[2017]

Testing a SEL-300G Generator Protection Relay Using RTDS™

RTDS Technologies Inc.

[November 2017]

Testing a SEL-300G Generator Protection Relay Using RTDS™

By:

Ali Banitalebi Dehkordi & Mayssam Amiri

RTDS Technologies Inc.

Nov. 2017

Table of Contents

Chapter 1: Introduction

This manual explains the detail procedure of using a Real Time Digital Simulator (RTDS) for testing a 300G SEL relay. The RSCAD library component "_rtds_PDSM_FLT_v3" which is a phase-domain synchronous machine model capable of modeling internal faults is used in the simulation. The following documents and files should be accompanied by this document:

1. Documents and manuals:
    a. SEL-300G Multifunction Generator Relay Instruction Manual (300G_IM_20160122.pdf) which can be downloaded from the SEL website.
    b. Documentations for the phase-domain SM model (PDSM.pdf) and for the Generator Relay Model (generator_relay.pdf) available in RSCAD software.
2. RSCAD files: "PDSM_RELAY_300G_5.dft" and "PDSM_RELAY_300G_5.sib".
3. A prepared relay data-base file (300Gsample.Rdb) which contains a sample setting for the relay (SEL_300G_Ali_AUG_4_2010).

Chapter 3 explains the elements in the simulated circuit, setting up the CTs and PTs, and inputting and outputting signals. Chapter 3 of this document also explains the procedure of communication with the relay and sending the settings to the relay.

Chapter 4 explains the procedure of setting relay elements one by one and testing them by applying various faults in the simulation.

Chapter 2: Description of the Simulated Circuit in RTDS

In this chapter, the capabilities and limitations of the faulted _rtds_PDSM_FLT_v3 model are briefly explained. The circuit which is used to test the relay is presented and the method of calculating the turns ratio of CT's, PT's and adjusting the scaling factors of the GTAO will be discussed.

2.1 Phase-Domain Synchronous Machine (PDSM) Model for Simulating Internal Faults

A detailed description of this machine model and its capabilities are explained in the documentations for the phase-domain SM model (PDSM.pdf). The following is a brief description of the model.

The basic icon for the _rtds_PDSM_FLT_v3 component appears as shown in the Figure 2.1.

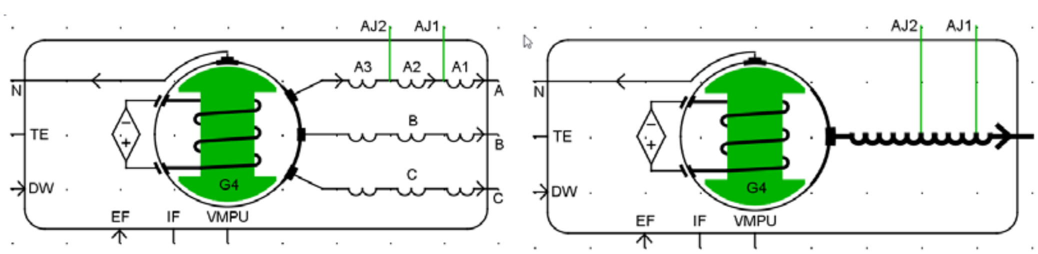

Figure 2.1: _rtds_PDSM_FLT_v3 component icon

The stator terminals (A, B, and C), the neutral of the machine (N) and two internal fault points to phase A (AJ1 and AJ2) are available for connection to other power system components.

The “embedded phase domain” approach [4] is used to implement this model in the environment of RTDS. The term “phase domain” means that the values of machine inductances change with respect to the rotor position and the level of saturation. The term “embedded” means that the network solution is incorporated in solving the differential equations of the machine. This approach shows superior numerical performance in comparison with the conventional interfaced approach [5].

The phase domain feature of this model gives the capability of simulating synchronous machines internal faults. In order to be able to simulate synchronous machine internal faults, the self and mutual inductances of machine windings including faulted windings must be computed as functions of rotor position and saturation. The phase domain synchronous machine model can use two methods to compute the inductance matrix of the machine:

DQ−Based Method: In this approach [6], [7], it is assumed that not only the healthy windings create a perfect sinusoidal distributed magneto−motive force (MMF), but also the MMF due to the faulted windings will be sinusoidal. The advantage of this method is that the users do not need to know the information about the distribution of the windings and rotor geometry. Also the “dq” data required for operating the component ”lf_sharc_sld_MACV31” is adequate for operating this PDSM component. This method however does not show the phase−belt harmonics (3rd, 5th, and 7th harmonics due to the non−sinusoidal distribution of the windings and permeance). Furthermore, as the point of fault becomes closer to the end of a winding, the MMF of the sub−winding becomes less sinusoidal; therefore this approximation becomes less accurate.

In the phase−domain synchronous machine model (_rtds_PDSM_FLT_v3), the rotor damper grid is modeled as amortisseur windings along d−axis and q−axis, which is the conventional method of modeling damper grids in power system studies [10]. It is shown that this representation may cause significant errors in modeling turn to turn faults for multiple pole synchronous machines [9]. Alternatively, one d-axis damper winding and one q-axis damper winding must be considered for each pole of a synchronous machine for accurate simulation of solid turn to turn faults [9] . Please note that, such detailed representation of damper grid requires detailed knowledge of machine design as well as significant increase (100s fold) in computational capacity of the simulator. On the positive note, this error is less significant for machines with only two poles or machines with much higher number of poles with practical distribution for the windings.

When stator-to-ground faults are the subject of study, the PDSM model ”_rtds_PDSM_FLT_v3” can be used, since the synchronous machine neutral is grounded with an impedance much larger than the leakage impedance of the stator and the dampers [9], [11], [12]. Therefore, the primary application of the phase-domain synchronous machine model”_rtds_PDSM_FLT_v3” is closed−loop testing of stator-ground fault protection devices. However, turn to turn faults can also be modeled and simulated waveforms (although inaccurate in magnitude in some cases) are capable of tripping protective elements for turn to turn faults such as line current negative sequence.

If the dq-based method is used for computing synchronous machine inductances, the model can be used for differential and neutral overvoltage protection schemes during stator to ground faults. Appendix C shows a method of generating the 3rd harmonic voltage of the neutral and terminals separately and adding them to the fundamental voltage. By using this method, even a dq-based model can be used for ”100% stator-ground fault protection scheme”, although 3rd harmonic voltage is not naturally produced as the result of phase belt harmonics.

2.2 Simulation Circuit for Testing a Generator Relay using RTDS

The RSCAD files “PDSM_RELAY_300G_5.dft” and PDSM_RELAY_300G_5.sib” are used to simulate different fault scenarios on the machines and send the corresponding signals to the relay. The simulated system consists of a 500 MVA, 22 kV synchronous generator which is connected to a source through a transformer. A circuit breaker is used to separate the generator terminals from the transformer. Phase A of this machine model consists of three sub-windings A1, A2 and A3. The two points of connection between these three sub-windings are available as power system nodes (AJ1 and AJ2). These two connection points can be connected to the ground through a fault impedance to simulate stator-ground faults. Connection of this nodes to each other will represent a turn to turn fault. The neutral point N is also a power system node and can be connected to other power system components such as impedances and transformers.

Two common methods of neutral grounding are low-impedance and high-impedance grounding [11]-[12]:

- In the low impedance grounding method, a resistor or a reactor is connected between the generator neutral and the ground. In general, this impedance is selected to limit the generator’s contribution to a single phase-to-ground fault at the generator terminals to a value up to 150% of the rated full-load current [11]-[12]. Solid connection of the neutral to the ground is not recommended [11]-[12] as a stator-ground fault in this case will be equivalent to a turn-turn fault causing a large amount of current to flow in the faulted winding. In this type of grounding, a stator-ground fault provides sufficient current for differential relaying systems.

- In the high-impedance grounding method, a distribution transformer is connected between the generator neutral and the ground and a resistor is installed across the transformer secondary. The resistor limits the ground fault current, and the transformer's secondary voltage can be used to detect ground faults. The high impedance normally limits the fault current to levels considerably below the practical sensitivity of the differential relay. Therefore, differential relaying will not detect stator-ground faults for the high-impedance grounded generators. Techniques such as neutral overvoltage or existence of the third harmonic in the neutral and terminals of the machine are often used to detect a stator-ground fault for a high impedance grounded generator.

In this example, a 0.5 Ohm (~ 0.5 pu) resistance is used for low-impedance grounding, and for high impedance grounding tests, a 50 Ohm (~ 0.5 pu) resistance is used to connect the neutral of the machine to the ground. The users of this document can replace these resistances by grounding transformers where high or low impedances are connected to the secondary of the transformer.

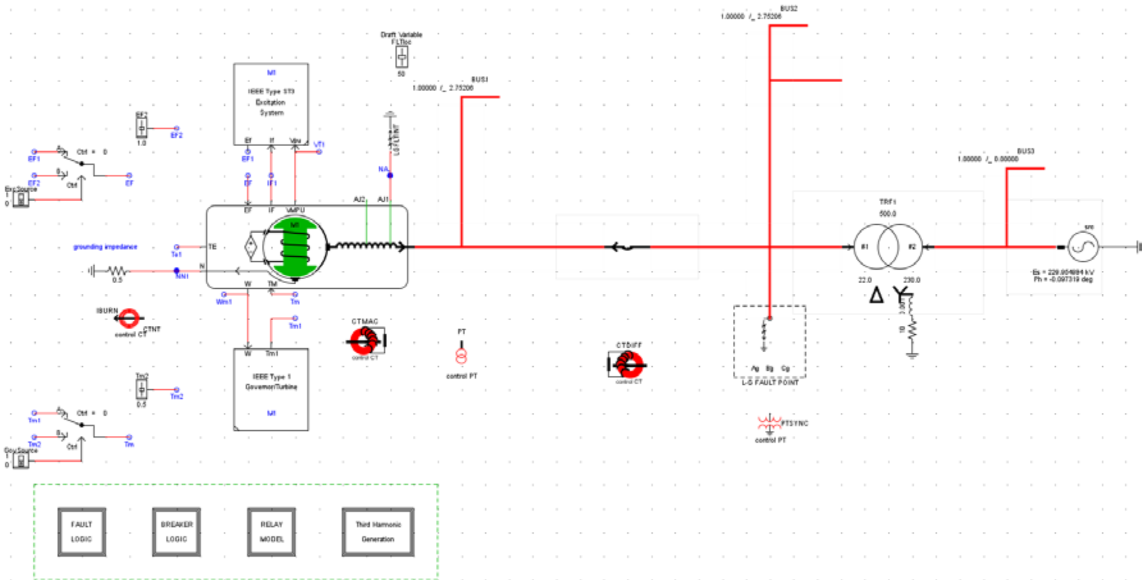

Figure 2.2: **PDSM_RELAY_300G_5.dft**

A switch (Excsource) is added to this circuit which enables the user to choose the source of excitation. The excitation voltage can be received from the exciter model or from a run-time slider. This option enables the user to imitate the “loss of field excitation” fault. Similar arrangement is made for the governor to simulate the “loss of prime mover fault”. Note that, the connection of AJ1 to the ground which is depicted in Figure 2.2 represents a stator-ground fault.

2.3 Monitoring signals, setting up CT's and PT's, sending signals to analogue output, and adjusting the scaling factors of the GTAO

Generally, for the generator protection, the following signals need to be sent to the relay:

- Stator currents (note that for phase A, the current of sub-windings A2 and A3 must also be monitored).
- Differential current (currents in the circuit breaker). These current are used for differential protection scheme and they must be monitored with the direction opposite to the direction of the stator currents.
- Neutral current
- Terminal voltages
- Neutral voltage
- Phase A voltage on the other side of the breaker (node 4 on Bus 2). This node voltage is used for synchrono-check element.

The circuit shown in Figure 2.2 contains a generic relay model for generator protection. This relay model is capable of receiving the primary signals directly or from the secondary side of the CT's and PT's.

The PT's turn ratio is adjusted such that the secondary voltage is close to **115 V RMS** for the rated voltage:

$$PT\ turn\ ratio = \frac{22\ kV}{115\ V} = 191.3 \tag{2.1}$$

The CT's turn ratio is adjusted such that the secondary current is close to **5 A RMS** for the rated current. The turn ratio of 2624 is selected for the CT's. See Appendix A for more details. The monitored signals and the RTDS generic generator relay model are shown in Figure 2.3 and Figure 2.4, respectively.

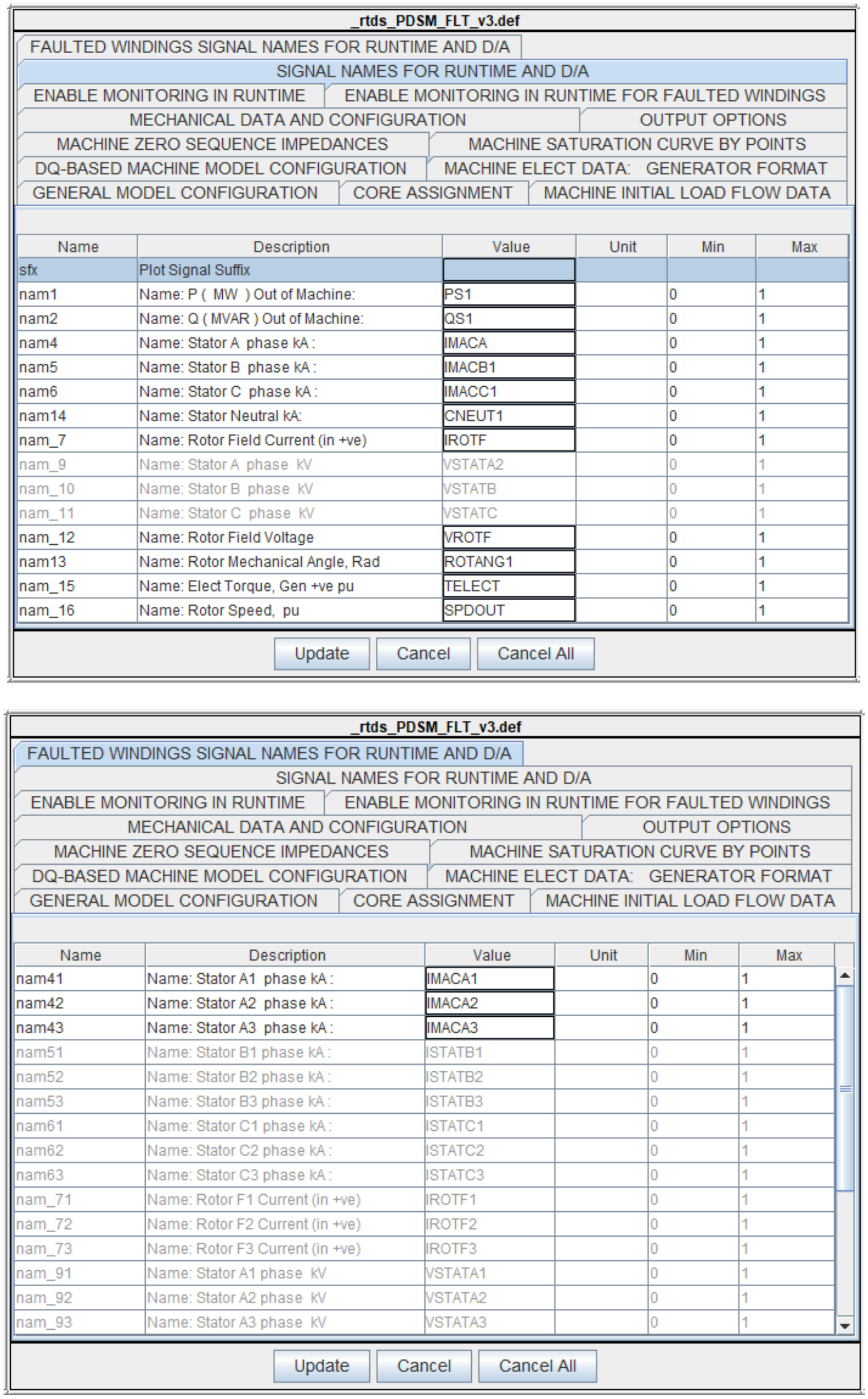

Figure 2.3: Monitored signals

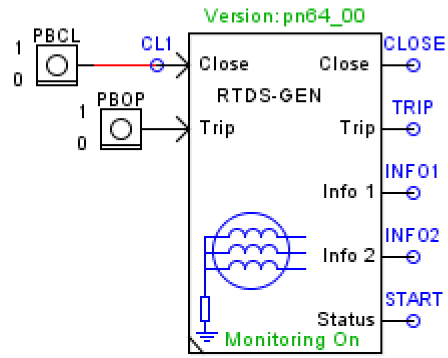

Figure 2.4: **RTDS generator generic relay model**

The determined CT and PT settings should be input to the CT, PT models in the circuit, and sent to the relay model and the quickset menu for relay settings. Figure 2.5 shows the RTDS generator data setting.

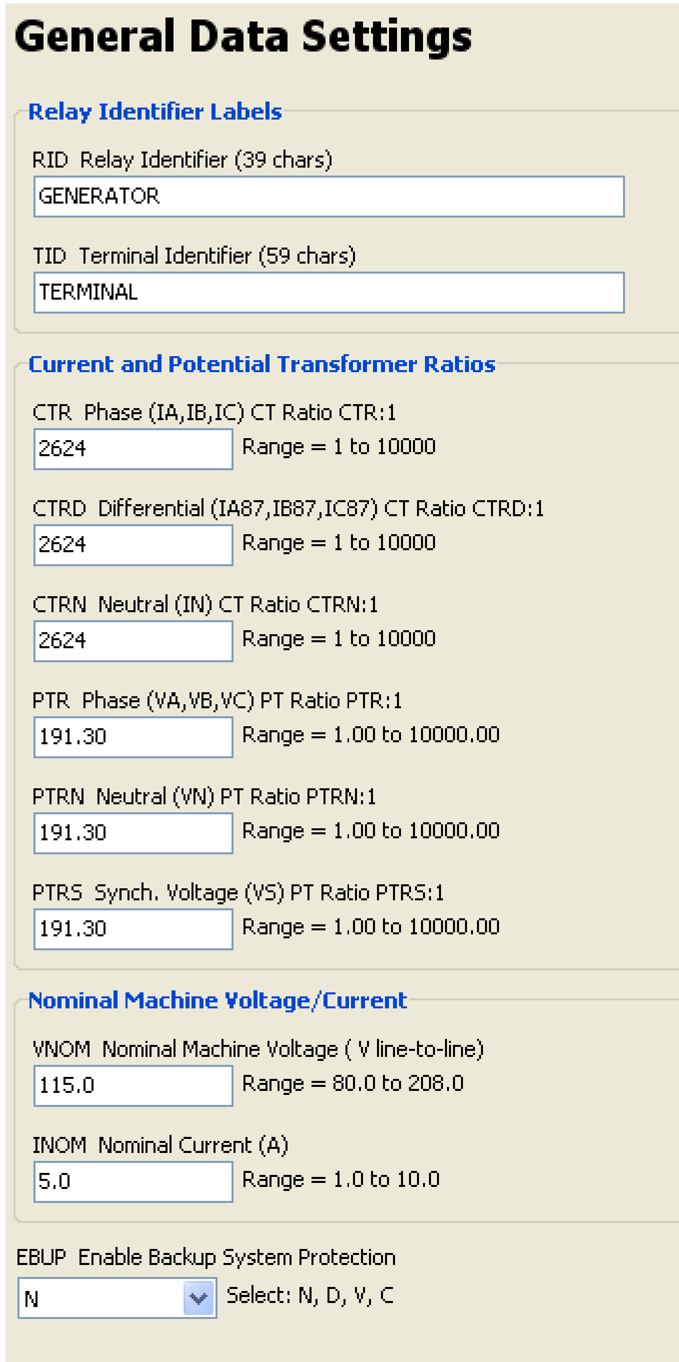

Figure 2.5: RTDS generator data setting

2.3.1 Sending signals to the D/A and adjusting the scaling factors of GTAO:

In this tutorial, the interface between the relay and the RTDS simulator is done through the low-level interface. The required signals explained in Section 2.3 are sent out to the low-level test interface using a GTAO card. Figure 2.6 shows the low level interface of the SEL-300G relay.

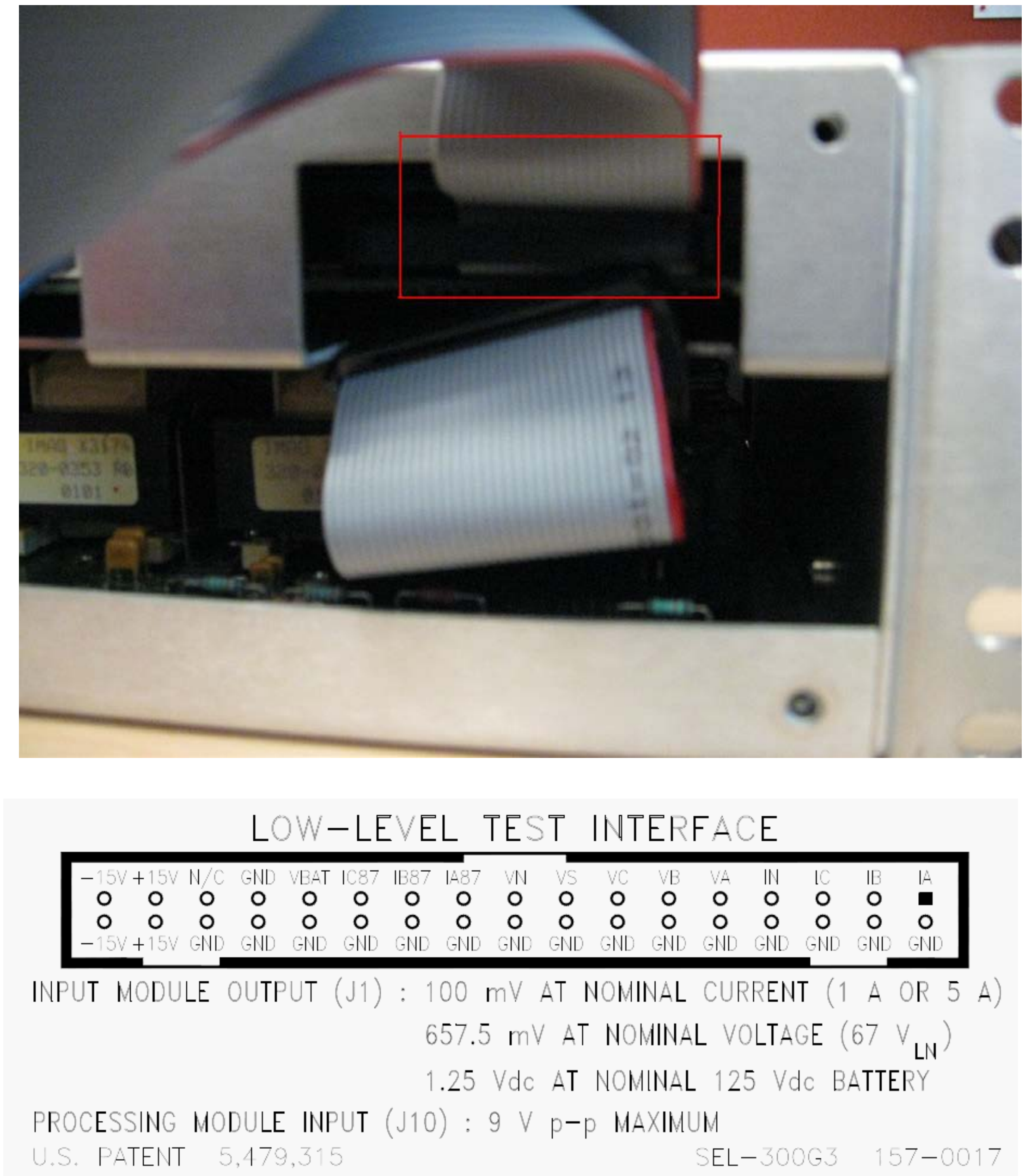

Figure 2.6: Low-Level Test Interface of SEL-300G

The input signals to the low-level test interface from right to left are:

- Stator currents: IA, IB, IC
- Neutral current: IN
- Terminal voltages: VA, VB, VC
- Synchrono-check voltage VS.
- Neutral voltage: VN
- Differential current (currents in the circuit breaker). IA87, IB87, IC87.

Figure 2.7 shows the input signals to the GTAO card corresponding to the aforementioned signals and Figure 2.8 shows the necessary connections to the relay.

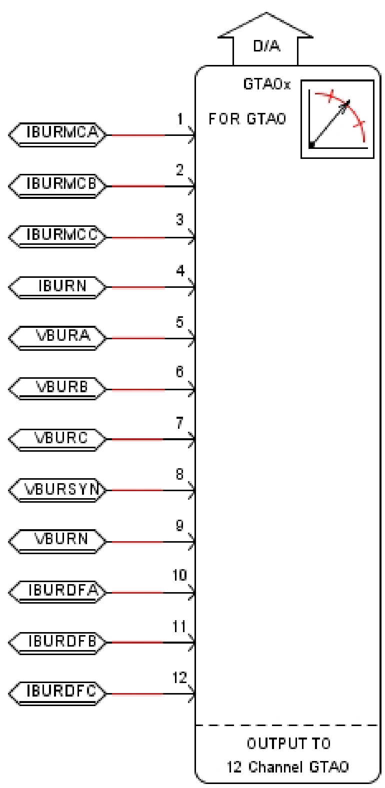

Figure 2.7: Sending out analogue signals using a GTAO card

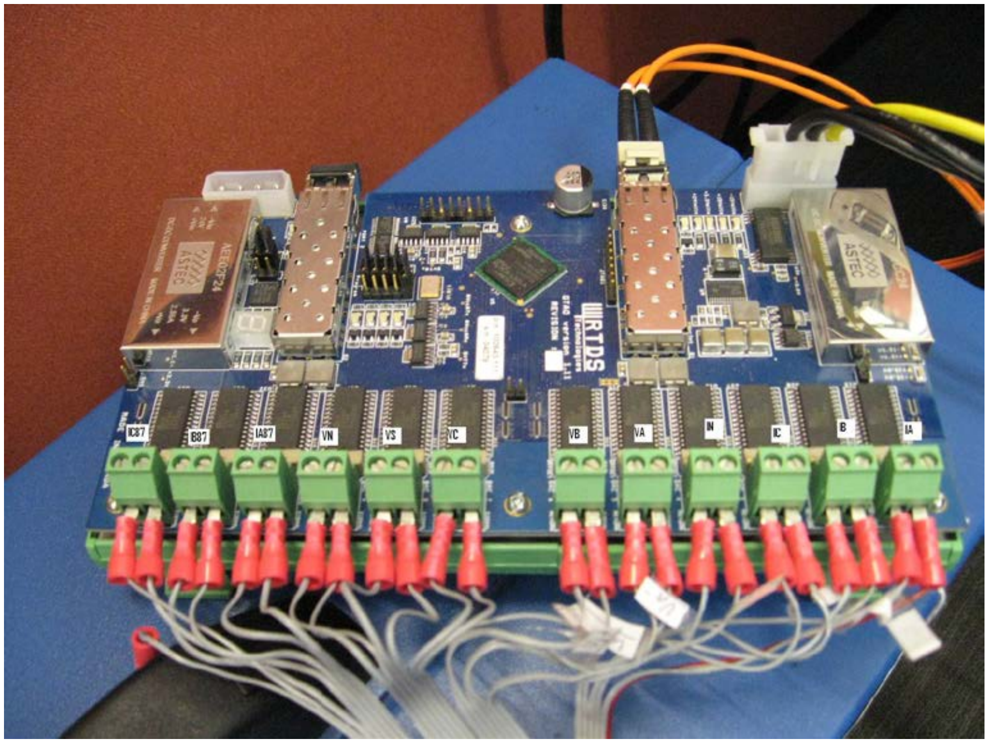

Figure 2.8: Connection of the relay test harness to the GTAO card

2.3.1.1 Calculating GTAO scaling factors:

In this section, a systematic procedure of adjusting the scaling factors of a GTAO card channels is explained. Figure 2.9 shows the relationship between the GTAO card input and analogue output.

Each channel of the GTAO has a scaling factor which scales the analogue signals to the levels desired by the interfaced hardware. This relationship is shown by the following equation:

$$Analouge\ Output = \frac{5\,Volts}{G} \times RTDS\ Signal \tag{2.2}$$

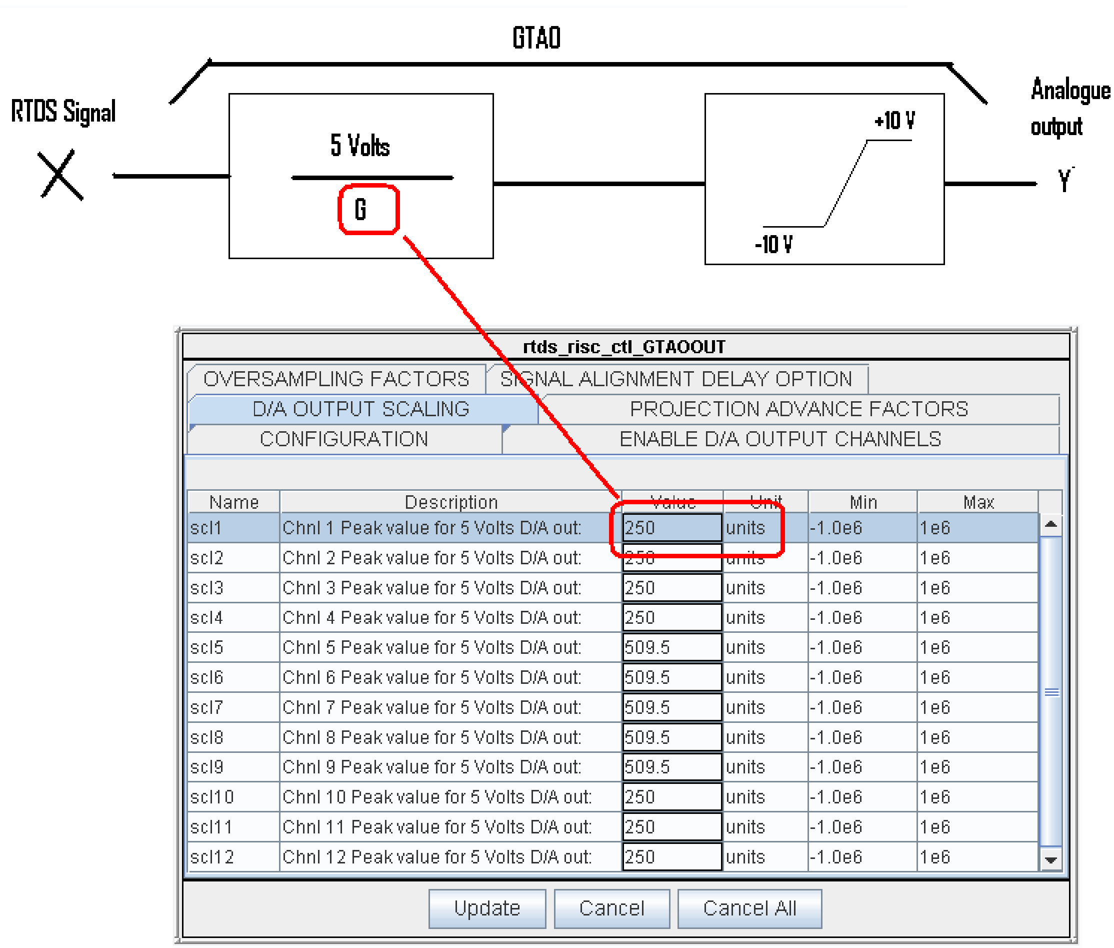

Figure 2.9: The GTAO card scaling factor

According to the SEL-300G relay documentation for the low level test interface (see Figure 2.6), at rated current the RMS current of the **CT** is **5A** which corresponds to **100 mV** for the input of the low-level test interface. Therefore:

$$100\ mV = \frac{5\ V}{G} \times 5 \ \Rightarrow G = \frac{5\ V}{100\ mV} \times 5 = 250 \tag{2.3}$$

Similarly, for the channels that output voltage signals:

$$657.5\ mV = \frac{\frac{115}{\sqrt{3}}\ V}{G} \times 5 \ \Rightarrow G = \frac{67\ V}{657.5\ mV} \times 5 = 509.5 \tag{2.4}$$

With the above scaling factors, at rated current and rated voltage the output of the GTAO for the current signals is 100 mV and for the voltage signals is 657.5 mV.

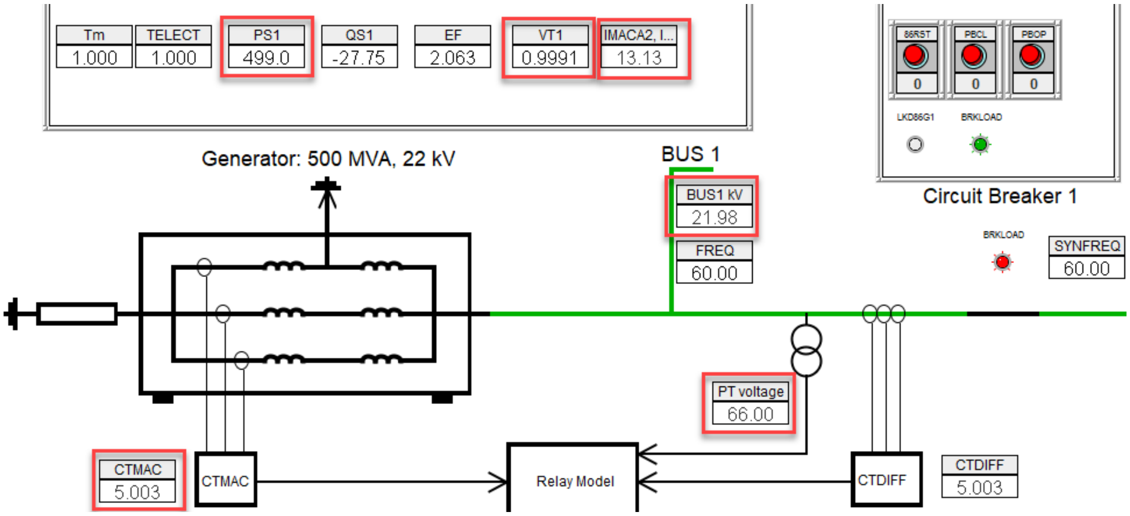

Figure 2.10: Runtime canvas when the machine is at rated voltage and rated current

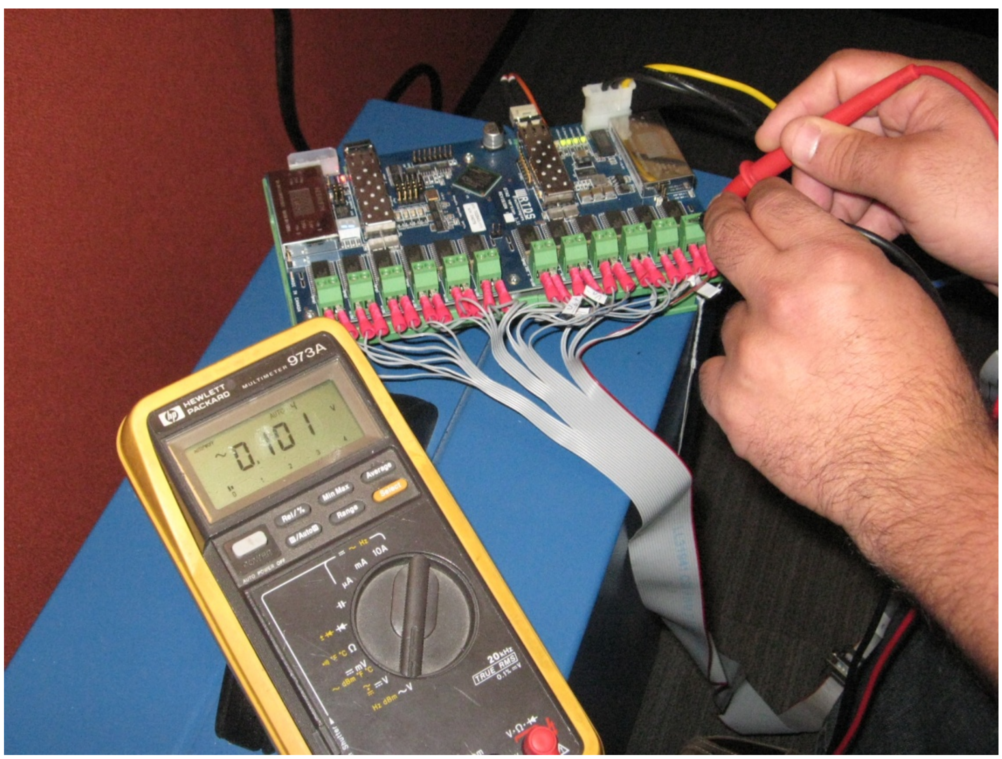

Figure 2.11: Output voltage of the GTAO card current channel.

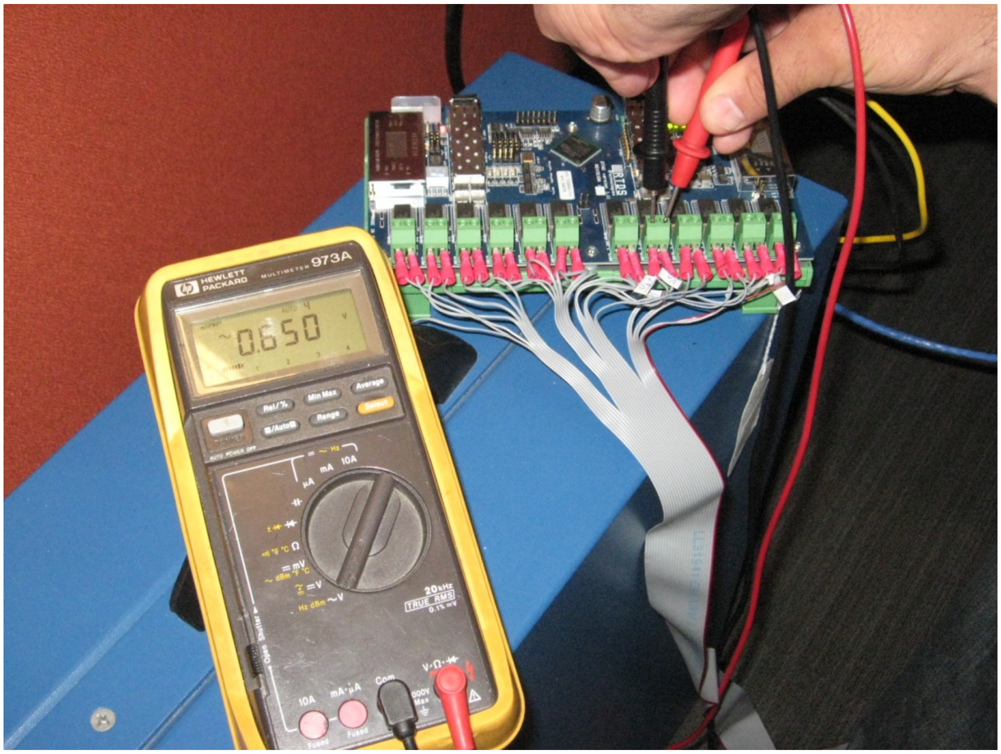

Figure 2.12: Output voltage of the GTAO card voltage channel.

2.4 Communicating with a 300G Relay Using the AcSELerator Quickset Software

In this chapter, the basics of communicating with a SEl-300G relay and creating settings are explained.

2.5 SEL acSELerator QuickSet® Software

The SEL acSELerator QuickSet® Software can be downloaded from SEL website:

http://www.selinc.com/sel-5030/

The size of this file is relatively large and it usually takes more than 10 minutes for the file to be downloaded. After installation, this program will usually be located in:

C:\Documents and Settings\user\Application Data\SEL \AcSELerator\QuickSet\

After starting the program the following window appears:

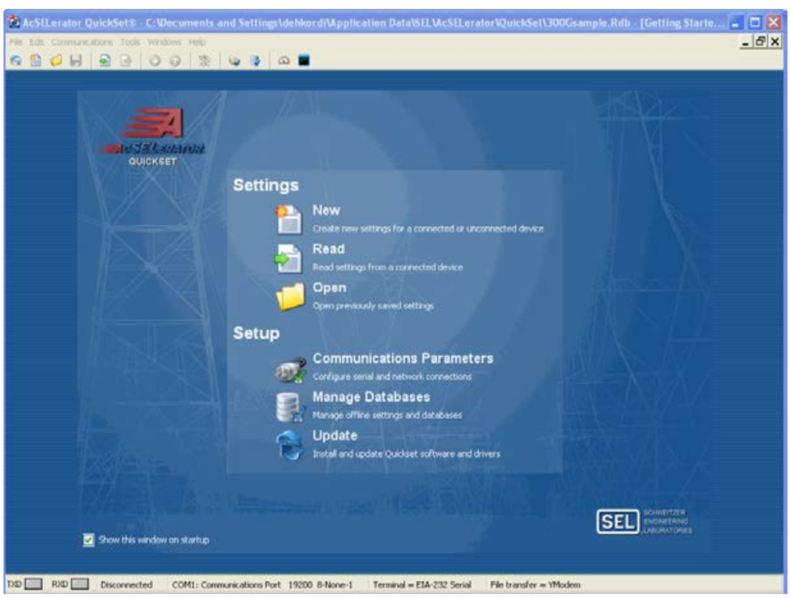

Figure 2.13: SEL Quickset Software main window

2.6 Serial Communication with the relay

- **Communication PORT**: select one of the relay serial ports and connect it to the serial port of your computer using one of the SEL special serial cables.

Figure 2.14: SEL serial cable

- Use the **front panel display** to observe which serial port of the relay is selected; also record the communication parameters such as: Data Speed, Data Bits, Stop bits, Parity, RTS/CTS. Play the video "MVI_4768.avi" for the instructions.
- The username and password are usually default values: USER: OTTER, PASS: TAIL
- Serial communication can be done using **Quickset program** see Figure 2.16 or Windows **HyperTerminal** program see Figure 2.17.
- Commands such as "acc", "2ac" enter the user to access level #1 and access level #2. The command "id" can be used to show the **firmware identifier string** (**FID**).
- Record the FID. FID is needed to create new settings for the relay. Firmware version of the relay should be compatible with the version that the Quickset software accepts. The user may need to upgrade the firmware in the relay. Please read the instructions in "**300G_IM_20100430.pdf**" for further information.
- In addition to the FID the user needs to record the **part number** (P/N) and the **serial number** (S/N) from the **serial number sticker** located on the back of the relay see Figure 2.18.

FID	P/N	S/N
SEL-300G-R242-V30H425XX4X-Z200200-D20081231	**0300G30H425XX4X**	**2001050103**

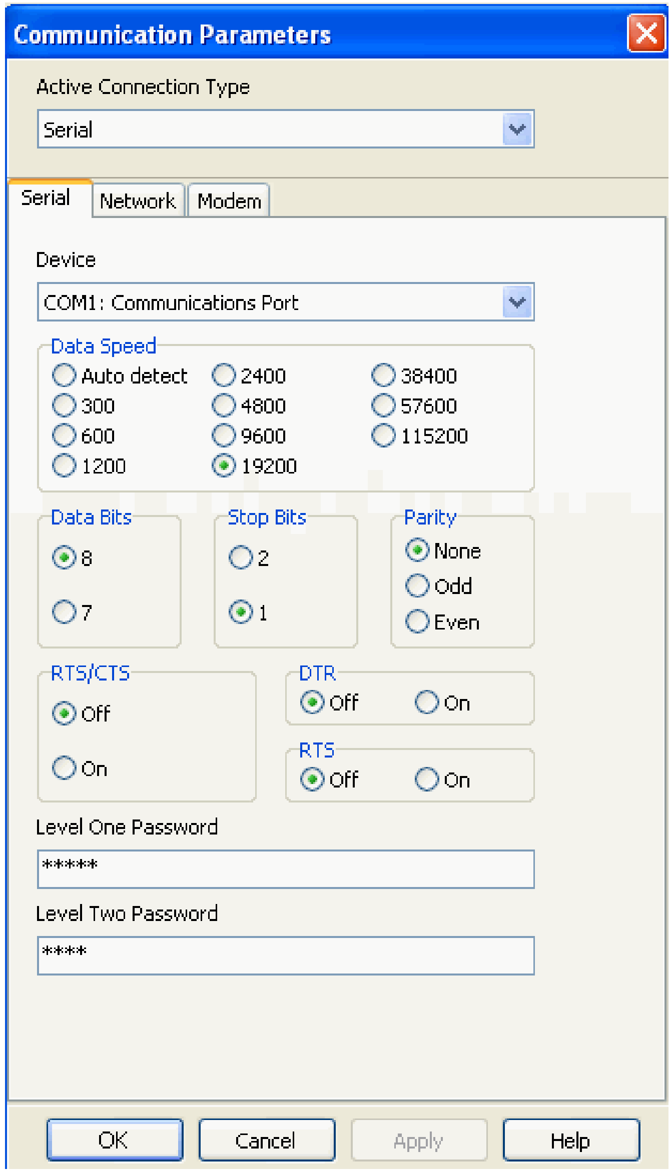

Figure 2.15: SEL Quickset Communication parameters

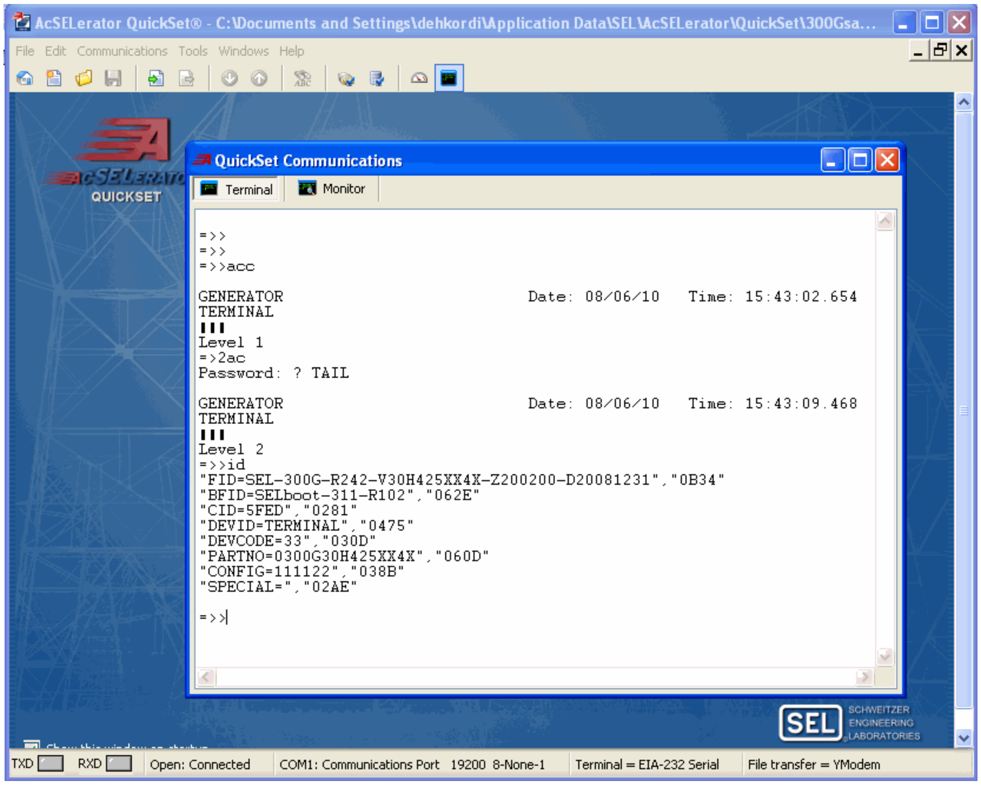

Figure 2.16: SEL Quickset serial Communication

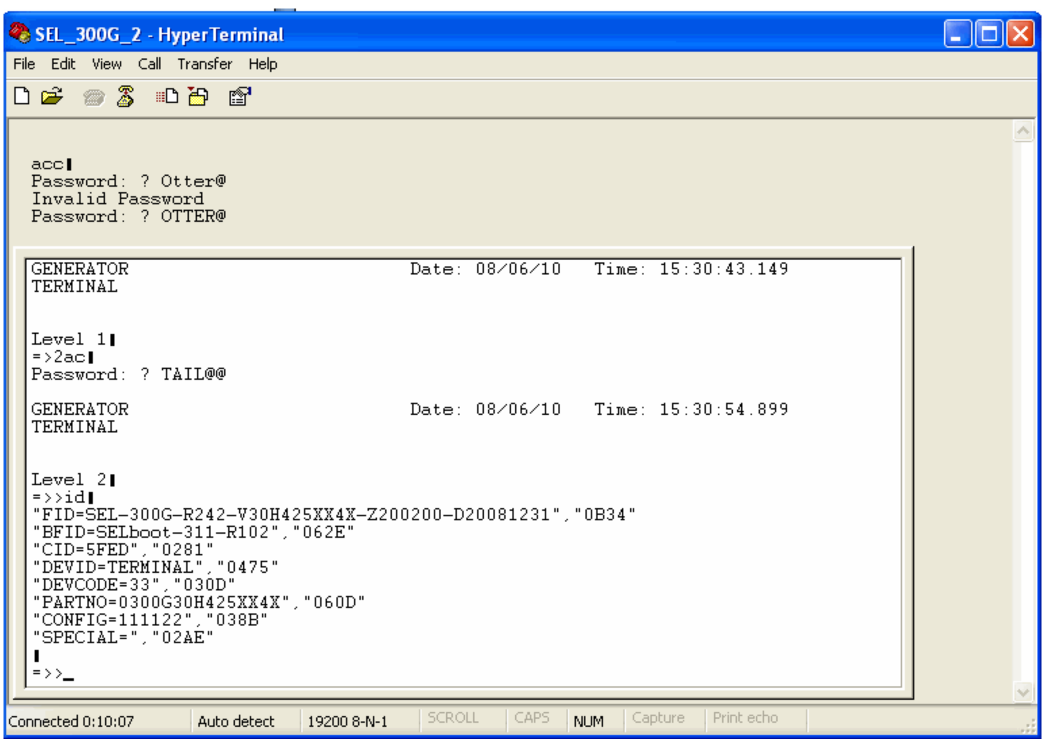

Figure 2.17: SEL hyper terminal communications

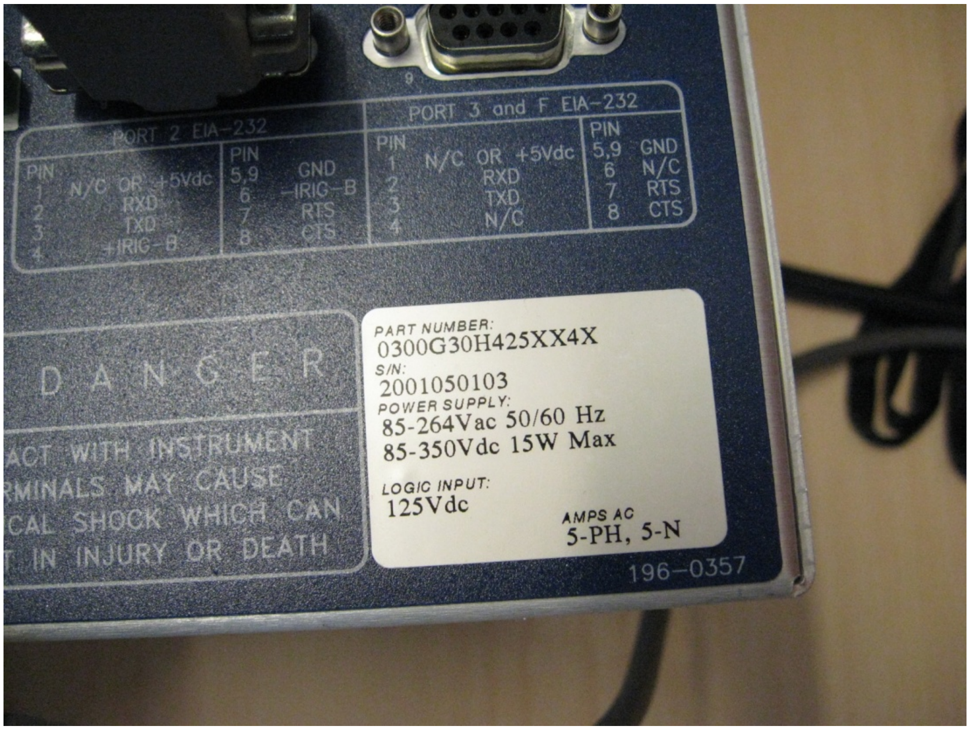

Figure 2.18: **Serial number sticker**

Note: In addition to the serial communication, communicating with the relay can be done using ETHERNET communication if installed in the relay.

2.7 Read relay settings and create/save new settings

Use the quickset software to read the existing settings of the relay. Save the settings as a backup.

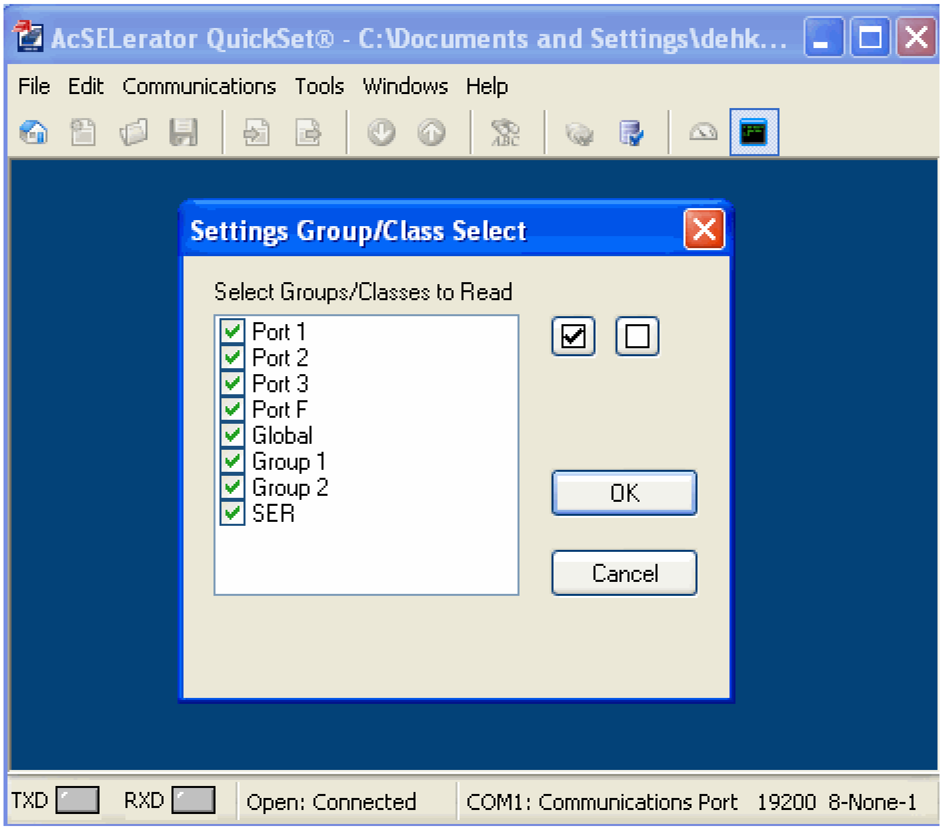

Figure 2.19: Reading the SEL relay settings

New settings can be created and sent to the relay using quick set. In this procedure the FID and P/N are needed. The following figures demonstrate the procedure.

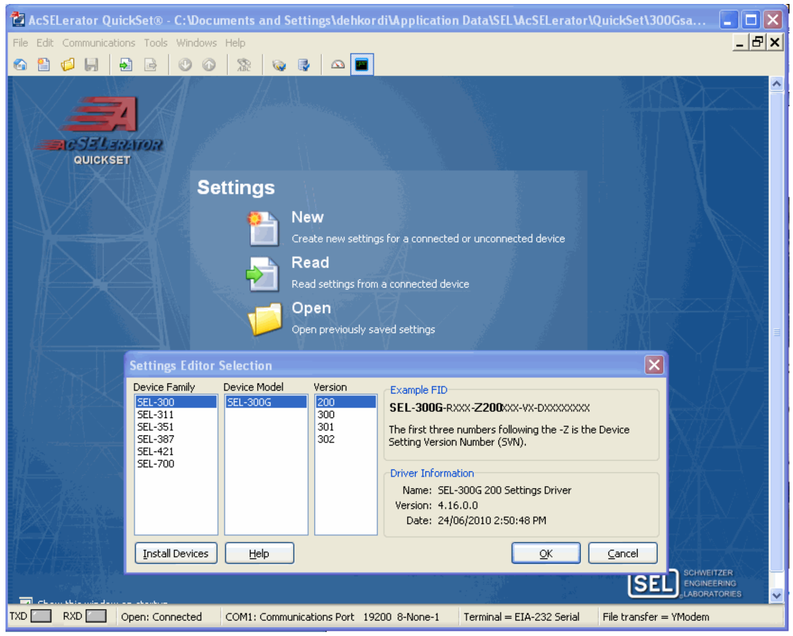

Figure 2.20: Using FID in creating new settings

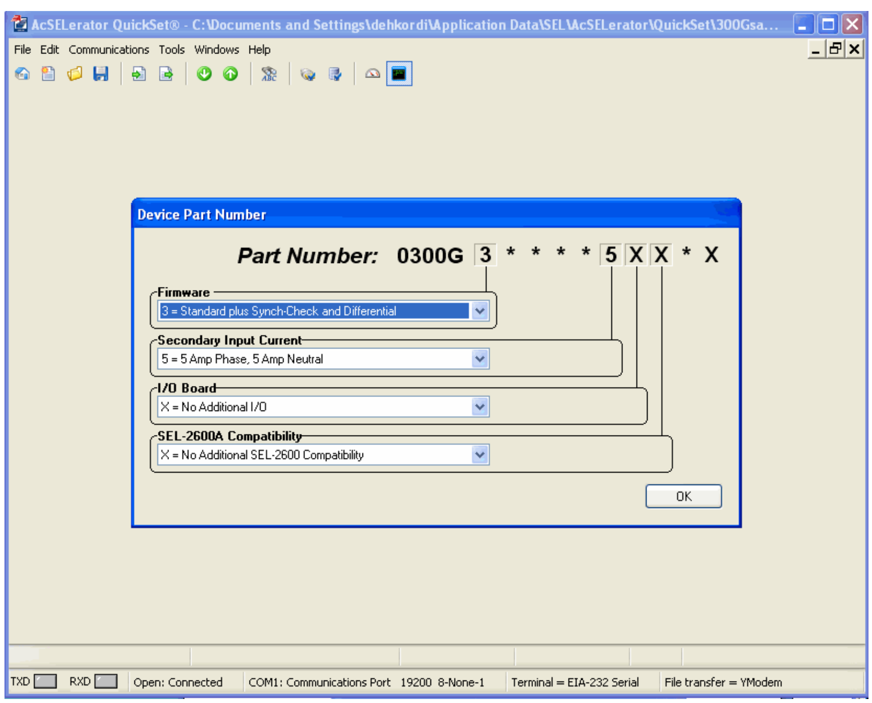

Figure 2.21: Using Part Number in creating new settings

Settings such as group selections, front panel display, settings for various elements of protection and serial port parameters, and trip logic can be identified using the following menu which appears after the part number is sent.

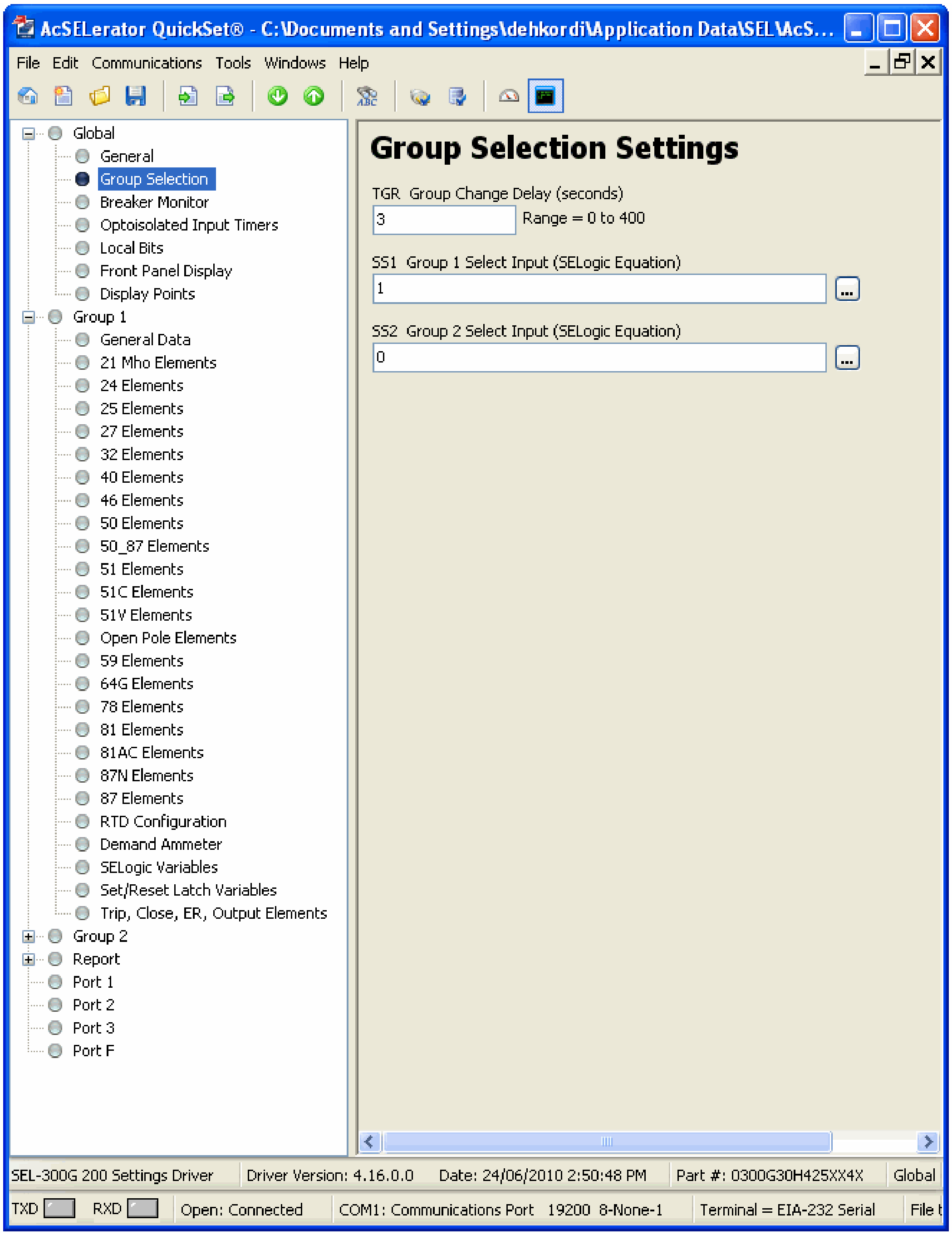

Figure 2.22: The SEL Quickset menu for setting the relay

2.8 Human Machine Interface (HMI) Menu

Human Machine Interface menu (HMI) can be used to observe the measured instantaneous values such as voltages, currents, etc and their phasor diagrams. It also shows the status of relay bits. Recorded events can be downloaded and data can be analyzed using the personal computer. Using the control window the main breaker can be tripped and closed if the proper trip logic is developed. (see Chapter 3) .

From the quickset HMI, the values of machine terminal voltages, stator currents, active power, etc can be observed and compared with the meters in runtime. The following figures are instantaneous metering values and phasor measurements from quickset HMI. Comparison between these figures and Figure 2.10 show that the setting of the relay CT and PT and GTAO scaling factor is done correctly.

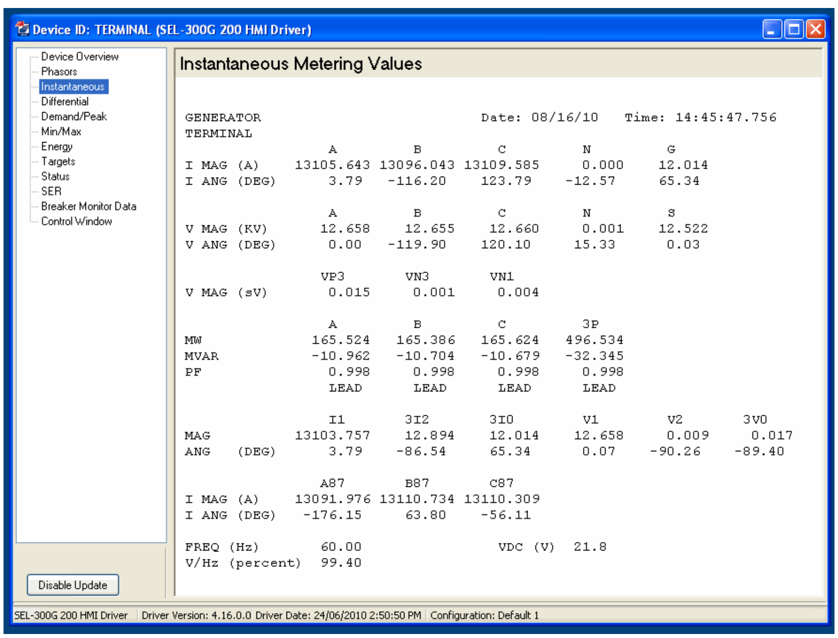

Figure 2.23: Instantaneous metering values from Quickset HMI.

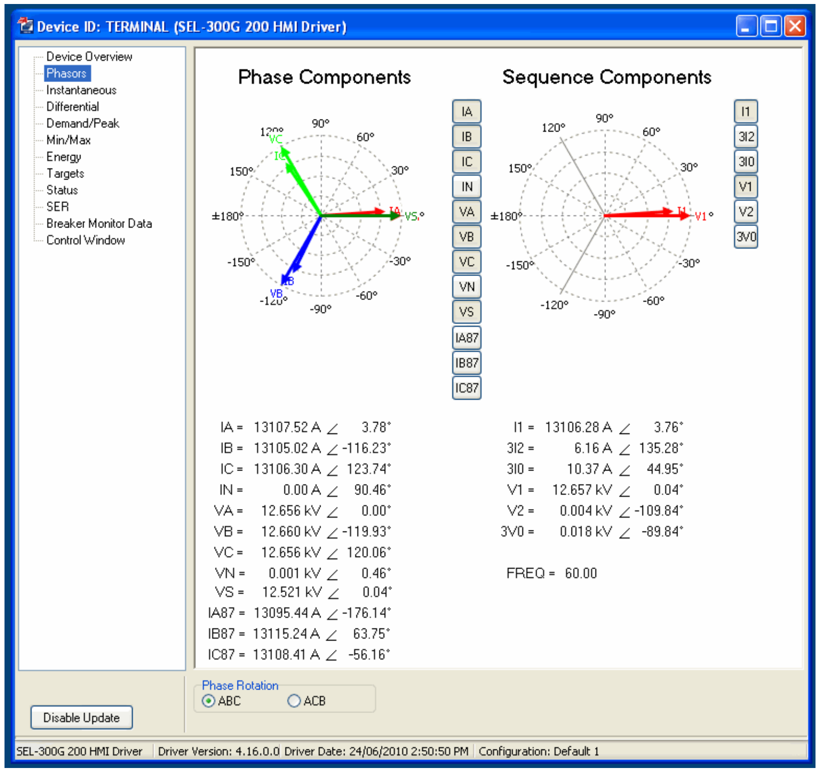

Figure 2.24: Phasor measurements from HMI.

Chapter 3: Setting the Relay Elements and Testing the Relay for Various Faults

In this chapter, the systematic procedure of testing various elements of the relay is explained. The readers are expected to study the following documents and have a basic understanding of the operation of synchronous generators.

a. SEL-300G Multifunction Generator Relay Instruction Manual (300G_IM_20160122.pdf) which can be downloaded from the SEL website.

b. Documentations for the phase-domain SM model (PDSM.pdf) and for the Generator Relay Model (generator_relay.pdf) available in RSCAD software.

The procedure is as follows:

- All of the possible relay elements are turned off
- The relay elements are activated one-by-one
- A corresponding fault is applied and trip signal and corresponding bits to that element are observed

Note that, the generator's prime mover is not tripped after each fault. Therefore, after each breaker trip generator accelerates and the frequency of the machine increases. For reclosing the breaker, the voltage at the terminals of the generator and the voltage at the other side of the breaker must be synchronized.

Note that, in this report the testing of the relay is not a closed-loop test. Figure 3.1 shows the logical expression which is developed to avoid sending the status of the breaker to the relay.

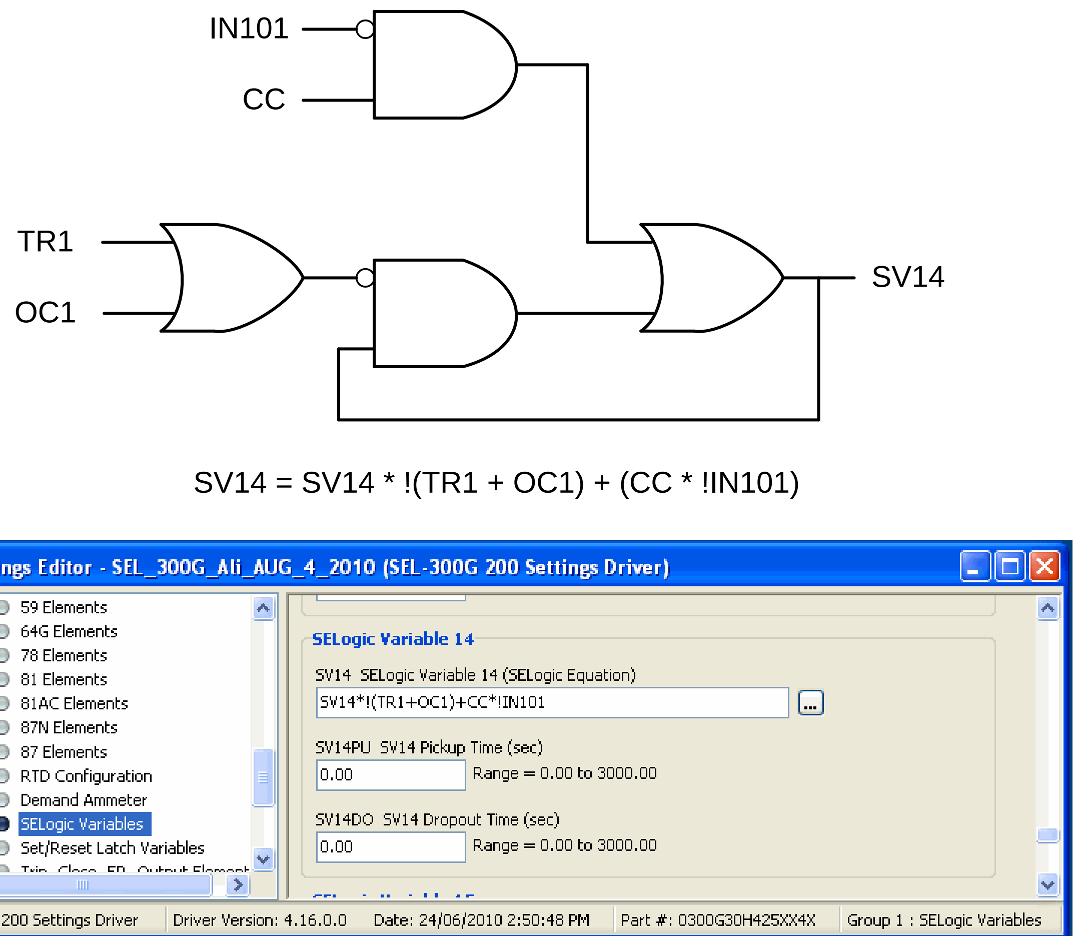

Figure 3.1: Developed SEL variable logic SV14

The SEL logic variable SV14 appears in the settings for open pole elements and display point. The logic indicates that in the absence of breaker status, SV14 is used.

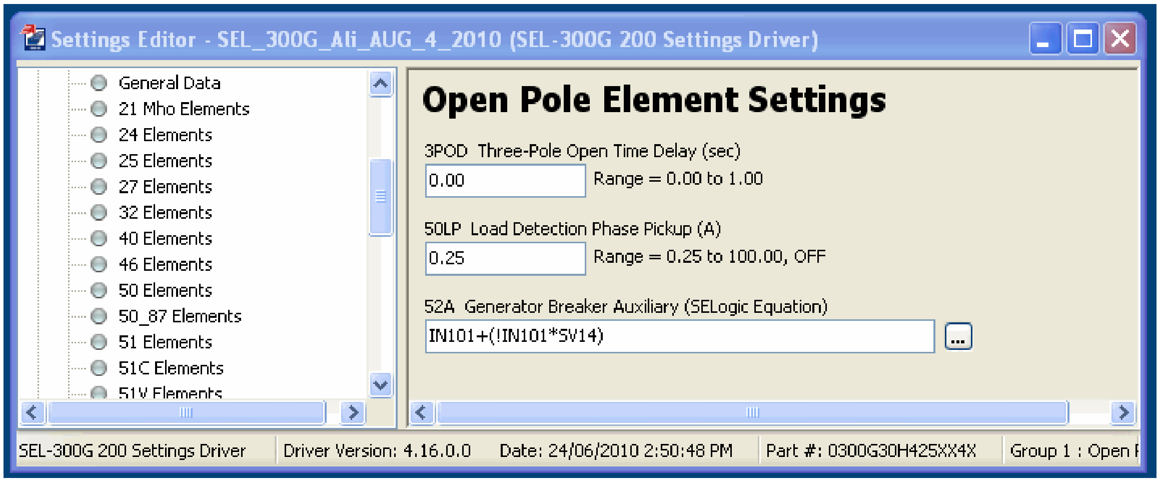

Figure 3.2: SV14 in the open pole element setting

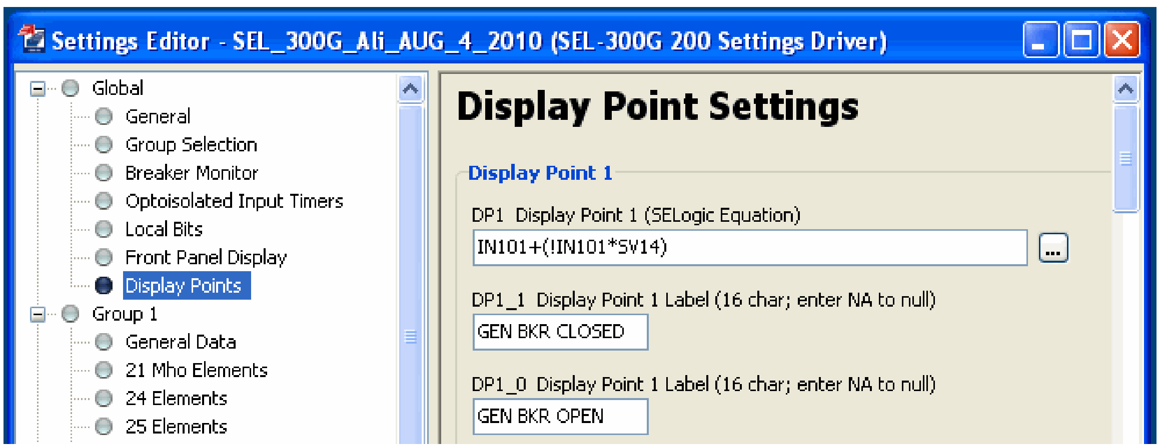

Figure 3.3: SV14 in the display point settings

<u>Users may like to have different arrangements for the trip and reclose logic.</u>

The active group of relay elements should be selected from the group selection menu, as shown in Figure 3.4.

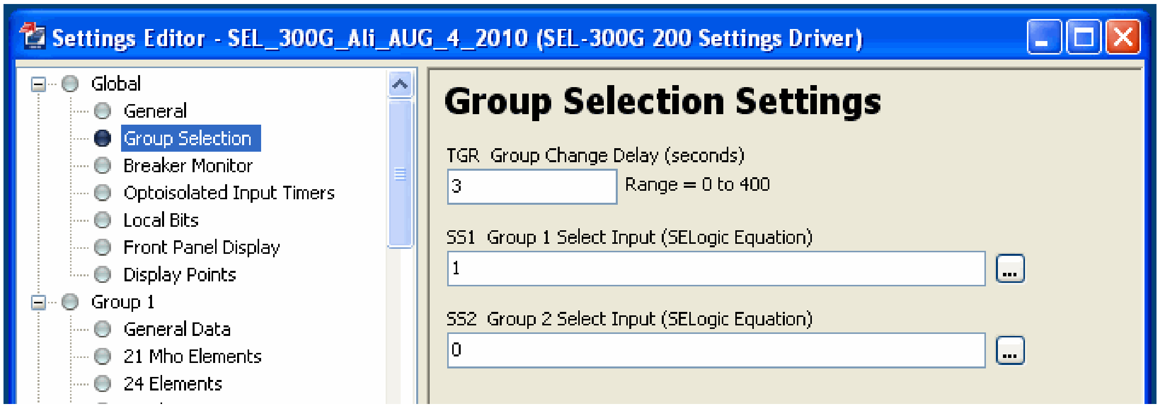

Figure 3.4: **Selection of group 1 in the group setting selection**

Various variables such as currents, voltages and power can be displayed using the front panel display or HMI. As can be seen from Figure 3.5, the user has the option of selecting variables that has to be displayed on the front panel.

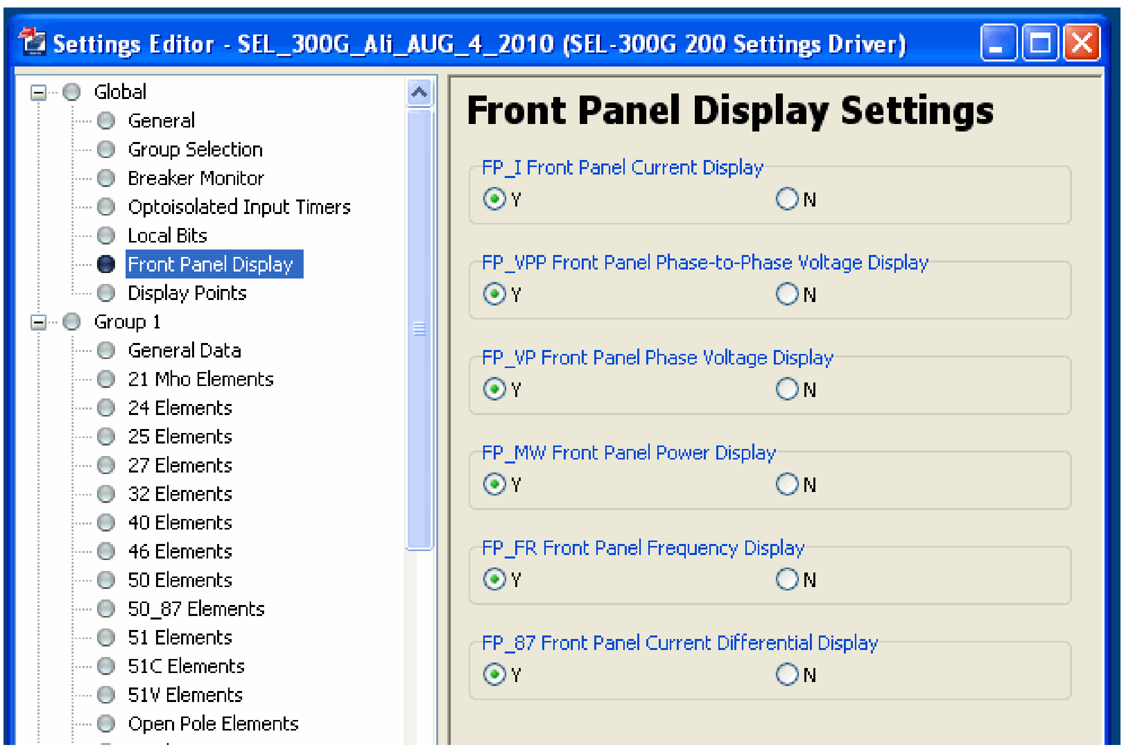

Figure 3.5: **SEL front panel display settings**

3.1 Testing the Protection Elements of the Relay

A systematic procedure of testing relay elements is disabling all possible elements and enabling only the elements of interest. Using this approach, applying a relevant fault during the simulation can test the functionality of the relay for that element.

Many of synchronous generator protection elements have overlapping functions. Sometime it is necessary for the user to set the time-delays of certain elements unusually small to observe the trip signal for that particular element. **The attached setting (SEL_300G_Ali_AUG_4_2010) in the relay data-base file (300Gsample.Rdb) is a setting that tries to distinguish the importance of each element for various types of fault by adjusting the time-delays of that element. These settings may not be what are used in practical operation of synchronous generators.** The following results are achieved using the aforementioned settings for the SEL-300G and the settings for the RTDS generator relay model in the RSCAD draft file. **The required information about the generator, which is necessary for setting some elements, can be found in the MAP file** (PDSM_RELAY_300G_5.map).

3.1.1 Testing the relay for stator-ground fault

The reported tests are performed for low impedance and high impedance grounding as well as fault on various locations of the winding.

3.1.1.1 A ground fault in the middle of the winding with the neutral grounded through a low impedance

With the ground impedance of 0.5 Ohm (low impedance grounding), a solid fault-ground is applied to the middle of phase A winding.

As discussed earlier, with low impedance grounding the phase differential element (87) is capable of detecting stator-ground faults. Variation of phase A operating current versus the restraint current overlaid on the differential characteristics of the relay (50% of the neutral) is shown in Figure 3.6.

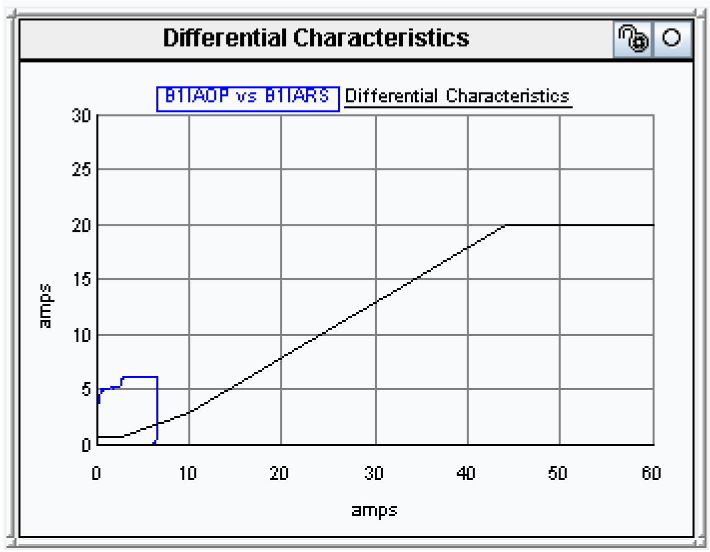

Figure 3.6: Variation of phase A operating current versus the restraint current overlaid on the differential characteristics of the relay (50% of the neutral)

Figure 3.7 shows the terminal voltages, machine currents and neutral voltage and current. As can be seen, in addition to the large flow of current in the stator winding A2, which causes the phase differential element to trip, the neutral also experiences large overvoltage and over-current. This causes other protection elements such as 64G1 (neutral overvoltage) and 50N (neutral over-current) to be activated as well.

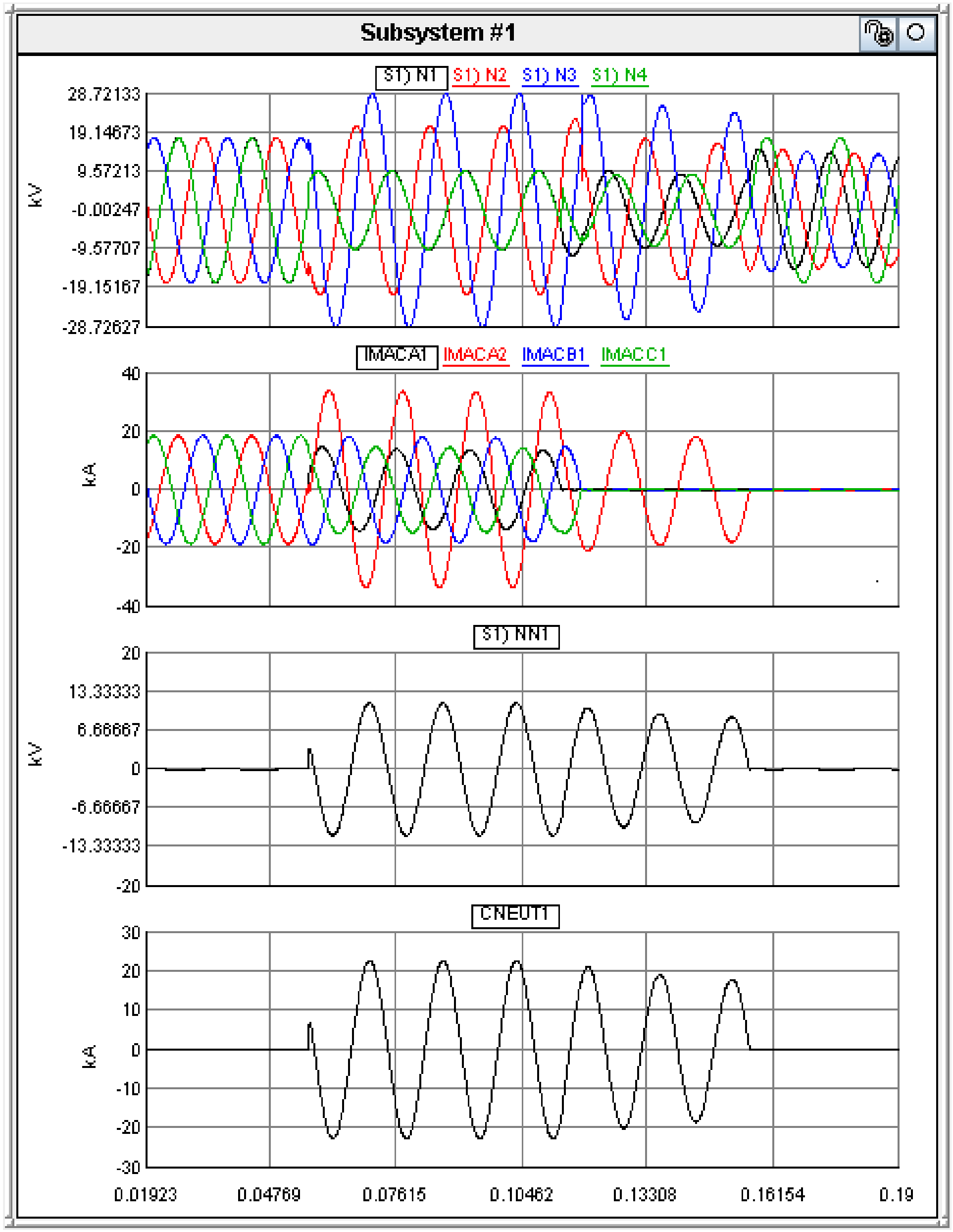

Figure 3.7: **stator voltages, currents and neutral voltage and current (fault at 50% from the neutral)**

This is shown in the Figures 3.8 and 3.9 captured from RUNTIME screed and SEL 300G relay, respectively.

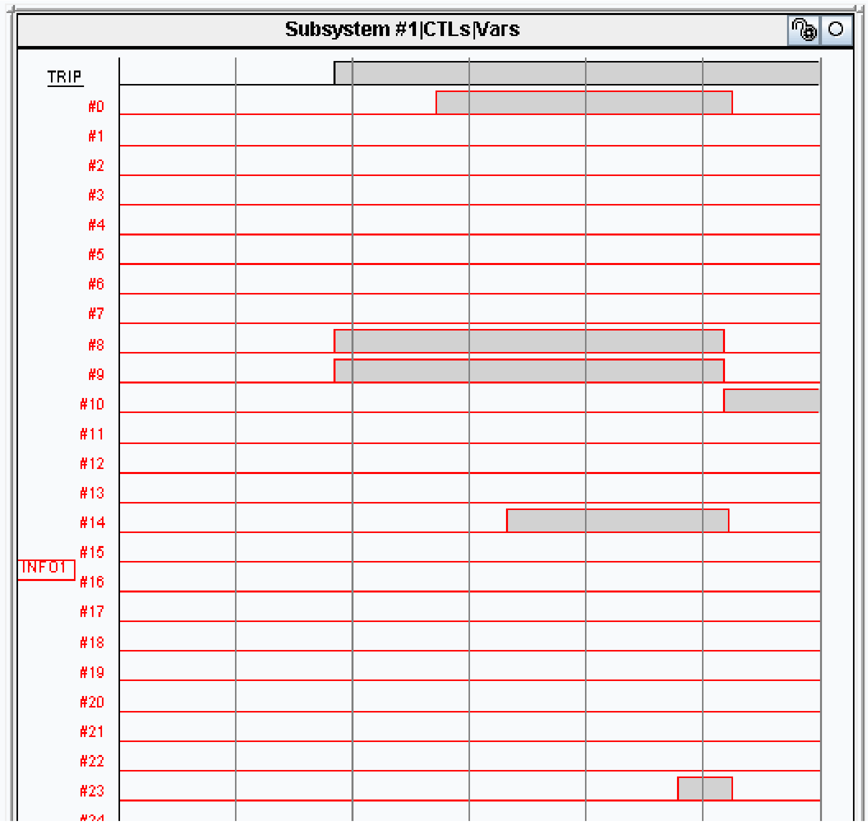

Figure 3.8: INFO1 signal from the relay model

Figure 3.9: SEL 300G front panel view for the fault with low impedance grounding

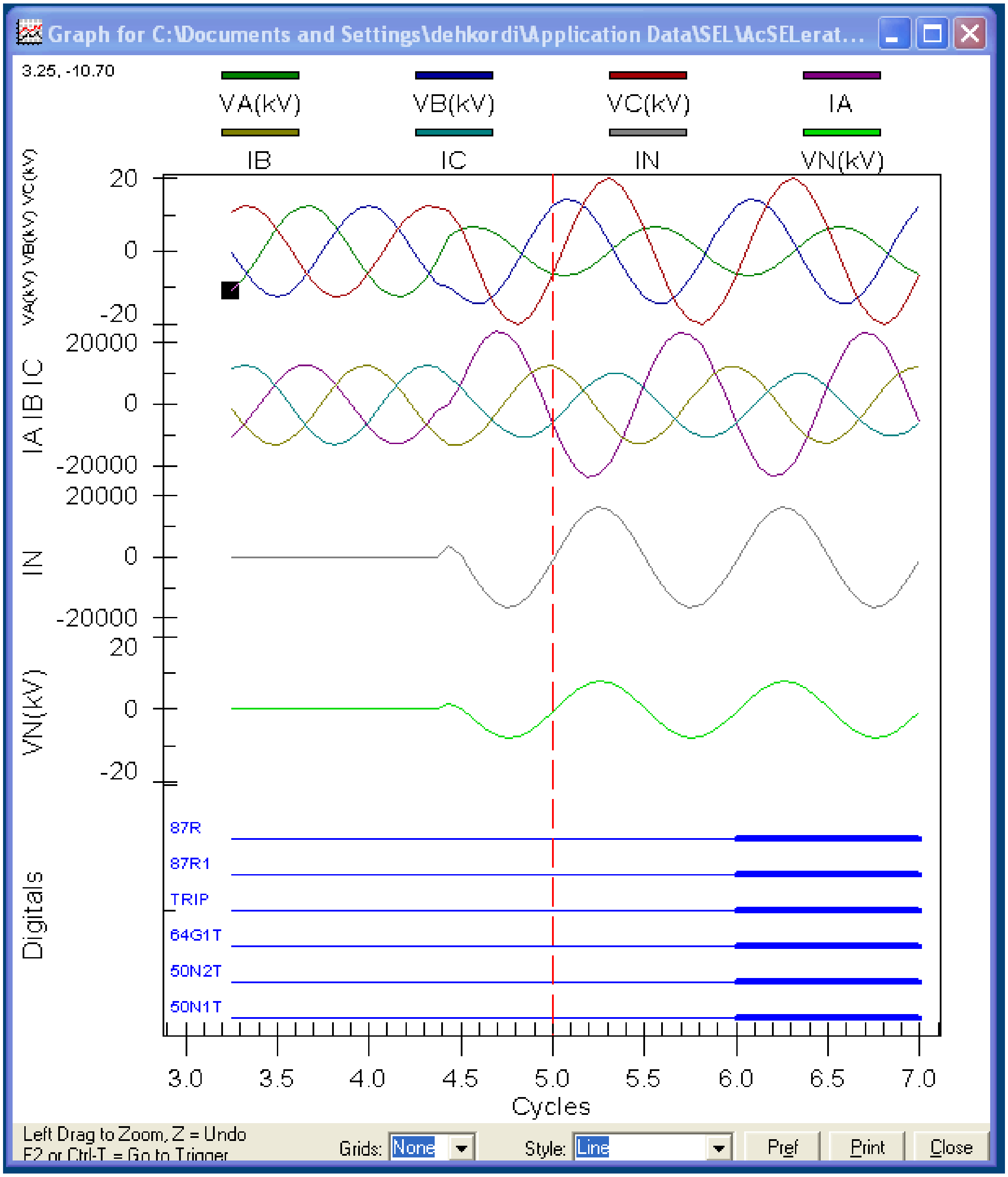

Figure 3.10: **Waveforms and trip signals from SEL-300G recorded events**

3.1.1.2 A ground fault at 8% from the neutral with the neutral grounded through a low impedance

With the ground impedance of 0.5 Ohm (low impedance grounding), a solid fault-ground is applied to the phase A winding close to the neutral (8%). As expected, the operating current in this situation is not large enough to activate the 87P element. The reason is that the closer the fault is to the neutral, the ratio of induced voltage on the sub-winding to the impedance which limits the fault current (in this case the grounding impedance) becomes smaller. Figure 3.11 shows the relation between the operating and the restraining current of the relay in this situation. As can be seen from Figure 3.11, the operating current does not cross the differential characteristics of the relay and therefore the element 87P does not operate.

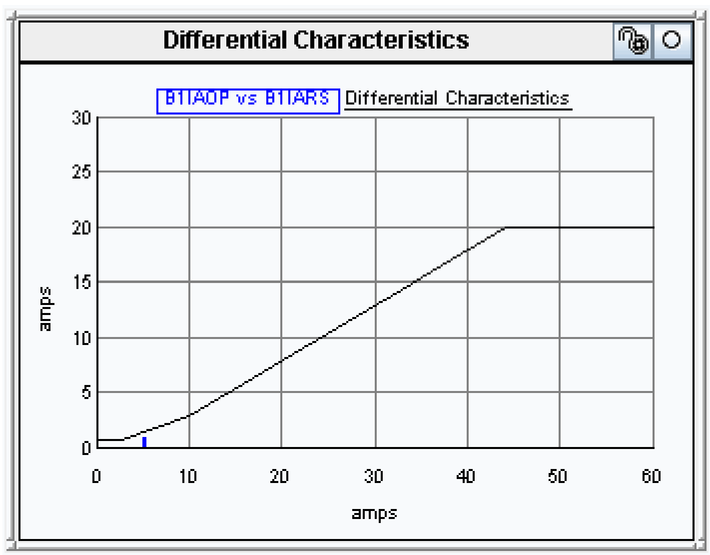

Figure 3.11: Operating vs restraining currents when the fault is too close to the neutral

The front panel display of the relay (Figure 3.12) shows that SEL-300G did not react to this fault.

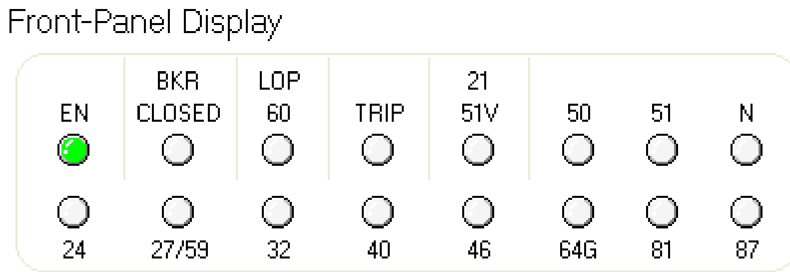

Figure 3.12: Front-Panel Display from the HMI of the SEL-300G after the fault very close to the neutral

Usually the element 64G2 which operates based on the existence of the third harmonic on the neutral and terminals of the machine detects the faults which are close to the neutral. However, in the machine model simulated in this circuit, the option of DQ-BASED is used which assumes sinusoidal assumption for the windings and actual distribution of the windings is not considered. Therefore, winding and permeance-related harmonics are not represented.

3.1.1.3 A ground fault at 50% from the neutral with the neutral grounded through a high impedance

With the ground impedance of 50 Ohm (high impedance grounding), a solid fault-ground is applied to the middle of phase A winding. As can be seen in Figure 3.13, due to the high neutral impedance, the current in winding A2 is very close to the current in winding A1. Consequently, the differential element does not operate. However, the large neutral over-voltage causes the element 64G1 of the relay to trip. This is shown in the front panel display of the relay in Figure 3.14.

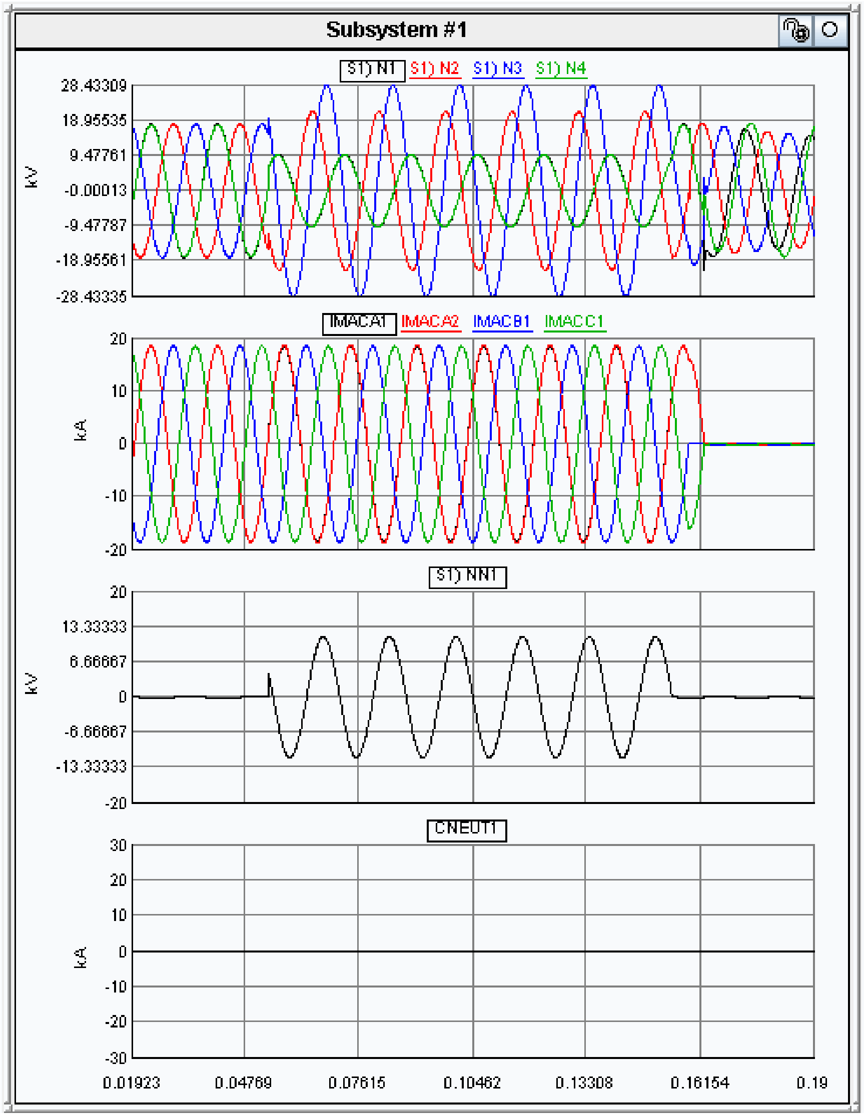

Figure 3.13: Stator voltages, currents and neutral voltage and current during a fault with the high impedance grounding

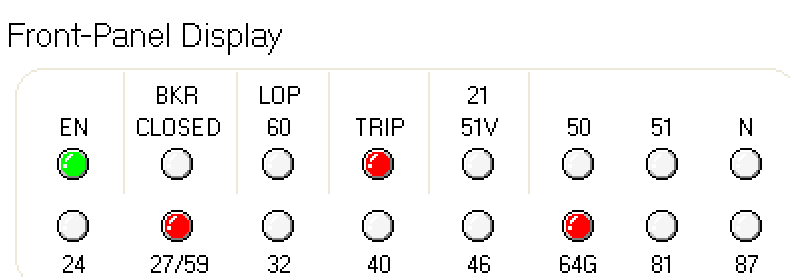

Figure 3.14: Front panel display from the HMI of the SEL-300G after a fault when the neutral is grounded using a high impedance.

3.1.1.4 A ground fault at 5% from the neutral with the neutral grounded through a high impedance

With the ground impedance of 50 Ohm (high impedance grounding), a solid fault-ground is applied to the point of phase A winding at 5% of the neutral. As can be seen in Figure 3.15, the neutral over voltage is not large enough to trip the element 64G2. Using the circuit shown in Appendix C, the 3rd harmonic voltage on the neutral and terminals of the machine is simulated. By adding this circuit to the simulation case, the 3rd harmonic voltage will change during the fault and hence trips 64G2 (see Figure 3.16).

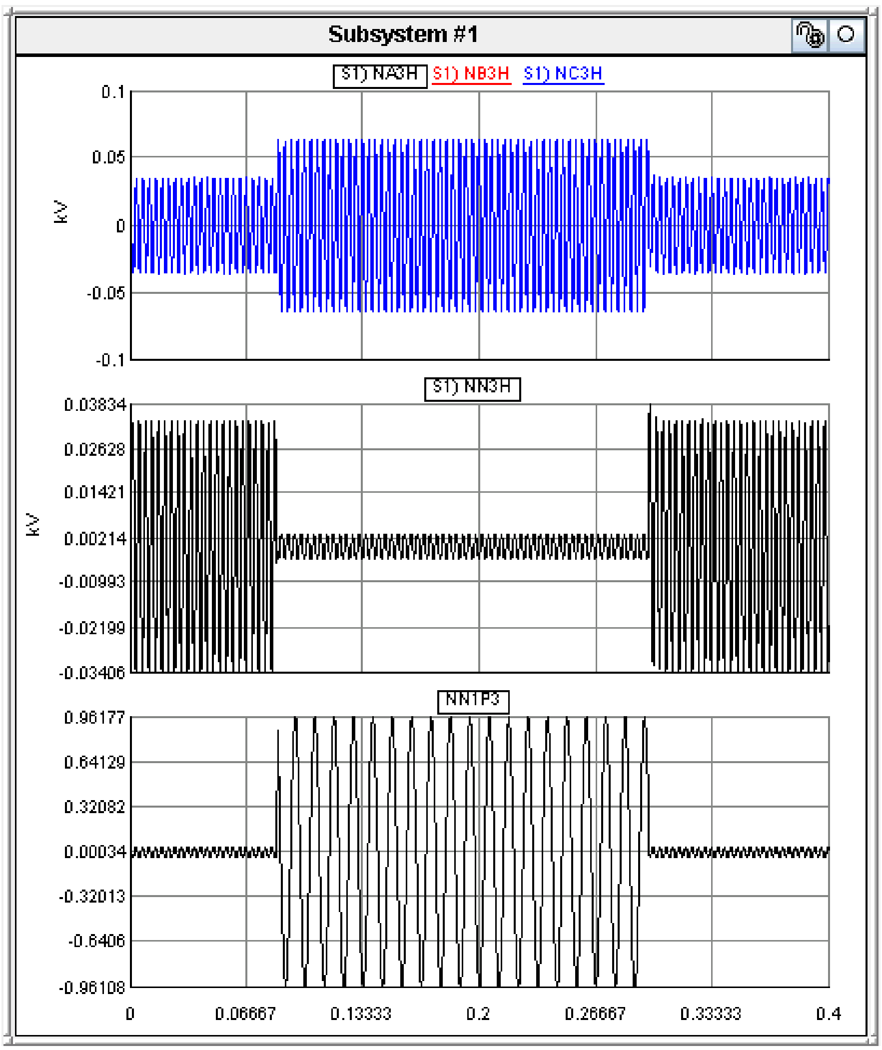

Figure 3.15: Stator 3rd harmonic voltages, neutral 3rd harmonic voltage and neutral voltage during a fault at 5% with the high impedance grounding

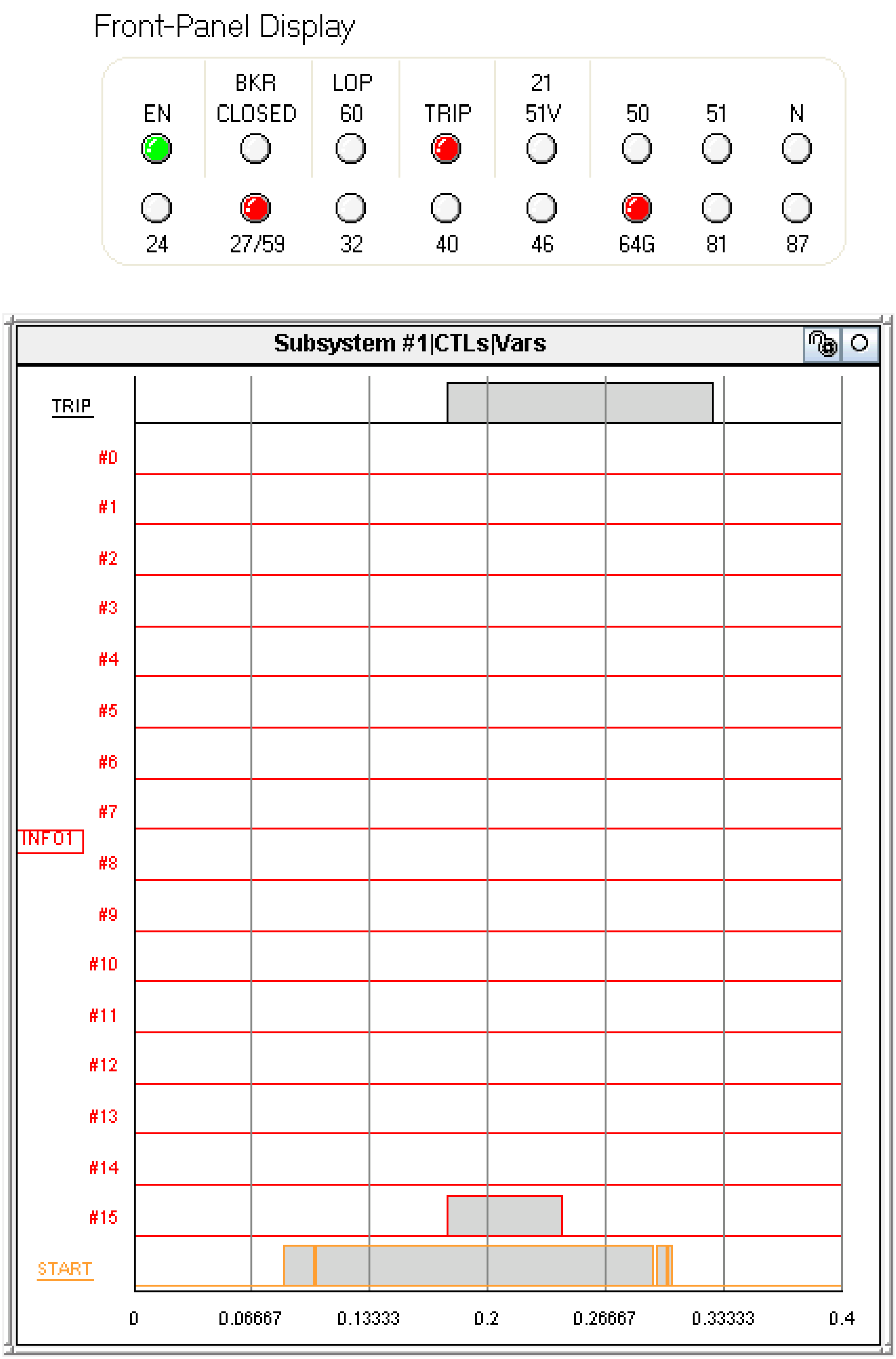

Figure 3.16: Front panel display from the HMI of the SEL-300G and INFO1 signal from the relay model after a fault when the neutral is grounded using a high impedance.

3.1.2 Testing the relay for the loss-of-field excitation fault

Generators are normally operated so they are slightly overexcited and thus normal stable operation is in the 1st quadrant. However, when the excitation field is lost, the generator must absorb reactive power and consequently the operation will be in the 4th quadrant. This area of operation is unstable and should be avoided. If there is no excitation and the system can sustain the voltage and provide the necessary reactive power, the machine will act as an induction generator. Otherwise loss of synchronism will occur. In addition, if the excitation is sufficiently low, overheating may occur that can damage the machine.

This fault is simulated by switching the “ExcSource” switch to manual and letting the machine to receive its excitation voltage from the run-time slider EF2 = 0.4. The relay element detects the fault using the MHO characteristics and sends the TRIP signal to the load breaker. Figure 3.17 shows the variation of the imaginary part of the impedance seen from the terminals versus the real part overlaid on the MHO characteristics of the relay. Figure 3.18 shows the front panel display of the relay after this fault. As can be seen, element 40 is activated.

Please refer to the documentations for the Generator Relay Model (generator_relay.pdf) and IEEE standards [11], [12] for more details about the loss-of -field excitation fault.

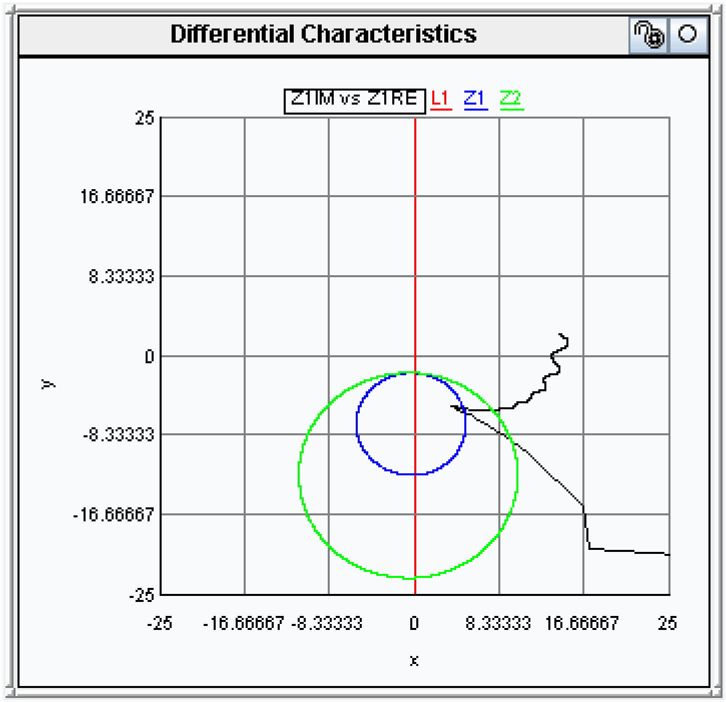

Figure 3.17: Trajectory of the imaginary part of impedance versus the real part seen from the terminals of the machine during a loss-of –field excitation fault overlaid on the MHO characteristics of the relay.

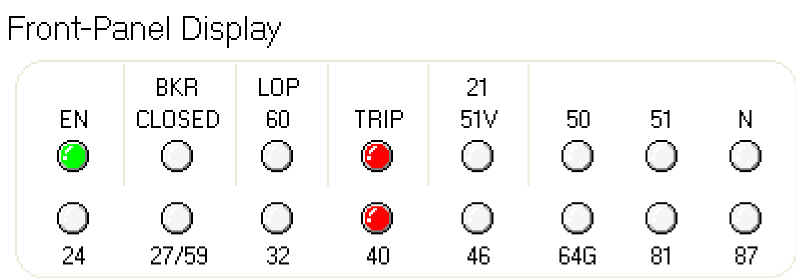

Figure 3.18: Front-Panel Display from the HMI of the SEL-300G after a loss-of-field excitation fault

3.1.3 Testing the relay for turn-to-turn faults

Since the machine model has two points of fault on each phase, a turn-to-turn fault can be easily modeled by connecting the fault nodes to each other. Figure 3.19 shows a phase A turn-to turn fault between AJ1 and AJ2 fault nodes) Element 46 of the SEL-300G relay uses the negative sequence to detect such faults. The front panel display of the relay is shown in Figure 3.20.

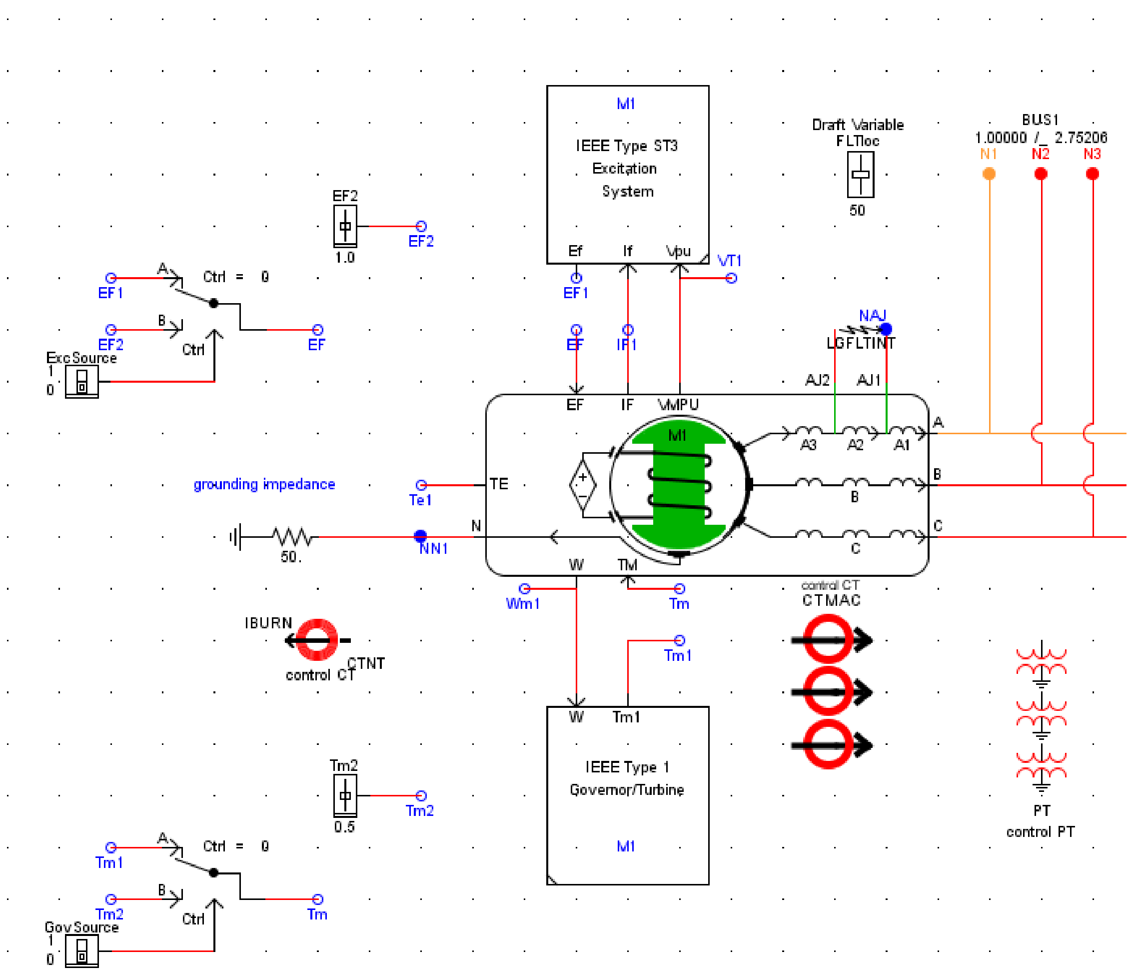

Figure 3.19: Modeling of a phase A turn-to-turn fault using the phase-domain machine model

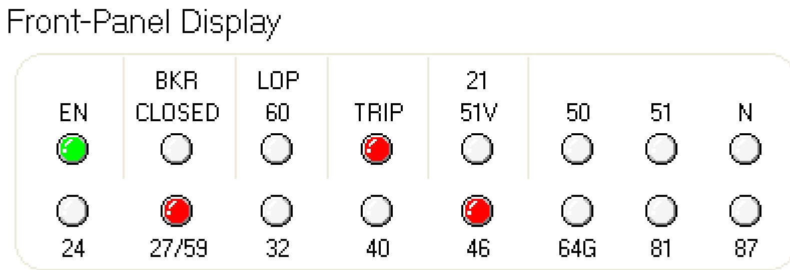

Figure 3.20: Front-Panel Display from the HMI of the SEL-300G after a turn-to-turn fault

3.1.4 Testing relay for turn-to turn faults on phases (B, C) of the generator

The machine model allows the user to simulate turn-to-turn faults on phases B and C. Figure 3.21 shows how to set the parameters of the machine to have a fault on phase B. As can be seen in Figure 3.22, by adjusting the parameters, the fault points on phase B will accessible for fault connection.

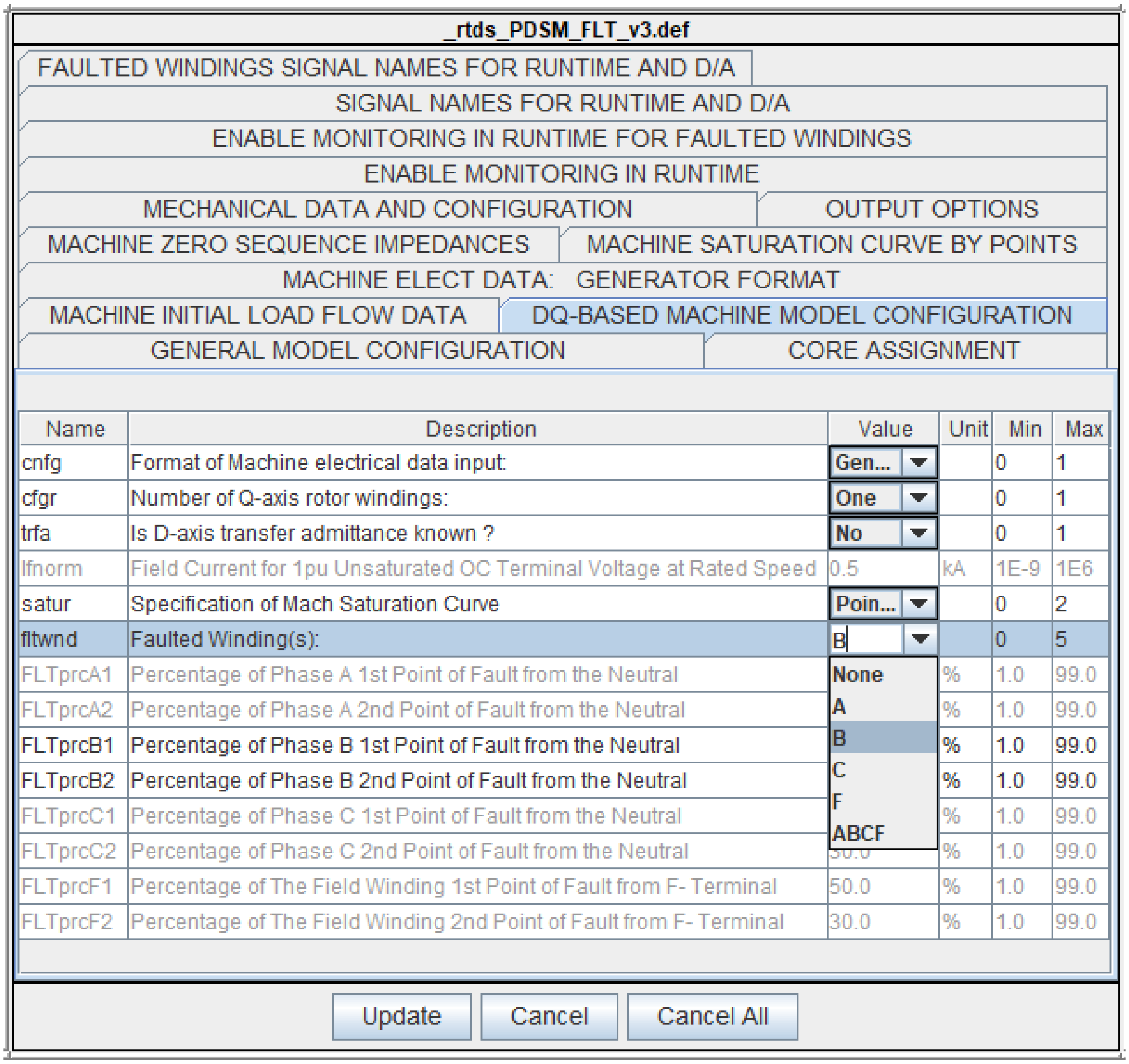

Figure 3.21: **Setting the machine parameters for the purpose of testing a fault on phase B**

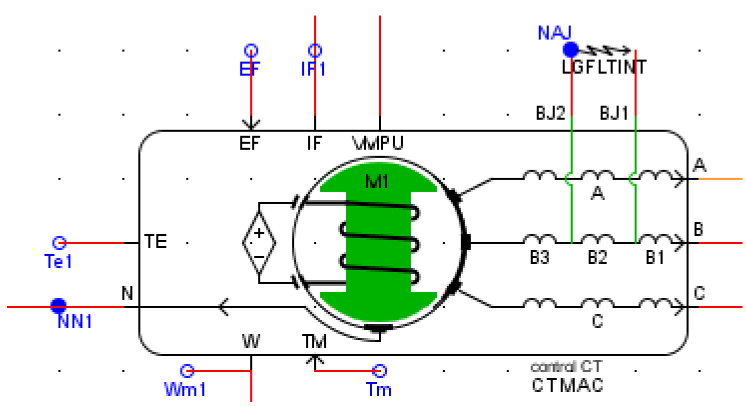

Figure 3.22: **Modeling of a phase B turn-to-turn fault using the phase-domain machine model**

Chapter 4: Miscellaneous notes

This chapter essentially contains the appendices mentioned in the document.

4.1 Appendix A: calculation of CT's and PT's turns ratio and GTAO Scaling Factors

Data prepeartion for the PDSM model for Generator ptotection:

$Vll\_rms := 22.0kV$ $\qquad \Delta t := 50\mu \qquad \Delta t = 5 \times 10^{-5}$

$f := 60 \qquad \omega := 2\pi \cdot f$

$Prated := 500MVA$

$$Il\_rms := \frac{Prated}{\sqrt{3} \cdot Vll\_rms} \qquad Il\_rms = 13.122 \cdot kA$$

$Vll\_rms = 22 \cdot kV$

$$Vln\_rms := \frac{Vll\_rms}{\sqrt{3}} \qquad Vln\_rms = 1.27 \times 10^{4}$$

PT and CT ratios:

$rel\_nom\_vol := 115V$ $\qquad \frac{rel\_nom\_vol}{\sqrt{3}} = 66.395$

$rel\_nom\_cur := 5A$

$$PT\_ratio := \frac{Vll\_rms}{rel\_nom\_vol} \qquad PT\_ratio = 191.304$$

$$CT\_ratio := \frac{Il\_rms}{rel\_nom\_cur} \qquad CT\_ratio = 2.624 \times 10^{3}$$

GTAO Scaling factors:

scaling factor for current signals:
Nominal current of the CT in the secondary = 5A
corresponding low level input for the rated current = 100mV

5 A * (5/scl_curr) = 100 mV

$$scl\_curr := \frac{5A \cdot 5}{100mV} \qquad scl\_curr = 250$$

scaling factor for voltage signals:
Nominal voltage of the PT in the secondary = 115/sqrt(3) = 67 V
corresponding low level input for the rated voltage = 657.5 mV

67 V * (5/G) = 657.5 mV

$$scl\_vol := \frac{67V \cdot 5}{657.5mV} \qquad scl\_vol = 509.506$$

4.2 Appendix B: sending signals using the front panel analogue output

The required signals by the relay can be also sent using the front panel analogue output as shown in Figure 4.1.

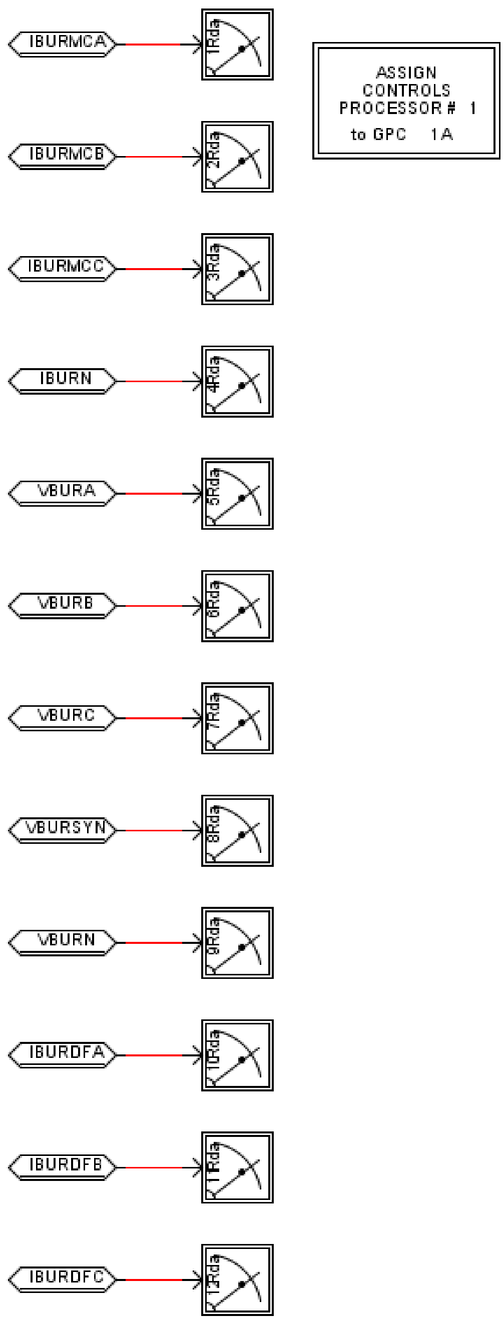

Figure 4.1: Sending out analogue signals using the front panel analogue output

The required signals explained in Section 2.3 can be sent out to the low-level test interface using the front panel analogue output, as it is shown in Figure 4.2.

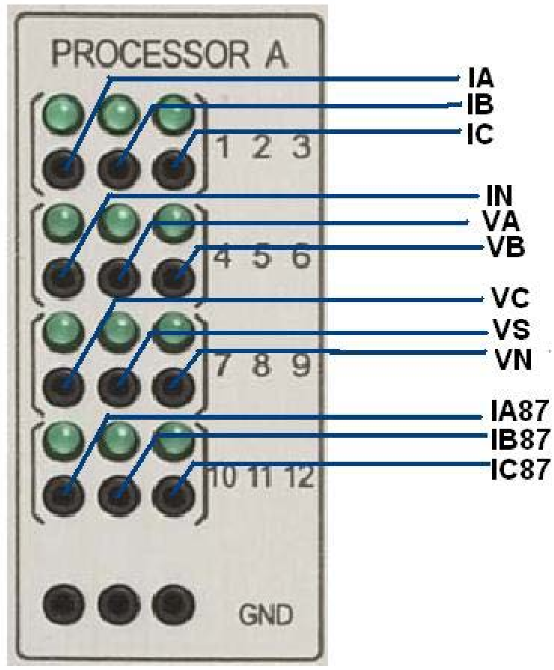

Figure 4.2: Sending out signals using the front panel analogue output

Note that Figure 4.2 shows the older generation of the RTDS Simulator analogue front panel input whereas Figure 4.3 shows the front panel analogue output of a NovaCor chassis. The same order of currents and voltages shown in Figure 4.2 will be applicable to Figure 4.3.

Figure 4.3: Front panel analogue output of a NovaCor chassis

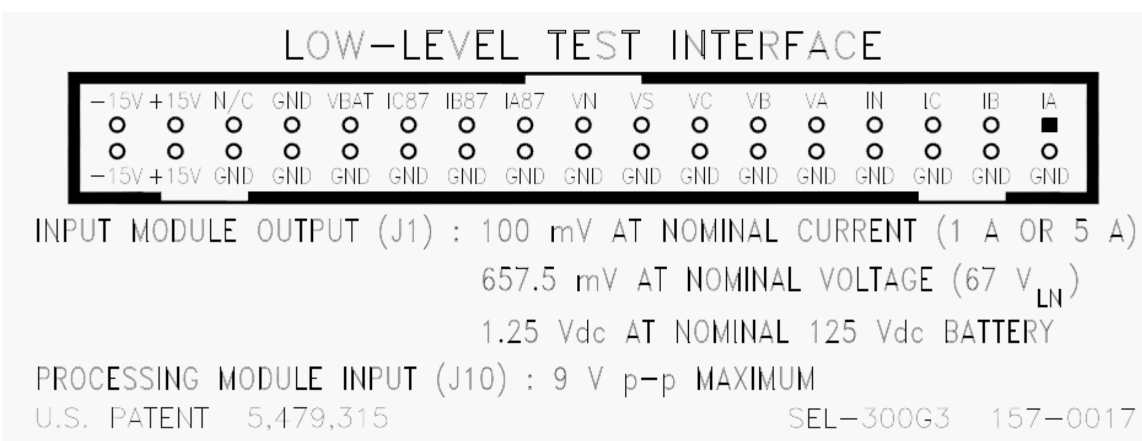

Figure 4.4: Low-Level Test Interface, 0300G3

The input signals to the low-level test interface from right to left are (See Figure 4.4):

- Stator currents: IA, IB, IC
- Neutral current: IN
- Terminal voltages: VA, VB, VC
- Synchrono-check voltage VS.
- Neutral voltage: VN
- Differential current (currents in the circuit breaker). IA87, IB87, IC87.

4.3 Appendix C: Artificial Generation of the 3rd Harmonic Voltage on the Neutral and Terminal of the Machine

As mentioned earlier, the dq-based faulted machine model does not generate the winding- and permeance-related harmonics. Some of these harmonics such as the 3rd harmonic of the neutral and terminals are used for protecting the stator of synchronous machine against the ground faults.

However, these harmonics can be generated, added to the terminal and neutral voltage and passed to the relay as shown in Figures 4.5 - 4.7. The third harmonic voltage across the windings is proportional to the active power of the machine [11], [14]. The circuit in Figure 4.4 shows the generation of the 3rd harmonic voltage across a synchronous machine winding. The required input for this circuit is the percentage of the 3rd harmonic in full load and no load operation of the machine.

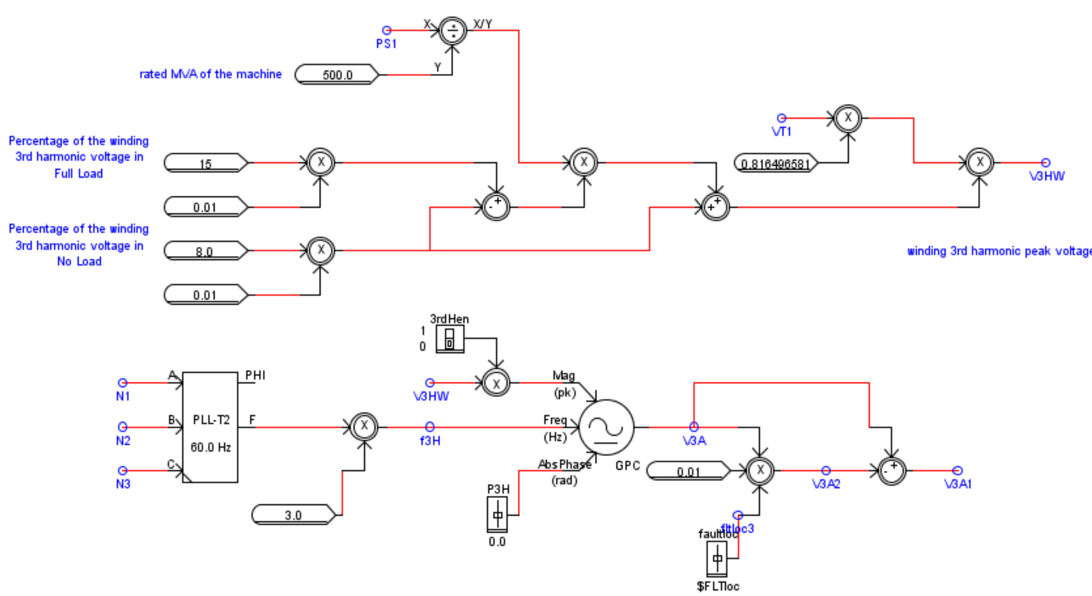

Figure 4.3: **Simulating the 3rd harmonic voltage across the winding of a synchronous machine**

The third harmonic across the winding is divided proportional to the number of turns across the sub-windings. Figure 4.5 shows the equivalent circuit for the sources of the 3rd harmonic and the neutral impedance and stray capacitances that these sources see.

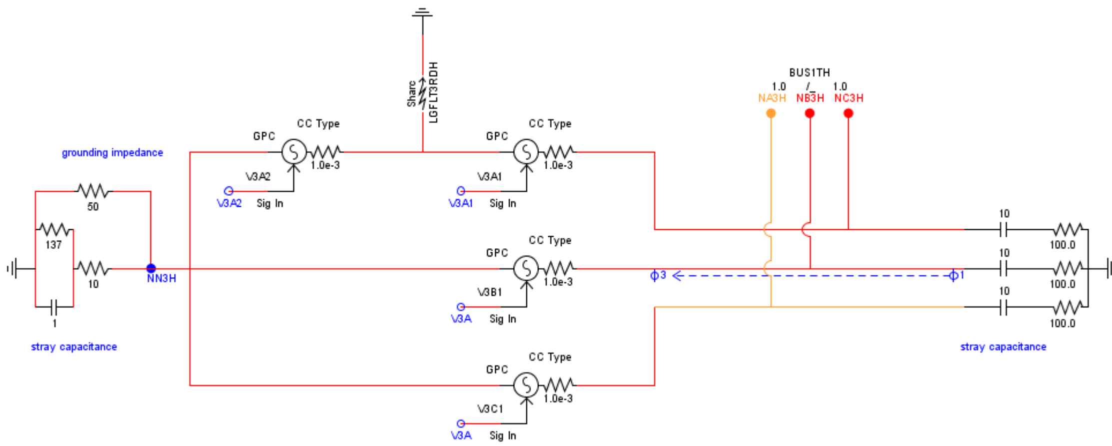

Figure 4.4: **Simulating the 3rd harmonic voltage across on the terminal and neutral during a ground fault**

These voltages can be added to the node voltages and send to the relay as shown as Figure 4.6.

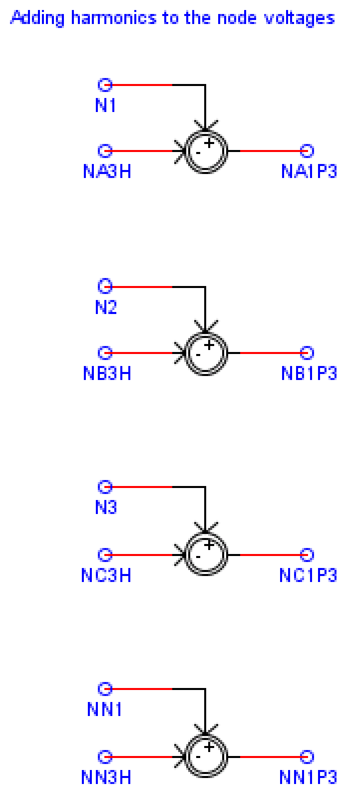

Figure 4.5: Adding the 3rd harmonics to the terminal and neutral voltages

Refrences:

[1] I.M. Canay, “Modelling of Alternating−Current Machines having Multiple Rotor Circuits”, IEEE Trans. on Energy Conversion, Vol. 8, No. 2, June 2, 1993, pp. 280−296.

[2] “First Benchmark Model for Computer Simulation of Subsynchronous Resonance”, PAS−96, Number 5, Sept/Oct 1977, pg. 1565.O. Anaya-Lara, E. Acha, "Modeling and analysis of custom power system by PSCAD/EMTDC," IEEE Trans. Power Delivery, vol. 17, no. 1, pp. 266-272, January 2002.

[3] T. Sebastian, and G.R. Slemon, ”Transient modeling and performance of variable−speed permanent−magnet motors, ” IEEE Trans. Industry Applications, vol. 25, No.1, pp. 101−106, Sep. 1986. Y. H. Liu, J. Arrillaga, N. R. Watson, "Multi-level voltage sourced conversion by voltage (F.1).

[4] A. B. Dehkordi, P. Neti, A.M Gole, and T.L. Maguire, ”Development and Validation of a Comprehensive Synchronous Machine Model for a Real−Time Environment,” IEEE Trans. Energy Conversion, Vol. 25, No. 1, March 2010.

[5] A.B. Dehkordi, A.M Gole, and T.L. Maguire, ” Permanent magnet synchronous machine model for real− time simulation”, International Conference on Power System Transients (IPST 2005), Montreal, June, 2005.

[6] P. P. Reichmeider, D. Querrey, C. A. Gross, D. Novosel, and S. Salon, ”Internal faults in synchronous machines part I: the machine model,” IEEE Trans. Energy Conversion, vol. 15, no.4, pp. 376−379, Dec 2000.

[7] P. P. Reichmeider, D. Querrey, C. A. Gross, D. Novosel, and S. Salon, ” Internal faults in synchronous machines part II: model performance,” IEEE Trans. Energy Conversion, vol. 15, no.4, pp. 380−385, Dec 2000.

[8] N.A. Al−Nuaim and H.A. Toliyat, ”A novel method for modeling dynamic air−gap eccentricity in synchronous machines based on modified winding function.

[9] A. B. Dehkordi, ”Improved Models of Electric Machines for Real−Time Digital Simulation” Ph.D. Thesis, University of Manitoba.

[10] P.S. Kundur, Power system stability and control, New York, McGraw−Hill., 1983, Chapter 3.

[11] IEEE Guide for Generator Ground protection, IEEE Standard C37.102TM−2006, Feb. 2007.

[12] IEEE Guide for AC Generator Protection, IEEE Standard C37.101TM−2006, Nov. 2007.

[13] A.B. Dehkordi, D.S. Ouellette, P.A. Forsyth, ”Protection Testing of a 100% Stator Ground Fault Scheme Using a Phase Domain Synchronous Machine Model in Real−Time,” The 10th International Conference on Developments in Power System Protection (DPSP 2010), Manchester, UK, March−April 2010.

[14] A.B. Dehkordi, A.M Gole, T.L. Maguire, and P. Neti, “A Real-Time Model for Testing Stator-Ground Fault Protection Schemes of Synchronous Machines”, International Conference on Power System Transients (IPST 2009), Kyoto, June, 2009.