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Advanced Battery Ground Monitoring System (ABGMS)

D. MARTINO, R. JIMENEZ, T. SAUERS, R. SCHILLER, J. RODRIGUEZ

620240552
SENIOR ENGINEER
COMMONWEALTH EDISON (COMED)
PROFESSIONAL WITH LESS THAN 10 YEARS OF EXPERIENCE
DONATO.MARTINO@EXELONCORP.COM

SUMMARY

Developed via a cross-departmental initiative to mitigate risks introduced by DC battery grounds, the Advanced Battery Ground Monitoring System (ABGMS) aims to enhance the detection and management of DC battery grounds. Traditionally, the detection of battery grounds at ComEd has been a manual process, requiring field personnel to check voltages at the battery charger and confirm using a ComEd proprietary calculation, the Kugler Method, to determine the DC ohmic resistance to ground. This is a time-consuming process and lacks real-time notification capabilities.

The ABGMS automates this process by applying the Kugler Method every hour using a Schweitzer SEL-451 relay and SEL-3350 RTU, providing immediate local and remote alarms through SCADA when an issue is detected. The ABGMS also stores historical ohmic values in a centralized database, enabling trend analysis and correlation with external factors like weather patterns. Lab tests have shown that the ABGMS is as accurate as traditional methods but offers more reliability by mitigating the opportunity for human error.

The first pilot installation was executed in June 2024 at a ComEd substation, where it will be compared against a competing third-party system. Field personnel will provide regular updates and manual Kugler readings to ensure the ABGMS's accuracy and reliability. This implementation represents a significant step forward in the detection, analysis, and management of battery grounds, potentially reducing the time required for troubleshooting and improving system reliability.

KEYWORDS

Floating DC Battery Systems, DC Battery Grounds, Monitoring, Critical Ground Resistance Values

1. INTRODUCTION & THEORY

The concern with an undesired connection to ground on a utility DC battery system and the circuits it serves is of utmost importance as the system powers critical equipment intended to monitor and protect the utility grid. There are many types of DC battery ground monitoring systems commercially available to assist in the identification of a degraded wire, faulty equipment, or an issue with the DC battery itself. However, most of these systems provide a voltage-based approach at identifying a compromised circuit with an undesired connection to ground.

At Commonwealth Edison (ComEd), Chicago, Illinois, USA, we have developed a manual internal Floating Battery Ground Resistance Measurement System (FBGRMS) method for measuring the severity of a DC battery ground on our floating DC batteries (ungrounded). The manual FBGRMS method is most commonly known within ComEd as the Kugler Method for the ComEd engineer who developed it and may be used interchangeably throughout this paper.

On a floating DC battery, the identification of a single undesired battery ground provides the opportunity to remove the battery ground source before it becomes a greater problem. At a minimum, a floating DC battery system requires at least two battery grounds before a mis-operation can occur.

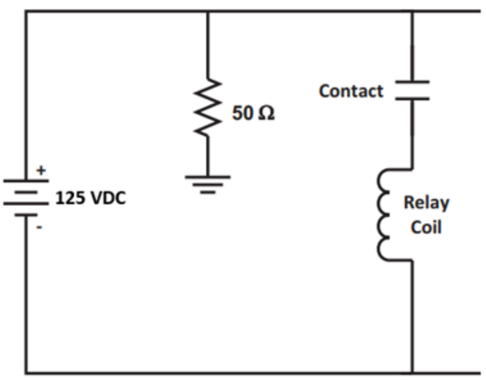

Figure 1 -- Single Battery Ground (Normal Operation)

To illustrate this point, in Figure 1, a 125 VDC battery system is supplying a simplified relay protection circuit with a single undesired battery ground of 50 Ohms as shown. The 50 Ohms is below the critical resistance value necessary to actuate the relay coil, however, nothing happens because there is no path to make up the circuit to the relay coil.

In Figure 2, for the same 125 VDC battery system, the wire between a protection relay tripping contact and an auxiliary tripping relay coil develops a 50 Ohm undesired battery ground in addition to the initial 50 Ohm battery ground already on the circuit. In this configuration, the two battery grounds complete a 100 Ohm pseudo circuit which is also below the critical resistance value necessary to actuate the relay coil; however, in this case, it causes the relay coil to actuate and results in a mis-operation.

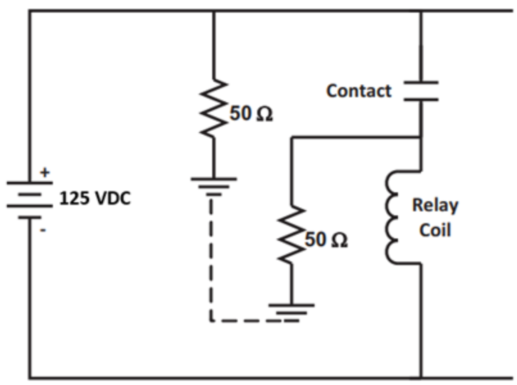

Figure 2 -- Two Battery Grounds (Misoperation)

It is important for an entity to understand the electrical response of critical components that are connected to the DC battery system circuits, specifically, their DC pickup and drop-out threshold characteristics. This information is necessary to establish Critical Ground Resistance Values (CGRV) for DC auxiliary relay equipment that can automatically actuate to open power system circuit breakers. This would be the most impactful, even though there could be other components that could operate without the same level of impact.

Let's consider a 125 VDC rated protective auxiliary relay coil with a measured field resistance of 4460 Ohms, lowest measured pickup voltage of 47 Volts, and lowest measured drop-out voltage of 14 Volts. It is important to know the CGRV of this protective auxiliary relay coil in a 125 VDC battery system circuit to understand what level of response should be given to a specific undesired battery ground. It could be the difference between stopping any immediate switching activities at a given substation to scheduling a planned maintenance task to mitigate the battery ground in a few days.

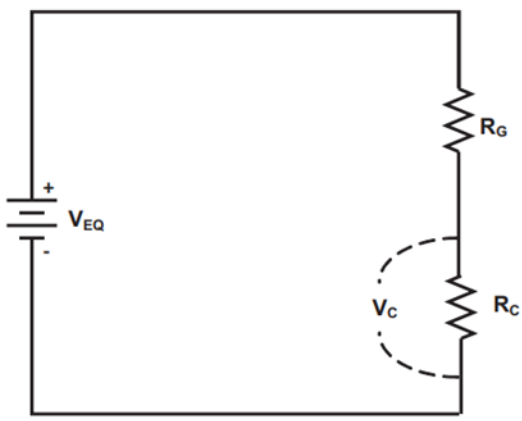

Figure 3 -- Calculating R_G

Using Figure 3, the CGRV will be calculated to establish critical thresholds to provide guidance when responding to undesired battery grounds for our protective auxiliary relay coil example. This calculation must be considered for the most limiting device connected to a DC battery system with the most immediate impact to the utility grid.

R_g := Equivalent DC Ground Leakage Resistance
R_c := Resistance of the Relay Coil = 4460 Ohms
V_{eq} := DC Battery Charger Voltage Set to Equalize = 135 VDC for a 125 VDC battery (at ComEd)
V_c := Relay Coil Pickup or Dropout Voltage = 47 VDC or 14 VDC

$$Rg = Rc \frac{(Veq - Vc)}{Vc}$$

$$Rg = 4460 \frac{(135 - 47)}{47}$$

$$Rg = 8351 \text{ Ohms}$$

$$Rg = Rc \frac{(Veq - Vc)}{Vc}$$

$$Rg = 4460 \frac{(135 - 14)}{14}$$

$$Rg = 38547 \text{ Ohms}$$

The two CGRV for the specific protective auxiliary relay coil used in this example are 8351 Ohms for the pickup measured voltage value and 38547 Ohms for the dropout measured voltage value. This means in order to avoid a mis-operation of the specific protective auxiliary relay coil used in this example, the equivalent undesired ground resistance values on the DC battery system circuits must be greater than 8351 Ohms on the pickup and the equivalent undesired ground resistance must be greater than 38547 Ohms on the dropout. It is understanding the DC electrical response of the equipment that has allowed us to establish guidelines around undesired battery grounds. At ComEd, for simplicity, on a 125 VDC floating battery system (ungrounded), the CGRV for an undesired battery ground must be greater than 40 Kilo-Ohms.

So, when the CGRV for a given DC battery system is understood, it provides the best reference for comparison of undesired equivalent battery grounds in terms of their resistance value. It is an in-depth indicator of the type of battery ground that you are dealing with as opposed to a simple battery ground present – no battery ground present identification method.

This is where the manual FBGRMS (Kugler) Method comes in to allow the direct comparison of measured undesired battery grounds against the DC battery system CGRV. The Kugler Method requires three (3) voltage measurements, the DC battery voltage (VPN), the DC positive voltage bus to ground (VPG), and the DC negative voltage bus to ground (VNG). The absolute magnitude is taken for all voltage measurements. The measurements are taken with a voltage meter with a 200 Kilo-Ohm resistor across its leads. The 200 Kilo-Ohm resistor value was determined based on the CGRV of all our DC battery systems, 250VDC, 125 VDC, 48 VDC, 32 VDC, 24 VDC, margin, standardization, lab testing, and field testing for accuracy. It is important to note, by taking the required measurements, a temporary 200 Kilo-Ohm battery ground is being introduced into the DC battery system while the ground measurements are taken but it is significantly above the CGRV.

The following manual Kugler Method equations for the equivalent battery ground Resistance Positive-to-Ground (R_{pg}) and for the equivalent battery ground Resistance Negative-to-Ground (R_{ng}) are representative of their respective test circuit configuration as follows:

$$Rpg = Test\ Resistor\ \frac{(Vpn - Vpg)}{Vng} - Test\ Resistor$$

$$Rng = Test\ Resistor\ \frac{(Vpn - Vng)}{Vpg} - Test\ Resistor$$

Also, the following constraints apply to the Kugler Method equations to ensure valid results:

- All voltages must be positive in the equation
- The Test Resistor used is 200 Kilo-Ohms
- The equation will fail if V_{pn} is less than or equal to ($V_{pg} + V_{ng}$)
- The equation will fail if V_{pg} or V_{ng} are zero

Let's consider a battery ground is present which requires applying the manual Kugler Method on a 125 VDC floating battery system (ungrounded). The three (3) measured voltages were taken using a voltage meter with a parallel 200 Kilo-Ohm resistor connected to its leads are as follows:

V_{pn} = 130 VDC
V_{pg} = 11.3 VDC
V_{ng} = 112.9 VDC

Using the manual Kugler Method equations for this example, the following are the calculation results:

$$Rpg = Test\ Resistor\ \frac{(Vpn - Vpg)}{Vng} - Test\ Resistor$$

$$Rpg = 200000\ \frac{(130 - 11.3)}{112.9} - 200000$$

$$Rpg = 10275 \text{ Ohms'}$$

$$Rng = Test\ Resistor\ \frac{(Vpn - Vng)}{Vpg} - Test\ Resistor$$

$$Rng = 200000\ \frac{(130 - 112.9)}{11.3} - 200000$$

$$Rng = 102655 \text{ Ohms}$$

The results indicate there is a significant 10.2 Kilo-Ohm battery ground on the Positive DC bus and no significant battery ground on the Negative DC bus as its reading is in the 102 Kilo-Ohm range. This information is used to assign a priority to work necessary to identify the source of the DC battery ground and a mitigation solution.

It is ComEd standard practice for field personnel to check for the presence of an undesired DC battery ground first thing when entering a substation using a DC battery ground meter associated with the battery charger. Typically, the guidance is if the battery ground meter needle deflects to greater than 60% of the nominal DC voltage, the manual FBGRMS (Kugler) Method testing must be performed to obtain a resistance value to determine the severity of the battery ground.

The Table 1, shown for a 125 VDC battery, was developed to provide guidance based on historical experience responding to DC battery grounds on the ComEd system. It established a response priority for a specific DC battery ground resistance value obtained by manual Kugler testing. This may or may not align with the priority level or response type for other companies for the same or other DC battery ground resistance values on their systems and respective CGRV.

R_{PG} or R_{NG} (Kilo-Ohms)	Priority Level	Response Type
Less than or equal to 10	10	Immediate
Less than or equal to 20, but above 10	20	Next business day or within two weeks
Above 20 up to and including 40	40	Next scheduled outage
Above 40	None	No response

Table 1 The 125 VDC Battery System Kugler Method Resistance Priority – Response Designation

As with any guidance, it is a balance of risk, resources, and realistically performing intrusive work to locate and mitigate a DC battery ground with the DC battery system in-service sourcing critical utility grid monitoring and protection systems circuits. However, over the years this practice has proven to be a good practical approach which is understood and has gained acceptance from our field personnel.

2. ABGMS SCHEMATIC DESIGN

While the FBGRMS (Kugler) method has proven reliable in its ability to identify and classify severity of DC battery ground conditions, its shortcoming has been its reliance on field personnel being present at each station, whether for routine preventative maintenance or emergent activities, to identify the ground condition. After experiencing several DC ground related equipment mis-operations over several years, an opportunity was identified to modernize our methodology of detecting DC battery grounds.

When beginning the initiative to develop a system to automate the measurement of DC ohmic resistance to ground, the team had to consider a few key pillars in the design. The system should be able to:

- accurately measure the DC to ground ohmic resistance values
- store the measurements for later analysis
- correctly alarm for specific conditions with minimal nuisance alarms
- be retrofit into any of our stations, regardless of DC battery voltage

It was the latter point that then led the team to start looking at existing devices currently utilized on the ComEd system and challenge ourselves to repurpose these devices to meet the needs of our design. ComEd utilizes primarily Schweitzer Engineering Labs (SEL) protective relays and SCADA RTUs which led the team to investigate if any of the existing relays currently being utilized had the features required to implement our vision. After some research, it was determined that the SEL-400 series relays would serve as the best platform for our design due to its built in VDC1&2 inputs which allowed us to take measurements of our DC system. The team also recognized that the SEL-400 series free-form Protection/Automation Logic would offer the best opportunity to realize our approach. The SEL-451and SEL-3350 RTAC specifically were chosen for our pilot design and installation due to their wide-spread use on the ComEd system.

With our platform selected, the team was then tasked to adapt the relay to perform the same methodology of ground resistance measurement already used at ComEd. This posed a couple key challenges for the team. The VDC inputs default purpose is to detect battery grounds through a ratio of the positive to ground to negative to ground voltages. To apply the FGBRMS (Kugler) method, we would require positive to ground and negative to ground measurements. Another challenge was that through conversations with SEL, we discovered that the VDC inputs are paralleled with a high impedance internal resistor while our traditional FBGRMS (Kugler) method utilizes a 200 kilo-Ohm resistor in parallel for the voltage to ground measurements. To allow for the individual voltage to ground measurements required, the schematic was designed with contacts in series with the positive and negative terminals of the VDC input so we could manipulate the contacts to align with the measurement being taken. To compensate for the internal high impedance resistor, external 200 kilo-Ohm resistors were introduced, supervised by additional contacts, to achieve an equivalent resistance of 200 kilo-Ohms when needed. See figure 4 for the resistor/contact design, coordination of these contacts will be discussed in a later section.

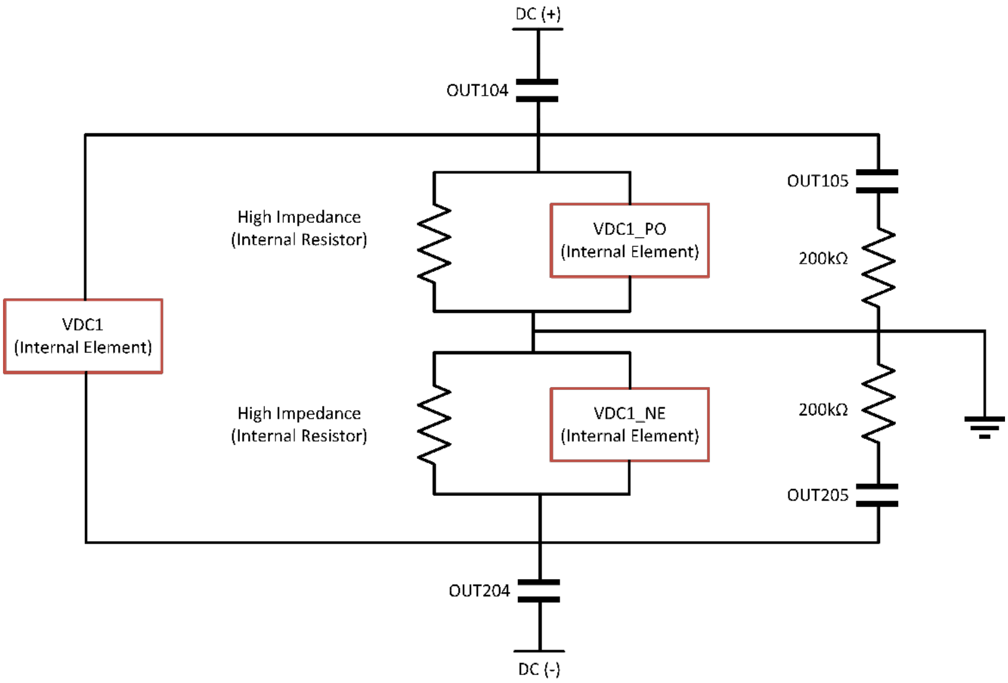

Figure 4 – ABGMS Circuit Development

3. ABGMS RELAY SETTINGS

With the Advanced Battery Ground Monitoring System (ABGMS), the goal was to design a system that could repeatedly mimic the existing Kugler Method test automatically without the need of field personnel. As previously described, the Kugler Method requires three (3) DC voltage readings to be recorded and entered in the Kugler Method equations to determine the Resistance to Ground ohmic values on the DC Battery system. For the ABGMS system, the SEL-451 is used to measure the three (3) DC voltages required, and the SEL-3350 RTAC is used to record the DC voltage readings and apply the Kugler Method equations. This configuration was selected due to the SEL-400 series relays inability to store analog values.

With the SEL-400 series relay and the schematic as described above, the three (3) DC voltage readings (V_PN, V_PG, V_NG) can be acquired by utilizing the four (4) output contacts (OUT104, OUT105, OUT204, OUT205) and three (3) DC voltage inputs (VDC1, VDC1_PO, VDC1_NE). The SEL-400 series relay is programmed to have three (3) stages, one for each of the three (3) required DC voltage measurements (V_PN, V_PG, V_NG). Prior to each stage, the outputs are configured to get the desired voltage reading across the desired DC voltage input (see below).

Stage 1 (V_PN):

- Output Contacts:
    a. CLOSED: OUT104, OUT204
    b. OPENED: OUT105, OUT205
- DC Voltage Input:
    a. VDC1 measures voltage

Stage 2 (V_PG):

- Output Contacts:
    a. CLOSED: OUT104, OUT105
    b. OPENED: OUT204, OUT205
- DC Voltage Input:
    a. VDC1_PO measures voltage

Stage 3 (V_NG):

- Output Contacts:
    a. CLOSED: OUT204, OUT205
    b. OPENED: OUT104, OUT105
- DC Voltage Input:
    a. VDC1_NE measures voltage

At the beginning of each stage, a binary input flag is sent to the SEL-3350 RTAC RTU to determine the start (rising edge) and end (falling edge) of each phase to indicate when each DC Voltage analog input measurement should be averaged and stored. After each of the three (3) DC voltage readings have been stored in the RTU, the RTU calculates the resistance to ground ohmic values and determines associated battery ground alarms; these ohmic values and alarms are sent back to the SEL-451 relay via analog outputs and binary outputs to be displayed locally on the front screen.

The SEL-451 relay is programmed to repeat these three (3) stages once per hour or can be initiated at any time via manual push button. The automated and manual tests can be enabled or disabled either locally via relay push button or remotely via SCADA control at any time to prevent interference while field personnel are troubleshooting battery grounds. The ABGMS adds continuous monitoring capability of the DC battery while also eliminating potential user error and safety risk when manually performing the FGBRMS (Kugler) method.

4. ABGMS SCADA INTEGRATION

Alongside the SEL-451 relay described in the previous section, the ABGMS makes use of both an SEL-3350 RTAC RTU and SEL-3555 RTAC HMI. The RTU acts as the main point of contact with ComEd's EMS system that monitors station telemetry, while the HMI provides a local interface for on-site engineers to view substation data. The RTU is set up to receive binary and analog input data from the SEL 400 series relay for the coordination of measurements as well as send binary and analog outputs to the relay to allow for the display of the Kugler results on the front panel. The HMI provides a real time data display to allow any on site personnel to observe the stages of the test and allows for visualization and comparison to the traditional hand testing process. Furthermore, to assist in the evaluation of the pilot and provide a comprehensive view of program results, a dashboard was developed in the PI Processbook application that concurrently trends all key values and allows remote viewing of historical data.

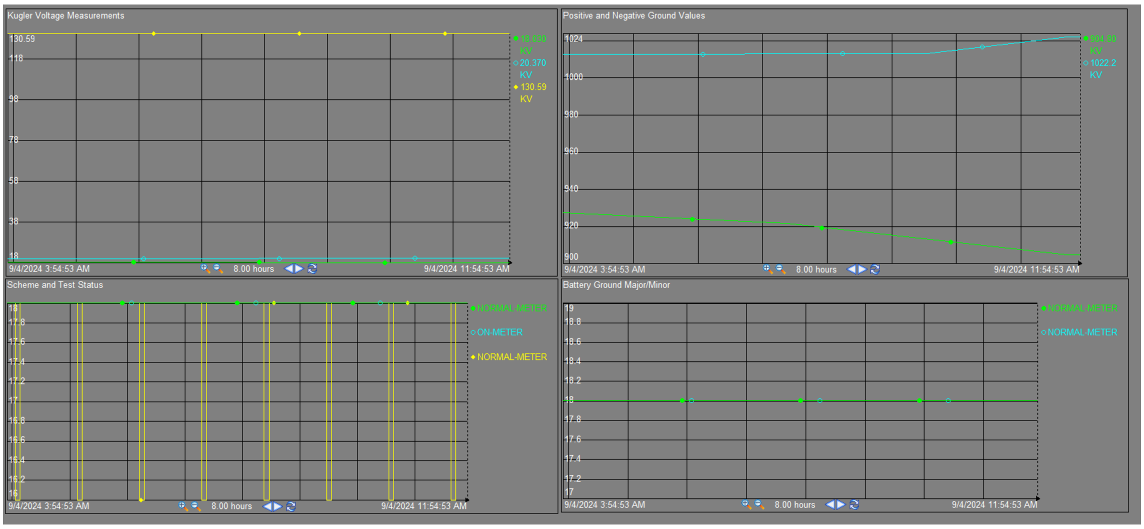

Figure 5 – PI Processbook Remote Dashboard

4.1 ABGMS SCADA RTU

To allow the SEL-3350 RTU to work in tandem with the SEL-451 relay, three (3) custom functions were developed that work together to comprise the overall ABGMS logic. These functions are listed and described below:

ABGMS Main Program

The main programming loop in which the inputs from the SEL 400 series relay are evaluated, and associated outputs are triggered based on the results of the test. The program analyzes the inputs given from the SEL-451 to dictate when each measurement of V_PN, V_NG, and V_PG should be snapshot in order to provide input into the Kugler equation. These values are each average values taken over a 60 second duration, which provides a more stable value than taking a single instantaneous reading. The results from the Kugler equation are then evaluated relative to the thresholds determined for a Priority 10 or Priority 20 alarm. If the threshold for either alarm is met in two consecutive tests, an alarm is triggered and sent to the SCADA system with the most recent priority rating. For instance, a Priority 20 battery ground result followed by a Priority 10 on the subsequent test would throw a Priority 10 alarm. The program then provides the Ohmic values of the battery ground as well as the alarm status back to the relay to display on the front display.

Sixty (60) Second Averaging Function

As mentioned above, the ABGMS Main Program makes use of this function to provide inputs to the Kugler Equation. It feeds the direct readings taken from the SEL 400 series for V_PN, V_PG, and V_NG into this function, which maintains a queue of values taken within a 60s timeframe that is constantly running. This allows the ABGMS Main Program to retrieve a 60s average value for any of these values at any snapshot in time.

ABGMS Kugler Function

This function is the implementation of the Kugler equation outlined in prior sections and provides the result when called. During each testing cycle, this function is called to provide the ohmic values for the battery grounds when fed with the measurements taken during that test. It also provides indication when the inputs meet criterion for a test failure.

4.2 ABGMS HMI Display

In addition to the data being sent to the ComEd SCADA system, the SEL-3350 RTU provides the data in parallel to a local SEL-3555 RTAC HMI on site. This HMI has a programmed display that allows on-site personnel to observe the test as it is being conducted and monitor the results in real-time. This can be useful when the personnel on-site do not have access to the RTU running the main ABGMS program. Below is the display used at the pilot substation:

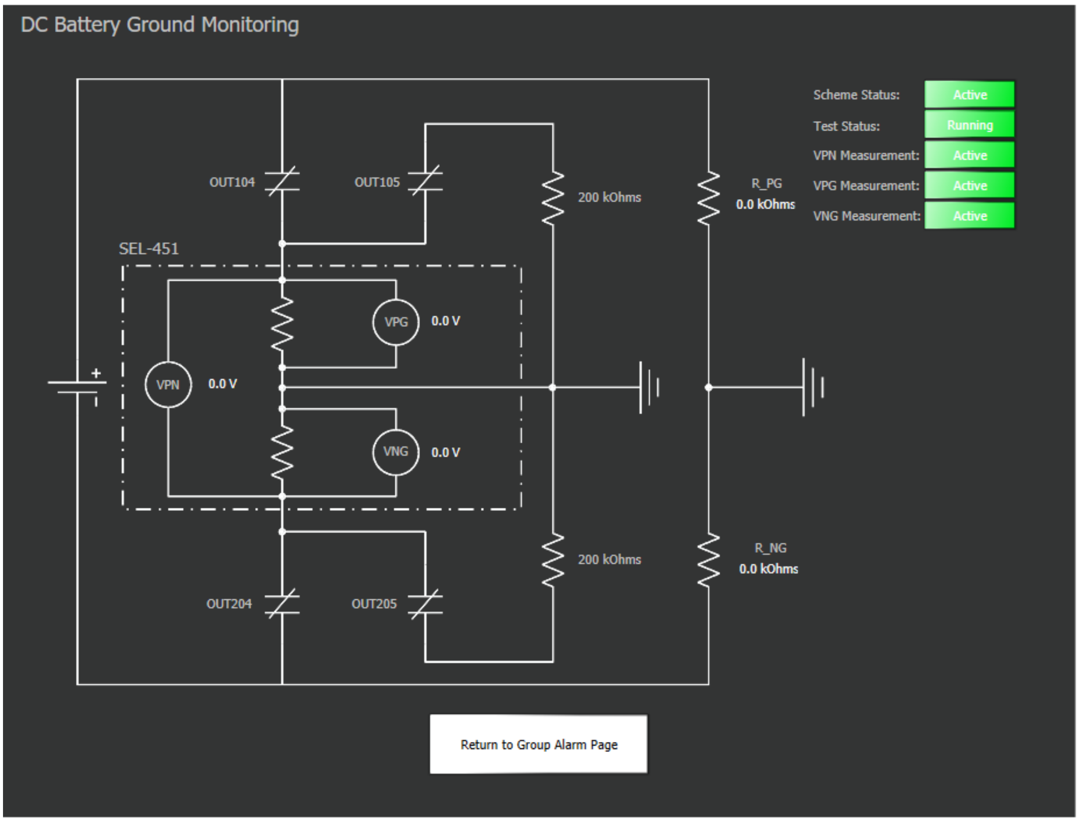

Figure 6 – Local HMI Display

5. ABGMS RESULTS AND FUTURE STATE

The ABGMS has been deployed at one of ComEds substations since mid-June 2024 and early results have been promising. To provide a control group to compare the systems results against, field technicians have been recording results via the traditional method every two weeks of the pilot install. The small sample size from June-September is showing a miniscule 2.58% difference on positive to ground measurements and 1.61% on negative to ground measurements. We expect these values to decrease further as additional data points are collected. A slight variation in results is to be expected due to the differing methods of data collection. As mentioned above, the ABGMS samples each value for sixty seconds and averages the results to obtain the most accurate value whereas in the traditional FBGRMS method, a field technician is capturing the data via a multimeter. These values can fluctuate slightly and are dependent on the value that the technician selects for their calculation.

Data and feedback will continue to be gathered from the pilot install through the end of 2024. In 2025, the team will evaluate this data as well as capture any lessons learned from field personnel to then be captured in a construction specification & general design diagram (GDD). Once this design is standardized, additional opportunities to install this design at ComEd substations will be evaluated. Safety and system reliability are of the upmost importance at ComEd which are the key drivers in the push to get this design into more stations. ComEd has experienced safety incidences in the past related to field personnel taking voltage measurements and the design team fully believes this innovation has the potential to reduce exposure for our peers. This innovation will position ComEd to become a next generation utility in an ever-evolving industry.

The ABGMS algorithm and design is patent pending.

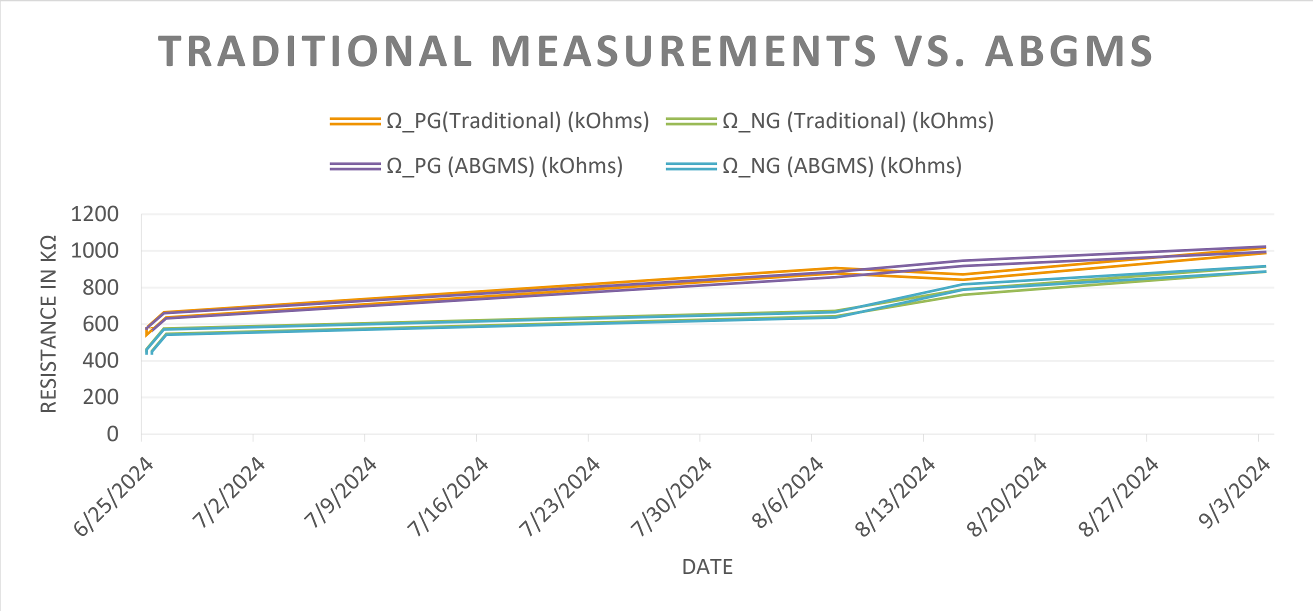

Figure 7 – Trending of traditional measurements vs. ABGMS

BIBLIOGRAPHY

No external pieces referenced.