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Engineering Note

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Project: Solenoid Energization, Controls, Interlocks & Quench Protection
Doc. No: H960801A

Subject: Solenoid Filter Analysis - Fast Dump / Worst case Ground Fault

In order to select properly rated components for use in the solenoid filter[1], the circuit was analyzed with ISPICE 1.41 during slow & fast dumps, with normal and reverse polarity; and with and without ground faults. The purpose of which was to determine the magnitude of the voltages which appear across the capacitors and the amount of energy dissipated by the damping resistors. Given that the dump switch opens on one side only, the absolute worst situation is a fast dump with maximum current (5000A), in the "normal" polarity (positive side of solenoid toward dump switch), full charging voltage (15V); and a ground fault on the positive side of the solenoid. That is the configuration that will define the maximum ratings to be required of the filter components.

Some notes regarding the simulations are as follows:

- Each simulation was run with an initial condition of 5000 Amps flowing through all coils and 15V across the input and output of the filter. This is the worst case. In reality, there will be less than 15V. The actual value will be determined by the total bus length ultimately required during the installation and/or the operational status during initiation of the dump i.e. Steady state or charging.
- At time zero, the power supply in the simulation is abruptly set to zero. Thus it does not appear in the circuit. It is bypassed by its actual free-wheeling diode as shown.
- The filter output has a free-wheeling diode to bypass the filter/power supply during slow dumps.
- Capacitor bleeder resistors and RC damping circuits were included included.
- Capacitor effective series resistances (ESRs) were estimated and included.
- The 0.048 Ohm dump resistor is shown as it is actually designed, that is as two 0.024 Ohm resistors center connected to ground through a 5000 Ohm ground fault detector resistor.
- RELTOL=.01 for all simulations.
- The "Gear method" of numeric integration was specified for all simulations as was "iteration count" time step control. Although not SPICE default settings, these options were chosen to provide more accurate results with transient analysis of linear, inductive circuits[2].
- Observe carefully the horizontal and vertical axis labeling.

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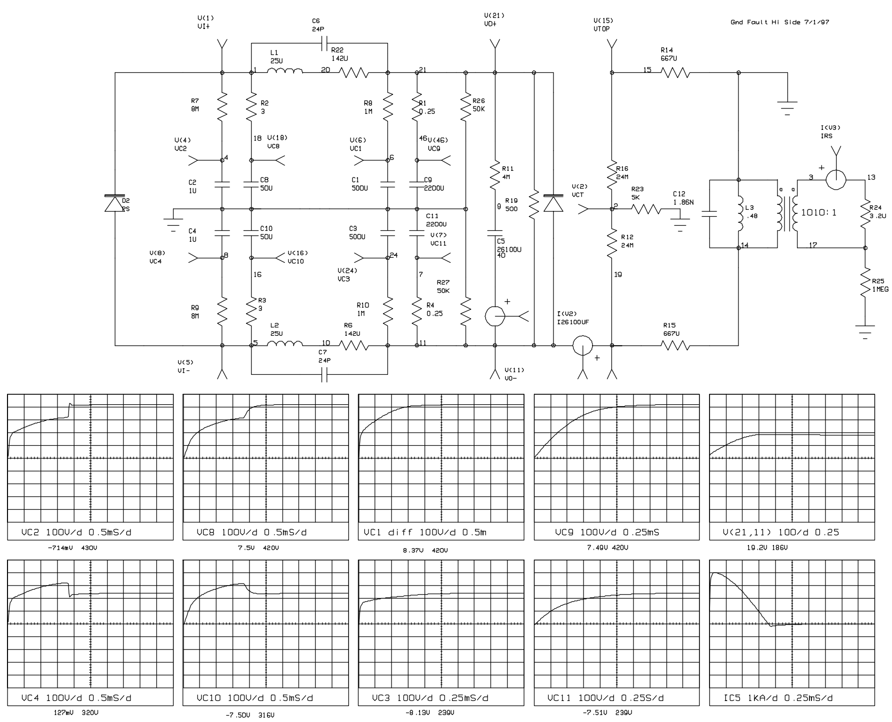
[1]Engineering Note H960703A - Power Supply Filter Design - R. Hance - 7/3/96

[2]Inside SPICE (McGraw-Hill) by Ron Kielkowski - Chapter four and five.

Worst Case Results

The only analysis to be discussed here is of the fast dump, normal polarity, full charging voltage, ground fault on the positive side of the solenoid. In this scenario, the solenoid is being charged with the full 15 volts of the power supply. It has just reached 5000A of current in the normal polarity direction; and a ground fault occurs on the positive side of the solenoid. The quench detector circuits have disconnected the filter from the dump resistor, bus and solenoid; and disabled the power supply. The filter components must withstand the voltage developed by the filter inductors as their fields collapse. And the energy stored in the filter must be dissipated. The ground fault occurring on the positive side of the solenoid has also made the solenoid energy available to the filter by virtue of the return path which is NOT disconnected by the switch. This energy boosts the voltages on the filter elements even higher. At time zero, the power supply is abruptly turned off or set to zero and thus does not appear in the model. The solenoid energy is discharged by the inherent resistance of the DC bus and the dump resistor. The filter coil energy is discharged by the bleeder resistors, damping resistors, capacitor ESR, coil resistance and the free-wheeling diode resistance. Although the solenoid will require 40 seconds to discharge, the filter energy is nearly spent in 5.0 milliseconds; and the maximum voltages are developed during that time. Thus this simulation focuses on the first 5.0 mS of the fast dump.

Note that this simulation includes a graph of the current through the 26100 uF capacitor bank. This current is significant in the fast dump situation and must be considered during component selection. For example the high current would indicate a preference for paralleling several smaller capacitors as opposed to using a single high capacity unit. This will minimize terminal and capacitor heating.



- The 1UF input common mode filter caps must be non-polarized and withstand at least 430V.
- The 50UF input dc blocking caps must be non-polarized and withstand at least 420V.
- The 500UF output common mode caps must be non-polarized and withstand at least 420V.
- The 2200UF output dc blocking caps must be non-polarized and withstand at least 420V.
- The 26,100UF must withstand at least 186V. It is protected against reverse polarity by the diode.

Energy Absorption

Given that 5000A is assumed to be flowing through the filter inductors ($E = 1/2 * L * I^2$), and 15V is assumed across the filter (7.5V each side to ground and 15V differentially -- $E = 1/2 * C * V^2$), then about 631 Joules of stored energy in the filter must be accounted for. The following table shows the result of using SPICE to analyze the energy disposition throughout the most relevant filter components during the initial 5.0 milliseconds of the fast dump during which the filter energy decays. This was done to analyze for any special robustness required to absorb the energy during a fast dump with worse case ground fault. The technique was to calculate dissipated wattage at each data point (25uS) and then numerically integrate over the entire transient period. At the end of 5.0 mS, the capacitors were evaluated for residual stored energy which would ultimately discharge over the rest of the fast dump cycle.

Power supply diode	Unknown but 1 to 5 Joules
1uF pos input filter cap with esr = 8 mOhm	Negligible (< 1 Joule)
1uF neg input filter cap with esr = 8 mOhm	Negligible (< 1 Joule)
3 Ohm pos input damping resistor	1.13J
3 Ohm neg input damping resistor	1.21J
500uF pos output filter cap with esr=1mOhm	Negligible (< 1 Joule)
500uF neg output filter cap with esr=1mOhm	Negligible (< 1 Joule)
0.25 Ohm pos damping resistor	100J
0.25 Ohm neg damping resistor	41.4J
26,100uF output diff filter cap with esr = 4 mOhm	55.2J
25uH pos coil with r=142uOhms	Negligible (< 1 Joule)
25uH neg coil with r=142uOhms	Negligible (< 1 Joule)
Residual energy on 1uF pos input cap	Negligible (< 1 Joule)
Residual energy on 1uF neg input cap	Negligible (< 1 Joule)
Residual energy on 500uF pos output cap	44.1J
Residual energy on 500uF neg output cap	14.2J
Residual energy on 2,200uF pos output cap	194J
Residual energy on 2,200uF neg output cap	68.2J
Residual energy on 26,100uF differential output cap	428J
Total accounted for	942J
Total expected from inductor and capacitor formulas	631J (where did excess come from? -- answer follows)
Total delivered from solenoid through return leg via ground fault path (V * I integrated over time -- measured at return leg)	330J
Grand total expected	961J (compare to 942J accounted for)