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Project: Solenoid Energization, Controls, Interlocks and Quench Protection
Doc. No: H970627A

Subject: Design Review - Ground Fault Detector

Introduction -- The purpose of this report is to provide an independent review of Walt Jaskierny's Ground Fault Detector NIM module. The source document for this report is drawing #3823-111-ED-330052 sheet 14 of 14. The primary purpose of this NIM module is to continuously monitor the electrical resistance to ground of the solenoid energization system. If this resistance is less than a preset lower limit (2.5k Ohms); or greater than a preset upper limit (25k Ohms), then the "Ground Fault Permit" interlock is opened and the energization system is disabled.

The solenoid energization system must be referenced to ground for safety reasons. Otherwise, the system could "float" to a hazardous voltage potential. However, the system operates at 5000A and all of this current must flow in the conductors which are designed for this purpose. If an inadvertent path to ground appears anywhere in the system, then some of the current might flow in that path with destructive results. The ground fault detector module is designed to sense such a condition of lowered resistance to ground and consequently to disable the system power supply until the problem is diagnosed and corrected.

Functions -- The module performs the following functions:

- Provides a +5V reference voltage to the center tap of the dump resistor and uses it to determine the resistance to ground at all times except during a fast dump.
- Provides a "Ground Fault Permit" relay contact to the interlock system to disable the energization of the solenoid if the ground resistance is not within preset limits.
- Provides status relay contacts to the control system to indicate if the ground resistance is less than or more than preset limits.
- Provides a status relay contact to the control system to indicate that the ground fault detector is enabled.
- Provides an analog signal to the control system that represents the actual resistance to ground of the solenoid circuit.
- Provides an analog signal to the control system that represents the actual lower limit setting of the ground fault detector.

Features -- The module provides the following inputs and outputs:

Inputs:

- GFD Disable -- Ground fault detector disable. This input connects to a normally open contact on the dump switch. If the dump switch "opens", as it does during a fast dump, then the contact closes and disables the ground fault detector. This avoids false tripping due to the high voltages generated during a fast dump. If the cable falls off, or the dump switch contact fails open, then the GFD is always enabled and will disable the system if a ground fault occurs.
- GND Sense -- Direct connection to the center tap of the dump resistor. This connection provides the point where the DC resistance to ground of the system is measured.
- NIM Power Supply -- +24V, +15V, -15V. +5V is generated on board by a regulator connected to the +15V input.

Outputs:

- Gnd Flt Pmt -- Ground fault permit. This is a pair of normally open isolated relay contacts connected in series. One contact is held closed if the ground resistance is lower than the upper limit. The other contact is held closed if the

ground resistance is greater than the lower limit. Thus, the series circuit (permit) is held closed as long as the ground resistance is within limits. This signal is normally routed to the interlocks system.

- Gnd < HiLim -- Ground resistance is less than the high limit. This is a normally open isolated relay contact which is held closed as long as the ground resistance is less than the high limit. The high limit is adjustable via a potentiometer. This signal is normally routed to the control system for monitoring.
- Gnd > LoLim -- Ground resistance is greater than the low limit. This is a normally open isolated relay contact which is held closed as long as the ground resistance is greater than the lower limit. The lower limit is adjustable via a potentiometer. This signal is normally routed to the control system for monitoring.
- GFD Enabled -- Ground fault enabled. This is a normally closed isolate relay contact which is forced open if the "GFD Disable" input closes. When "closed", it indicates that the ground fault detector is enabled. This signal is normally routed to the control system for remote monitoring of the GFD status.
- Buf GND Sense -- Buffered ground sense. This is a single ended, low impedance, 0 to 5V signal that is a buffered copy of the voltage at the "GND Sense" input. Test points are provided for local monitoring. This signal is normally routed to the control system for remote monitoring Voltage levels are interpreted as follows:

5.00V = Infinite resistance to ground
4.58V = 25.0k Ohms resistance to ground
3.30V = 2.50k Ohms resistance to ground
2.50V = 0.00 Ohms resistance to ground

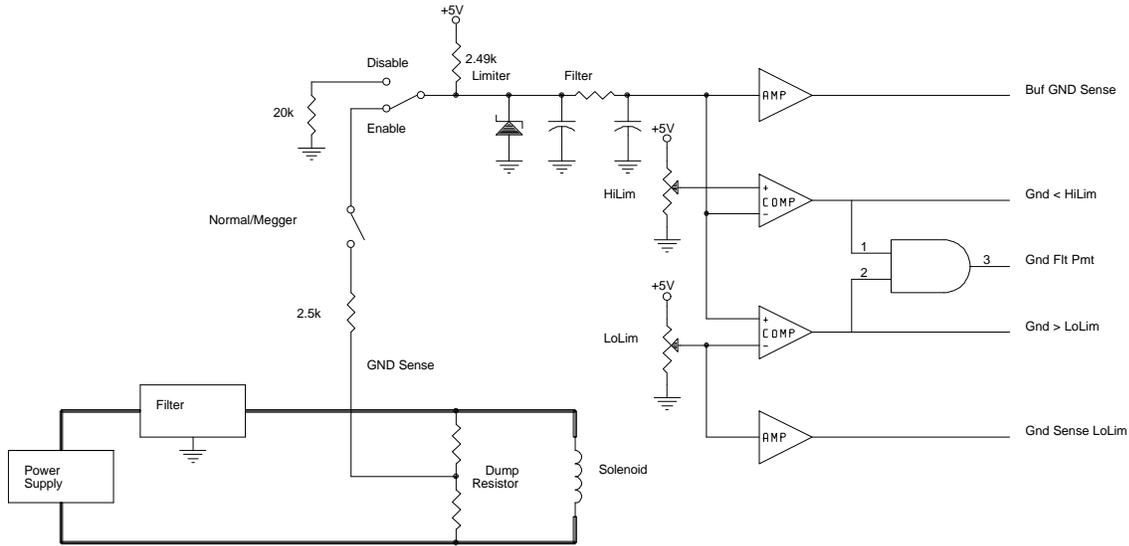
- Gnd Sense LoLim -- Ground sense lower limit. This is a single ended, low impedance, 0 to 5V signal that is a buffered copy of the voltage at the "low limit" potentiometer. Test points are provided for local monitoring. This signal is normally routed to the control system for remote monitoring Voltage levels are interpreted as described above under "Buf GND Sense".

LED Indicators, Switches and Test Points:

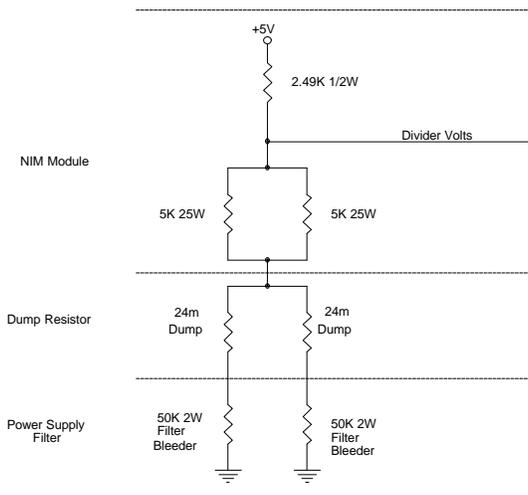
- Megger/Run Switch -- This switch is used to disconnect the module from the solenoid bus system during high voltage breakdown tests of the system. This feature is to allow for normal meggering of the system without achieving false results due to the conduction of input protection diodes on this module. The control system knows if this switch is in the proper position for normal operation by evaluating the "Buf GND Sense" signal described previously. If "Infinite resistance to ground" is measured, then the switch is in the "megger" position.
- High R Trip Level Pot -- This potentiometer is adjusted during commissioning to set the maximum resistance to ground that will be allowed without disabling the ground fault permit. The purpose of the high limit is to allow the control system to determine that 1) The ground fault detector is connected and 2) The filter capacitor bleeder resistors are intact. This pot allows a setting of 4.55V to 5.00V which represents slightly less than 25k Ohms to infinite Ohms as an upper resistance limit.
- Low R Trip Level Pot -- This potentiometer is adjusted during commissioning to set the minimum resistance to ground that will be allowed without disabling the ground fault permit. The purpose of the low limit is to set the point below which constitutes a ground fault in the system. If the "GND Sense" voltage falls below this value, then a ground fault exists.
- Gnd Sense Voltage Test Points -- Test points provided to monitor the Buf GND Sense voltage described previously. Series impedance is 2k Ohms resistive to the voltage test point. The GND test point is connected directly to GND. Voltages are interpreted as described previously in "Buf GND Sense".
- Gnd Sense LoLim Test Points -- Test points provided to monitor the Gnd Sense LoLim voltage described previously. Series impedance is 2k Ohms resistive to the voltage test point. The GND test point is connected directly to GND. Voltages are interpreted as described previously in "Buf GND Sense".
- GFD Disabled LED -- Red LED provided to indicate functional status of the module. When lit, the ground fault detector is being disabled by the dump switch.

Circuit Descriptions:

General -- The module generates a +5V reference via an integrated circuit regulator attached to the NIM +15V power supply. This "GND Sense" voltage is routed to the solenoid energization circuit at the center point of the dump resistor. The connection is part of one side of a voltage divider. The module determines the resistance to ground by measuring the voltage-to-ground at the voltage divider. An enable/disable relay is controlled by the dump switch to disable the circuit during fast dumps. A normal/megger disconnect switch is provided for the purpose of isolating the systems during high voltage breakdown tests. A limiter protects the circuit from quench voltages. A filter reduces nuisance trips. The basic functional diagram of the system is shown below: Theory of operation is straightforward and need not be extensively described. Refer to the full schematic for circuit details.



Resistance to Ground -- The resistance to ground is measured by use of a simple voltage divider. The circuit diagram below shows the elements and values of the voltage divider:



The "divider voltage" represents the resistance to ground "seen" by the comparators. This voltage is buffered and routed to the control system (Buf Gnd Sense) for remote monitoring, and compared to high and low limits on this module for determination of the gnd fault interlock status. The divider voltage is interpreted as follows:

- 5.00V = Infinite resistance between the solenoid system and ground
- 4.58V = 25k Ohms between the solenoid system and ground
- 3.30V = 2.5k Ohms between the solenoid system and ground
- 2.50V = 0.00 Ohms between the solenoid system and ground

The solenoid power supply filter contains bleeder resistors which combine to provide 25k Ohms to ground. Thus this module should never "see" more than 25k Ohms -- and it will open the interlock if it does. This "upper limit" is adjustable on the module with a variable resistor over a range of slightly less than 25k Ohms to infinity. The lower limit is also adjustable on the module with a variable resistor over a range of 2.5k Ohms to infinity. The lower limit setting is monitored by the control system which will expose any hanky panky with the adjustment in order to "override" a low ground resistance.

Circuits -- The following individual circuits make up the module:

- **Limiter** -- This module is connected directly to the center of the solenoid system dump resistor. It may occasionally be subject to voltages which exceed the rating of the components on the module. The limiter circuit is included on the input to protect the module. The limiter circuit is merely a zener diode that serves to protect the comparitors and amplifiers from voltages greater than 10 V and less than -0.6 V. The zener is protected from excess currents by 5k Ohm input resistance of the circuit ($(5k // 5k) + 2.49k$).
- **Filter** -- The filters provide defense against false trips which might be induced by noise. The filter is constructed of two stages of RC. The first stage which is comprised of the parallel 5k Ohm resistors and a 2uF capacitor, provides a break frequency of 32 Hz and rolls off at 20db per decade. This stage is common to all op amp and comparator circuits. The second stage is individual to each circuit and consists of 10k Ohms and 0.47uF for the comparator circuits; and 10k Ohms and 0.01uF for the op amp circuits. This second stage provides additional protection against noise. For the comparitors, the net break frequency is about 18 Hz with a 40 dB per decade roll off. For the op amps, the combined net break frequency remains at about 32 Hz and frequency response rolls off at 20 dB per decade. The comparitors naturally being more sensitive to the noise, are amply filtered to prevent false trips, yet fast enough to sense a ground fault. SPICE analysis indicates that a fast rise time input noise pulse clamped at 10 V by the limiter, would have to be of at least 7 mS duration to exceed the minimum setable hi-resistance limit of 4.55 V . An unusual source of this type of noise might be the enable/disable relay contacts in series with the circuitry. The contact bounce from these relays should be adequately rejected by the filter circuits.
- **Buf Gnd Sense** -- The buffered ground sense circuit is a single ended, non-inverting, gain of one op amp circuit. It provides a low impedance buffered signal to the control system representing the actual voltage being sensed at the voltage divider. The control system may interpret this voltage as a resistance to ground of the solenoid assembly according to the previous "resistance to ground" information. This circuit has filtering on its input as described earlier. The filtering provides a -3db frequency of about 32 Hz with an attenuation of 20 dB per decade.
- **Gnd < HiLim** -- The "ground resistance is less than the high limit" circuit is a simple comparator driving a relay. The ground sense voltage is compared to a reference voltage. The comparator reference signal (HiLim) comes from a PCB mounted adjustable pot. As long as the ground sense signal voltage is less than this value, then the comparator energizes a relay which holds its normally-open contacts closed. The contacts are to be monitored by the control system so as to provide status information. This circuit is non-latching. An LED is lit green as long as the ground resistance remains below the upper limit. This circuit has filtering on its input as described earlier. .
- **Gnd > LoLim** -- The "ground resistance is greater than the lower limit" circuit is a simple comparator driving a relay. The ground sense voltage is compared to a reference voltage. The comparator reference signal (HoLim) comes from a PCB mounted adjustable pot. As long as the ground sense signal voltage is more than this value, then the comparator energizes a relay which holds its normally-open contacts closed. The contacts are to be monitored by the control system so as to provide status information. This circuit is non-latching. An LED is lit green as long as the ground resistance remains above the lower limit. This circuit has filtering on its input as described earlier. .
- **Gnd Flt Pmt** -- The "ground fault permit" circuit is the logical AND of "Gnd < HiLim" and the "Gnd > LoLim". The logical AND is performed by the series connection of normally open contacts from the relays associated with these circuits. As long as the proper conditions are met, both relays remain energized and the contacts remain closed. This circuit is non-latching and accurately provides the system status at all times. This contact pair is monitored by the interlock module which does in fact latch any temporary contact opening.
- **Gnd Sense LoLim** -- The "ground sense lower resistance limit" circuit is a single ended, non-inverting, gain of one op amp circuit. It buffers the voltage from the "low resistance limit" potentiometer and makes it available to the control system for monitoring. This voltage is interpreted as described in the "voltage divider" section. This circuit has filtering on its input as described earlier.

Conclusion -- The GFD module appears to provide all the functions required to safely monitor the solenoid energization system for ground faults. During the design of this module and the process of conducting this review, several system problems were discovered and subsequently resolved by changes. Some examples are 1) The solenoid noise filter design was changed by adding dc blocking caps to the pole damping resistors thus eliminating a ground path not identified during the filter reviews. 2) The dump switch design was changed by adding latching to the dump switch to prevent short cycling or bouncing due to unlatched or uncertain inputs. 3) Adding the GFD Disable input to this module to disable the module during fast dumps thus avoiding false indications of ground faults. 4) Modifying status outputs for control system monitoring.