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Engineering Note

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Project: Solenoid Energization, Controls, Interlocks & Quench Protection
Doc. No: H960731A

Subject: Filter Component Ratings

Known Quantities:

- Maximum operating Voltage across filter 15Vdc[1] and operating current through filter 5000 A.
- Maximum Hi pot testing voltage from any point to ground 600 V[2]
- Power supply ripple voltage 4.67 Vrms differential @ 720 Hz[3].

Design criteria:

The greatest predictable strain on the filter components will occur during the following scenario: The solenoid is being charged in the "normal" polarity mode whereby the positive bus is connected to dump switch. A full 15V is being applied and the solenoid has reached 5000A of current. A ground fault occurs on the positive side of the solenoid and a subsequent fast dump is triggered. The filter components must be designed to withstand the voltage imposed across the capacitors when the current is interrupted; and to absorb the energy which will be released from the inductors and capacitors of the filter. Since the solenoid return path is NOT interrupted by the dump switch, the ground fault provides a path whereby the solenoid becomes an energy source to the filter. a so-called "slow dump" is benign. The energy is dissipated over a longer time period and high voltages are not developed in the circuit. The ratings of maximum voltage and maximum energy dissipation which follow were derived from a SPICE analysis of the worst case scenario[4].

1 uF filter Input Common Mode Capacitor:

This 1 UF capacitors are installed within the power supply and are connected to ground from each leg of the power supply. Their requirements are as follows:

- Must withstand the 600 V of hi-pot testing because it is always in the circuit. Add 50% for safety = 900Vdc
- Must withstand a 720 Hz 2.34 Vrms ripple produced by the power supply[5]. (4.67 Vrms across the power supply = 2.34 Vrms each leg to ground). Add 50% for safety = **3.51 Vrms @ 720 Hz**.
- Must withstand a polarity reversal of about 0.5V.
- Must remain capacitive at frequencies beyond 50 kHz, preferably up to 500 kHz[6].

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[1]D0 Engineering note 3823.111.EN-418 "Specification for Solenoid Energization, Controls, Interlocks and Quench Protection." 117/95.

[2]Memo - Hance to Smith - 1/3/96 re-defining hipot level to 600 V.

[3]Engineering note H960729A revised 7/31/96 "R. Hance - Power supply ripple calculation".

[4]Engineering note H960801A revised 7/1/97 "R. Hance - Solenoid Filter Analysis - Fast Dump / Worst Case Ground Fault"

[5]Capacitors are rated for ripple current. The current is the quotient of voltage and impedance. Impedance is the quadrature impedance of effective series resistance (ESR) and capacitive reactance (Xc) computed at 720 Hz.

[6]Engineering note H960703A revised 7/31/96 "R. Hance - Power Supply Filter Design"

50 uF dc Blocking Capacitors for 3 Ohm Damping Resistors:

These capacitors are used to block dc from flowing in the 3 Ohm input damping resistors. The requirements are as follows:

- Must be non-polarized and able to withstand the maximum of 420V during the worst case scenario. Add 50% for safety = **630V**.
- ESR is not an important factor. Must be less than about 0.30 Ohms (0.1 X 3.0 Ohms).

500 uF filter Output Common Mode Capacitor 500 uF:

This 500 UF capacitors are connected to ground through a hi pot switch from each output leg of the filter. Their requirements are as follows:

- Need not withstand the 600 V of hi-pot testing because ground will be disconnected at that time.
- Must withstand the 720 Hz ripple present at the output of the filter. Note that the filter chokes reduce the 4.67 Vrms input ripple by a factor of 31 to 0.151 Vrms and only 1/2 appears on each leg to ground; thus 0.075Vrms. Add 50% for safety = **0.112 Vrms @ 720 Hz**.
- Must withstand the approximately 420 Vdc developed across them. Add 50% for safety = **630 Vdc**.
- Must be non-polarized.
- Must remain capacitive at frequencies beyond 50 kHz, preferably up to 500 kHz.

2200 uF dc Blocking Capacitors for 0.25 Ohm Damping Resistors:

These capacitors are used to block dc from flowing in the 0.25 Ohm output damping resistors. The requirements are as follows:

- Must be non-polarized and able to withstand the maximum of 420V during the worst case situation. Add 50% for safety = **630V**.
- Must be low inductive construction and low ESR (< 0.1 X 0.25 Ohms = 25 milliohms).

25000 uF filter Output Differential Mode Capacitor:

This 25000 UF capacitor will likely be realized by paralleling several smaller capacitors. Specifically, nine 2900 UF units. The worst case scenario is actually slightly different for this capacitor than for all the others because it is differentially connected. Rather than the positive ground fault scenario, the worst case here is simply a fast dump without a ground fault. SPICE shows 197V across this capacitor in this situation. The requirements for each of these capacitors are as follows:

- Not required to withstand the 600 Vdc during hi-pot testing. This is because the hi-pot voltage will be applied simultaneously to each leg Thus the voltage will not appear differentially across the capacitors..
- Must withstand the 720 Hz ripple from the output of the power supply. Note that the filter chokes reduce the 4.67 Vrms input ripple by a factor of 31 to 0.151 Vrms; but that the entire differential ripple voltage is across the capacitor). Add 50% for safety = **0.225 Vrms @ 720 Hz**.
- Must withstand the approximately 200 Vdc produced by di/dt when the dump switch opens with 5000 A flowing in the filter inductors. Add 50% for safety = **300V Vdc.**
- Must remain capacitive at frequencies beyond 720 Hz, preferably up to the 7th harmonic which is approximately 5 kHz.
- Must dissipate approximately 55J of energy due to I^2R losss in the capacitor esr during the fast dump.

3.0 Ohm Filter Input Damping Resistors:

These 3-Ohm resistors must be non-inductive. They are in series with dc blocking capacitors and thus do not dissipate energy during normal operation. During a fast dump, they are required to absorb a portion of the energy stored in the filter inductors and capacitors as the energy in the filter redistributes. A SPICE analysis was used to determined the dissipated energy during a fast dump. The energy was calculated by squaring the voltage waveform across the resistor, dividing by the constant resistance; and integrating over time (see references). Over the initial 5.0 milliseconds of the fast dump, during the discharging of the filter components, the worst case resistor must dissipate a maximum of **1.21 Joules** of energy. Thus the resistors must be robust enough to absorb 1.21 Joules of energy in 5.0 mS.

0.25 Ohm Filter Output Damping Resistors:

These 0.25-Ohm resistors must be non-inductive. They are in series with dc blocking capacitors and thus do not dissipate energy during normal operation. During a fast dump, they are required to absorb a portion of the energy stored in the filter inductors and capacitors. A SPICE analysis was used to determined the dissipated energy during a fast dump. The energy was calculated by squaring the voltage waveform, dividing by the constant resistance; and integrating over time (see references). Over the initial 5.0 milliseconds of the fast dump, during the discharging of the filter components, the worst case resistor must dissipate a maximum of **100 Joules** of energy. Thus the resistors must be robust enough to absorb 100 Joules of energy in 5.0 mS.