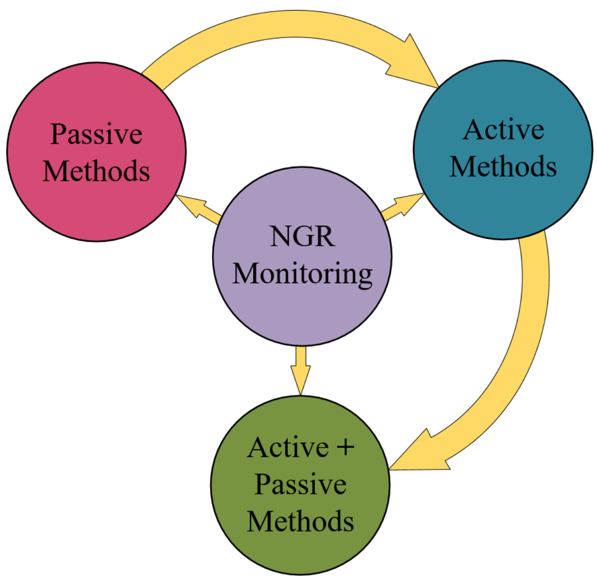

Fig. 3. Existing NGR monitoring methods and concepts.

In this paper, the NGR at neutral of unit-connected generators is monitored using both passive and passive-active methods depending on the configuration. The proposed passive method, which relies on the third harmonic of the neutral and residual voltages of the generator, is used for generators that lack the signal injection based generator stator ground protection. However, a passive-active method will be used for the generator equipped with the mentioned injection system.

II. Proposed Monitoring Technique for Configuration 1

A. Fundamentals of the proposed technique

The studied power system configuration is shown in Fig. 4. It consists of a high-resistance-grounded generator that is connected to high voltage system via a DYn transformer bank. This configuration is hereafter referred to as unit-connected generator. The neutral of the generator is connected to earth using a single phase Neutral Grounding Transformer (NGT) and a very low-resistance resistor that is installed at the secondary of the NGT. As a result, the neutral is high-resistance-grounded. The inherent and unintentional phase-to-ground capacitances of the generator and delta side are shown by c_g ad c_s, respectively. The generator terminal phase-to-ground voltages, neutral voltage, and neutral current are usually available for this configuration since the generator control, and protection systems need these parameters. The neutral grounding system of this generator is monitored using these measurements and the following proposed method.

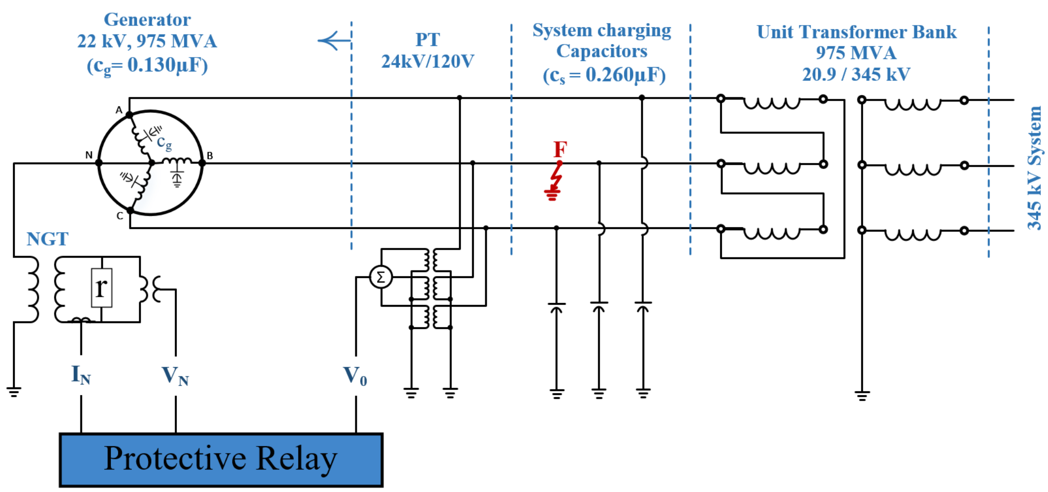

Fig. 4. Configuration 1: high-resistance-grounded unit-connected generator lacking neutral signal injection [9].

The proposed monitoring technique functions in both normal and faulted conditions of the power system. In the presence of the ground faults, the neutral voltage and current are accurately measured by neutral PT and CT. Hence, its resistance is available. The proposed monitoring method uses this resistance to monitor the NGR during the ground faults in the same way as the third passive method. In unfaulted condition, the proposed monitoring technique employs the third harmonic of neutral and residual voltages. The simplified third harmonic model of the configuration is shown in Fig. 5. In this figure, R represents the total resistance between the neutral and ground points. Furthermore, the $-jX_N$ shows the capacitive reactance related to half of c_g lumped at neutral side of the generator stator winding. The $-jX_T$ shows the capacitive reactance related to the other half of the c_g in parallel with c_s lumped at terminal side of the generator stator winding. Lastly, the E_3 is the third harmonic voltage that is generated by the generator.

The first criterion used for NGR failure detection is the opposite change of the third harmonic of the neutral and residual voltage phasors represented by V_{N3} and V_{R3}, respectively. In fact, when the R

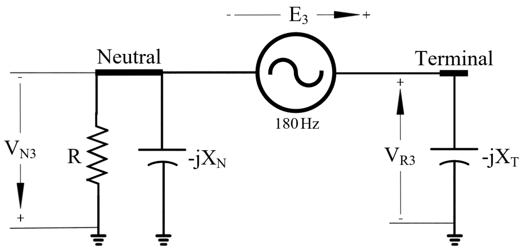

Fig. 5. Simplified third harmonic model of the configuration 1.

increases, the V_{N3} is expected to increase based on resistive potential division law. As a result, the V_{R3} has to decrease. Hence, it is concluded that if the V_{N3} increases and V_{R3} decreases, the NGR is failing short and vice versa. The second logic is the quicker acceleration of the magnitude of V_{R3} in case of any change in NGR resistance, i.e., R. In fact, the generator terminal side is more capacitive than the generator neutral side. Hence, the V_{R3} is expected to show a quicker response than the V_{N3} in case of NGR failure.

The ground fault condition can affect the employed criterion for NGR failure detection. This effect is mitigated using another function that distinguishes the ground faults from NGR failure. Practically, the NGR failure is a mechanical or thermal phenomenon that takes time while the ground faults are very catastrophic. Hence, the initiation speed of the two phenomena is the key criteria to distinguish them from each other. In this configuration, the ground faults near the neutral are detected by the third harmonic voltage comparator protection function. In fact, the ground faults are detected if the magnitude of the V_{N3} is less than 15% of the magnitude of E_3 while the magnitude of the V_{R3} becomes greater than 85% of that of E_3 [9]. The 15% and 85% are the pickup settings of the protection function. In this paper, two such ground protection functions are utilized. The pickup settings of the first function, called primary function, are set to 20% and 80%. The second function, called secondary function, operates with a time delay due to its pickup settings set to 15% and 85%. The time difference between activation of the two functions is used to distinguish the ground faults from the NGR failure. If the elapsed time is less than 5 ms, the ongoing disturbance is a ground fault. In fact, this characteristic shows that the parameters are changing very quickly or catastrophically which is expected in case of ground faults. Otherwise, the disturbance is not a ground fault, and the NGR Failure (NGRF) is reported.

B. Validation of the proposed technique for configuration 1

In this section, the proposed monitoring technique is studied using PSCAD in conjunction with Matlab. The studies are conducted for an NGR which grounds the neutral of a wye-connected 975 MW,22 kV generator that is connected to 345 kV transmission system via a 975 MVA,20.9/345 kV DYn transformer. The NGR has been designed based on details provided in [10]. Its resistance is 0.784 Ω which provides high resistance grounding, i.e., R =2400 Ω, when installed at secondary of a 50 kVA,13280/240 V single phase NGT. The generator has been modeled using the six segment per phase distributed pi-model based on [11]. This model provides the opportunity to distribute the generator phase-to-ground capacitances along the winding and also simulating the internal ground faults.

The performance of the proposed passive technique for monitoring the NGR has been investigated for various kinds of NGR degradations considering different modes of operation of the power system. Observations show that it functions reliably detecting the precise status of the NGR. Additionally, the ground faults are well-distinguished from failed-short NGR condition.

A sample case study is shown in Fig. 6 where the NGR fails short. Its resistance decreases from 100% to 5% in two steps, i.e., 100-50% and 50-5% representing consecutive failure of the resistive elements. The $\overline{|V_{N3}|}$ decreases, and $\overline{|V_{R3}|}$ increases showing opposite behavior enabling the first NGR failure criterion. On the other hand, the rate of change of $\overline{|V_{R3}|}$ is greater than that of the $\overline{|V_{N3}|}$ which satisfies the second criterion. As a result, the NGR failure is detected where the NGR resistance is about 1.5 kΩ since both the monitoring logics are satisfied. In fact, 38% drift in NGR resistance is detected which means the proposed technique can identify the partial failure of the NGR. Furthermore, the time duration between the operation of the two stator ground protection functions is clearly greater than 5 ms meaning that the NGR is failed-short.

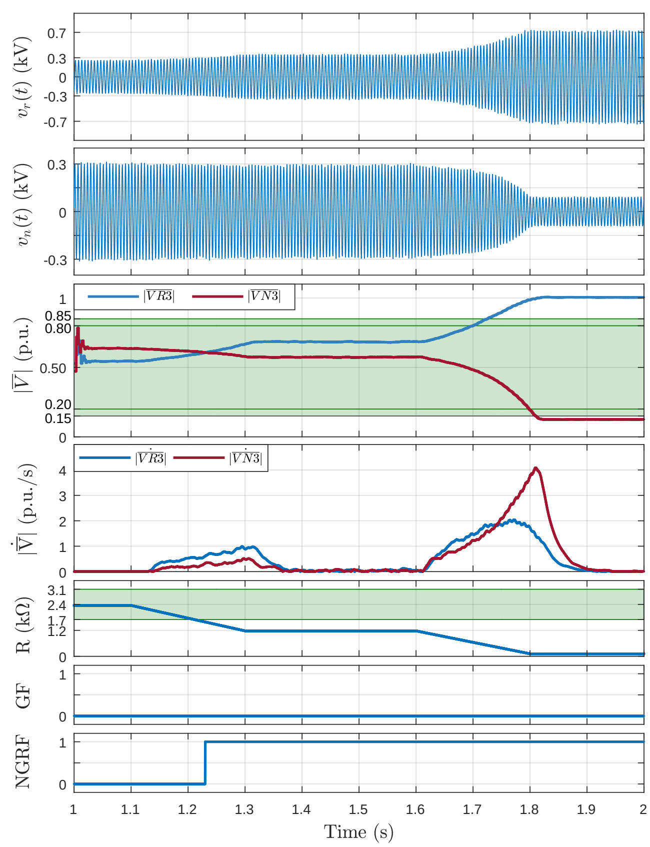

Fig. 6. Failed-short NGR condition in unfaulted system.

The other sample case study is shown in Fig. 7, which shows a failed-open NGR condition in unfaulted condition. Its resistance increases from 100% to 500% over 300 ms. Again, the $\overline{|V_{N3}|}$ and $\overline{|V_{R3}|}$ behave oppositely. Therefore, the opposite change of the parameters is detected. On the other hand, the rate of change of $\overline{|V_{R3}|}$ is greater than that of the $\overline{|V_{N3}|}$ which satisfies the second logic. As a result, the NGR failure is detected where the NGR resistance is about $5.5\,\mathrm{k}\Omega$ since both the monitoring logics are satisfied. As shown, none of the $\overline{|V_{N3}|}$ and $\overline{|V_{R3}|}$ pass through the thresholds of the ground protection functions. As such, the other logic of NGR failure detection is not activated. However, the quicker behavior of the $\overline{|V_{R3}|}$ than the $\overline{|V_{N3}|}$ helped identifying the NGR failure which has been reported $100\,\mathrm{ms}$ after that the resistance of the NGR drifts outside the safe region.

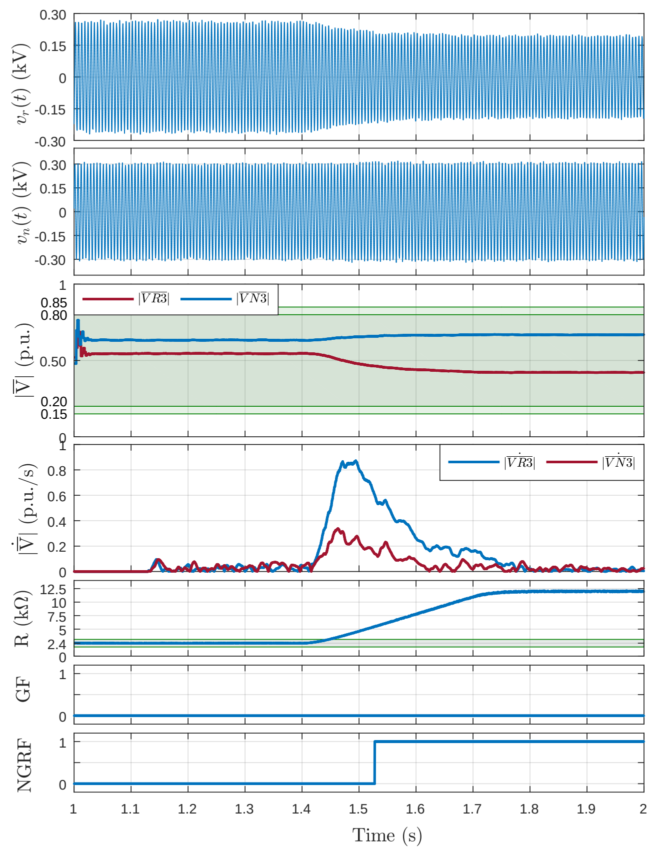

Fig. 7. Failed-open NGR condition in unfaulted system.

As observed, this technique does not use the resistance of the NGR for monitoring; but, it compares the neutral and residual voltages to detect NGR degradation. The studies show that the $\pm 20\%$ change in the resistance of the intact NGR is detected. It should be mentioned that the very slowly failing NGR condition is not detected unless the NGR becomes entirely shorted, which is detected by the elapsed time between activations of the thresholds of the two generator stator ground protection functions.

Distinguishing the ground faults from the failed-short NGR condition is demonstrated using an industrial generator protection relay, as shown in Fig. 8. The NGR failure and ground faults are simulated in PSCAD, and the waveforms are captured using COMTRADE 91. Thereafter, the waveforms are played back to the relay using LabVIEW and National Instrument cDAQ-9178. The prepared experiment is a low voltage injection hardware test setup since the PTs and CTs of the utilized relay are bypassed to be able to focus only on the proposed algorithm and avoid involving the high voltage testing challenges. The time duration between activation of the two 100% stator ground protection functions is captured using a timer. If the timer value is more than 5 ms, the failed-short NGR is reported. Otherwise, the ground fault is detected. This algorithm was added to the relay using the Logic Function Editor Tool that is provided by the relay manufacturer. This tool provides many logical elements that help the researchers to add the devised protection, control, and monitoring functions to enhance or improve the performance of the equipment, as performed here. The outcome of this scheme is interlocked with the ground fault trip signal, which blocks the near the neutral ground fault trip in case of NGR failure detection. The performance of this scheme has been analyzed comprehensively. Observations show that the entirely shorted NGR condition, i.e., at least 90% change in NGR resistance, is well-detected by this scheme except when the NGR fails very quickly. This phenomenon is considered as a ground fault at neutral and reporting NGR failure is not considered as a safe detection for this situation. Following, two case studies are represented which show the performance of the aforementioned algorithm.

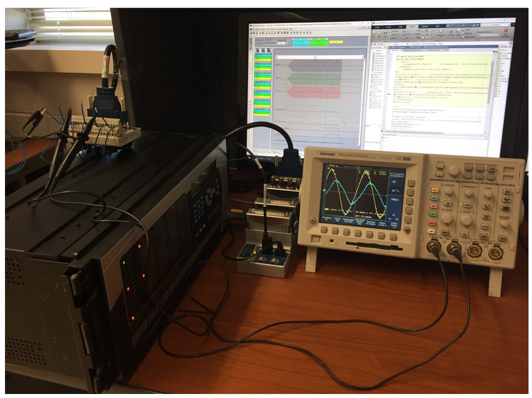

Fig. 8. Hardware test setup.

The first case shows a single-phase-to-ground fault at 5% of the generator stator winding near the neutral. The relay detections are shown in Fig. 9. The three-phase voltages at terminals of the generator and neutral voltage are played back to the relay. The magnitude of the total generated third harmonic by the generator, i.e. E_3 is calculated by vector sum of the three phase-to-ground voltages applied to the relay. As shown, the three phase-to-ground voltages remain unchanged during the single-phase-to-ground fault since the employed high resistance NGR limits the fault current to maximum of 5 A and suppresses the ground fault.

On the other hand, the neutral voltage oscillates with 180 Hz frequency before the ground fault incidence where the magnitude of the V_{N3} and total generated third harmonic voltage by the generator, i.e., E_3, are 208 V and 314 V, respectively. Once the ground fault occurs, the v_n shows oscillations in 60 Hz meaning that its third harmonic has decreased very much, as shown by its magnitude. Since the magnitude of the total generated third harmonic is constant, the $|V_{R3}|$ increases. As a result, the two 100% generator stator ground protection functions are activated. The time duration between activation of the thresholds of the protection functions is very low, i.e., 4.17 ms, as shown in the figure. The red trigger shows the moment that the first 100% stator ground protection function is picked up. There are two other pointers in blue and green. They are mostly used to show the information of specific

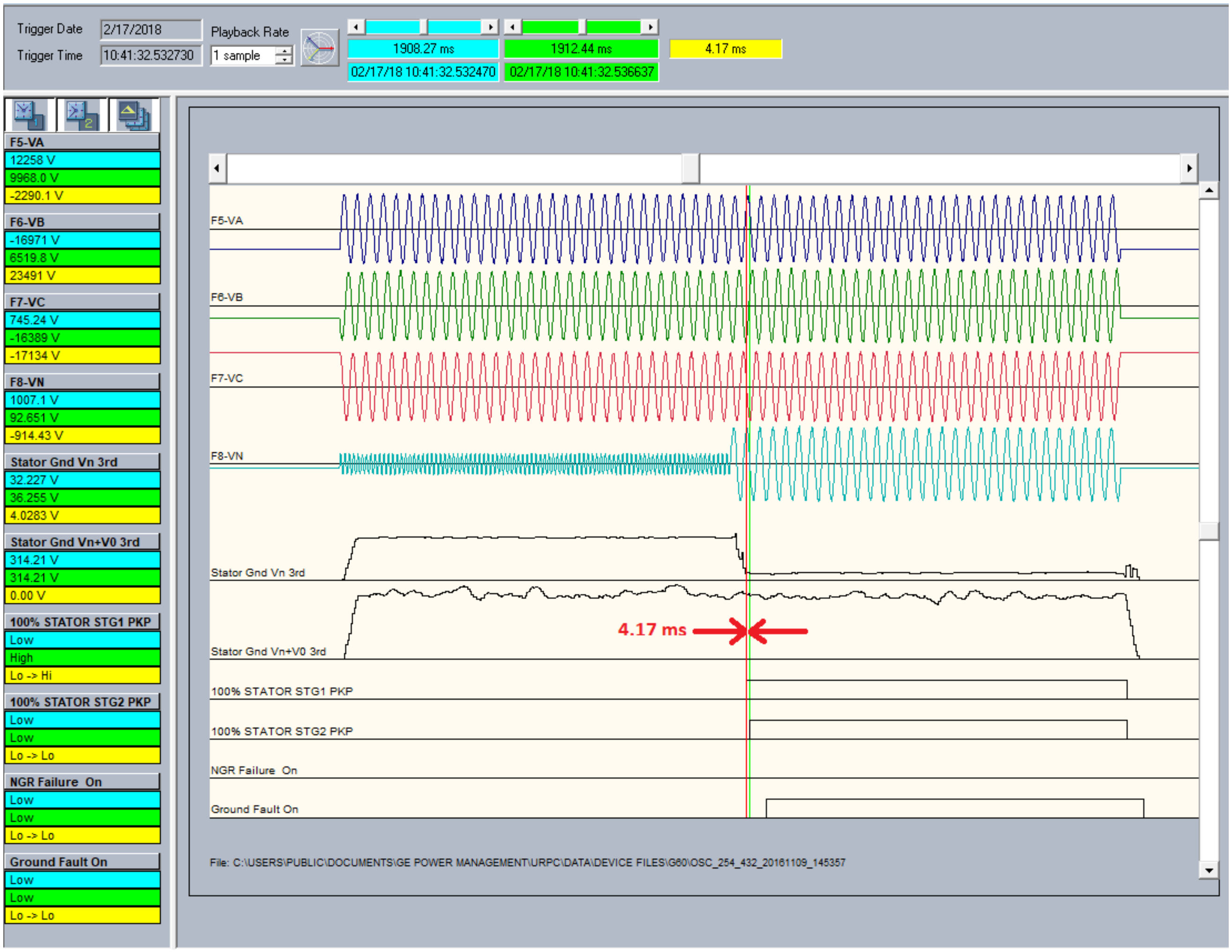

Fig. 9. Relay detections for single-line-to-ground fault at 5% of the generator stator winding.

moments of the waveforms and also the difference between two moments in volts or time. In this figure, the blue pointer is set on the red trigger which shows the moment that the primary 100% generator stator ground protection is picked up. It is not visible due to the red trigger. The green pointer is set at the moment that the main or secondary 100% stator ground protection function is activated. The time difference between the two pointers, i.e., 4.17 ms, is calculated by the relay and is shown in yellow at the top section of the figure. The relay detects the ground fault, and the NGR failure signal remains off since this time difference is less than the predefined threshold, i.e., 5 ms. This 5 ms setting has been obtained though comprehensive studies of ground faults and NGR failure conditions for the chosen relay.

The second case is regarding a failed-short NGR in the absence of the ground faults. In this case, NGR resistance fails short in the same way as shown in Fig. 6, i.e., 100-5% in two steps. The neutral voltage remains low during the entire event, and only contains the 180 Hz oscillation. The phase-to-ground voltages behave the same as the previous case even during the NGR failure. Once the NGR starts failing, the neutral voltage starts decreasing. At the same time, the residual voltage starts increasing. As a result, the primary 100% stator ground protection function, with the pickup settings set to 20% and 80%, is activated. After a time delay, the secondary 100% stator ground protection function, with the thresholds set to 15% and 85%, becomes enabled, as well. The time delay between operation of the two protection functions is 9.9 ms. The monitoring scheme reports NGR failure since this time difference is higher than 5 ms. Additionally, the ground fault trip signal remains off.

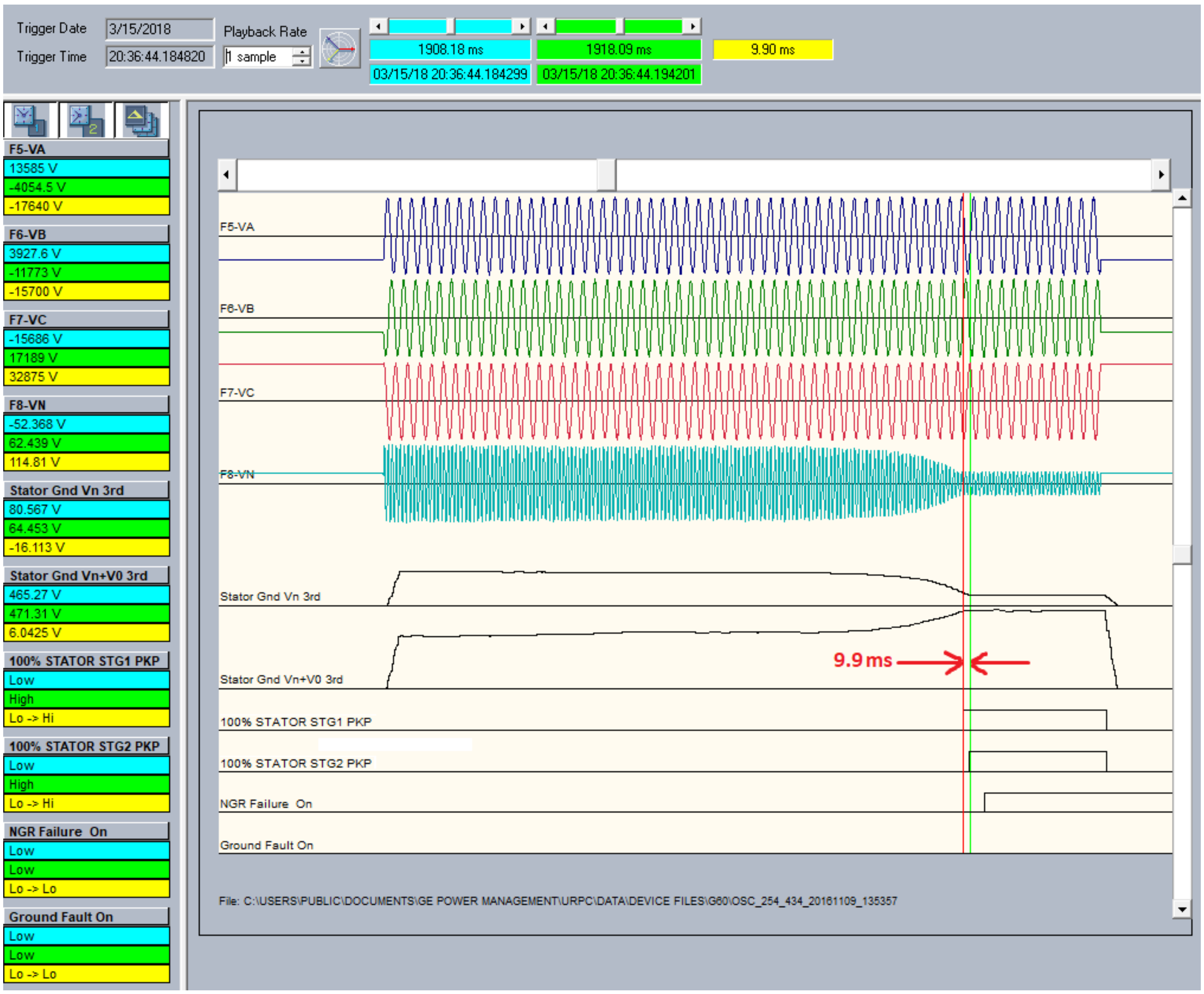

Fig. 10. Relay detections for failed-short NGR in unfaulted condition.

It should be mentioned that the proposed technique faces a few challenges. The first issue is the disappearance of the employed parameters. In some specific applications, the generators might not generate sufficient third harmonic voltage, which makes the proposed method non-functional. That is why the signal injection based protection and monitoring of the neutral system of the generators are emerging these days. The other issue is the duration of the failure of the NGR. This kind of degradation is detected if 1) the $|V_{N3}|$ and $|V_{R3}|$ vary oppositely and 2) the rate of change of $|V_{R3}|$ is greater than that of the $|V_{N3}|$. On the basis of the performed analysis, the very slow variation of the NGR resistance is not detected by this technique since the rate of change of the parameters are so low that cannot be detected.

III. Proposed Monitoring Technique for Configuration 2

These days, many generator protection systems employ signal injection to detect the ground faults near the neutral of the generator stator winding, as shown in Fig. 11 [12]–[14]. This figure shows the same configuration studied in the previous section except that it is equipped with 20 Hz injection means. The generator phase-to-ground impedance seen from the neutral, i.e., V_{inj}/I_N, is obtained using the injected signal. The ground faults are detected if the real part of the calculated impedance becomes less than a predefined threshold. This parameter is usually very high, i.e., in the order of $100\,\text{k}\Omega$, and decreases to less than $1\,\text{k}\Omega$ in case of a ground fault in generator stator winding.

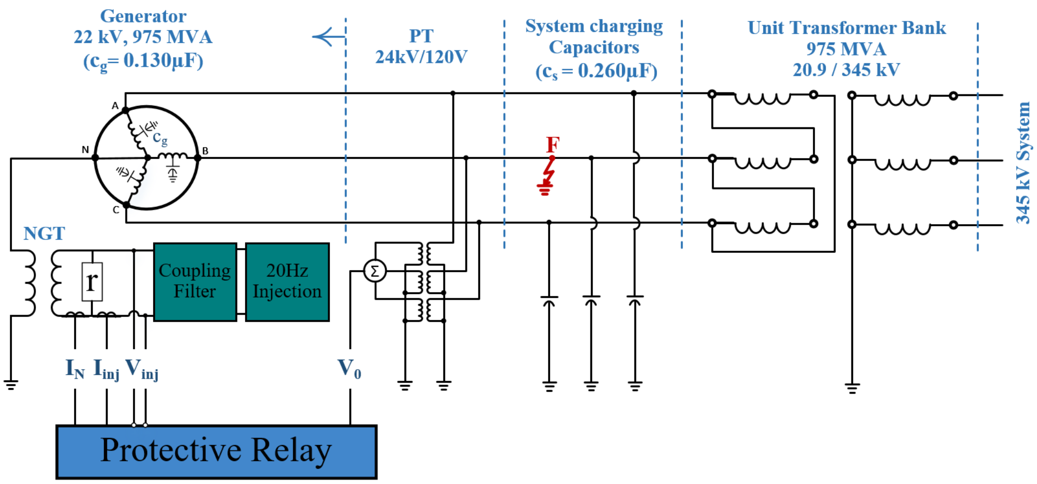

Fig. 11. Configuration 2: high-resistance-grounded unit-connected generator equipped with 20 Hz signal injection.

A. Fundamentals of the proposed technique

The signal injection means employed by the above-mentioned protective mechanism can be used for implementing the active NGR monitoring methods. An additional current sensor for measuring the injected current is needed to obtain the current that flows through the NGR. In fact, the NGR current is obtained by subtraction of the NGT secondary current from the injected current at the injection frequency. Since the NGR voltage is also measured by the relay, its resistance is available at the injected frequency. It should be noted that the injected signal cannot be extracted from the 60 Hz voltage during the ground faults since the level of the 60 Hz voltage is very higher than that of the injected voltage. Under this situation, the resistance of the NGR is obtained using the 60 Hz voltage and current that are measured by the line PTs and neutral CT.

B. Validation of the proposed technique for configuration 2

Along with comprehensive studies performed for investigating the performance of the proposed technique, two sample cases are explained in detail. The first sample case study is shown in Fig. 12. In this event, the NGR fails short from 100% to 5% in two steps, i.e., 100-50% and 50-5% representing two consecutively failing resistive elements of the NGR. As a result, the injected current increases. The voltage across the NGR and the portion of the injected current that penetrates to the high voltage system decrease due to shorted NGR. When the injected current decreases, the negligible harmonics in NGT secondary current becomes visible. The coupling filter of the injection system prevents these harmonics to penetrate to the injection source. The resistance of the NGR has been calculated accurately. The NGR Failure (NGRF) signal is enabled 200 ms after that the calculated resistance drifts to outside of the safe region, which is 70-130% of the rated resistance of the NGR.

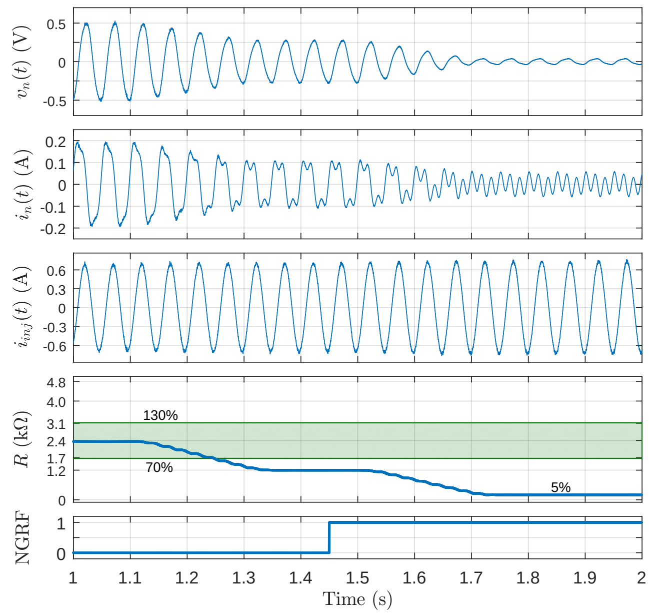

Fig. 12. Failed-short NGR in unfaulted system.

Another sample case study is shown in Fig. 13. In this event, the NGR becomes open. As a result, the injected current decreases. The voltage across the NGR, and the portion of the injected current that penetrates to the high voltage system increase due to open NGR. When the injected current decreases, the negligible harmonics in NGT secondary current become invisible. As shown, the resistance of

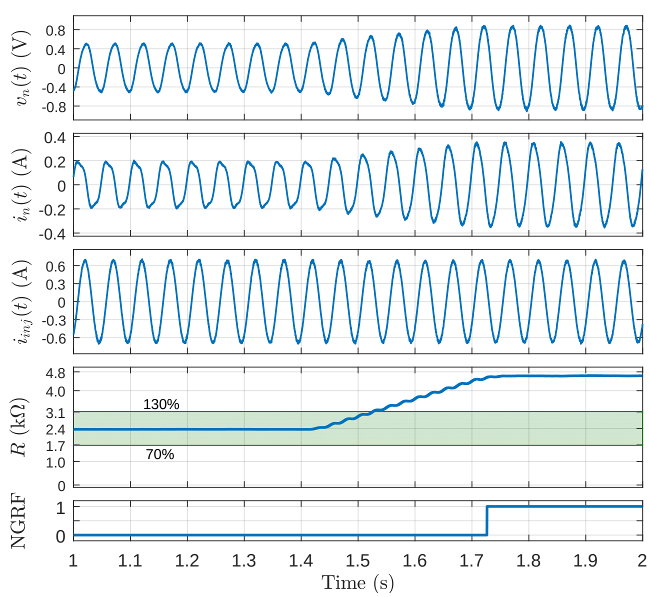

Fig. 13. Failed-open NGR in unfaulted system.

the NGR has been calculated accurately. The NGR Failure (NGRF) signal is enabled 200 ms after that the calculated resistance drifts to outside of the green area, which is greater than 130% of the rated resistance of the NGR.

It should be added that many other scenarios have been investigated to assess the performance of this technique. The observations show reliable operation of the proposed method even during the ground faults, where the fundamental harmonic of the residual voltage and neutral current are employed.

IV. Conclusion

Two new techniques were proposed that monitor the integrity of the neutral grounding resistor of the high-resistance-grounded unit-connected generators.

The first proposed technique detects the failure of the resistor using the third harmonic of the neutral and residual voltages. Furthermore, the monitoring is performed based on the calculated resistance of the resistor in the presence of the ground faults. This scheme shows reliable performance in both normal and faulted conditions.

The second proposed technique monitors the neutral grounding resistor using the existing injection infrastructures of the sub-harmonic injection based generator stator ground protection. This technique shows reliable operation as well. The integrity of the neutral grounding system during the ground faults is monitored using the neutral-to-ground resistance.

The second proposed technique is more of interest since it provides monitoring in de-energized systems as well. In fact, the third harmonic voltages used in the first technique might disappear or become very weak even in energized system condition. However, the commissioning costs of the second technique are much more than the first method unless they exist already.

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