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Engineering Note

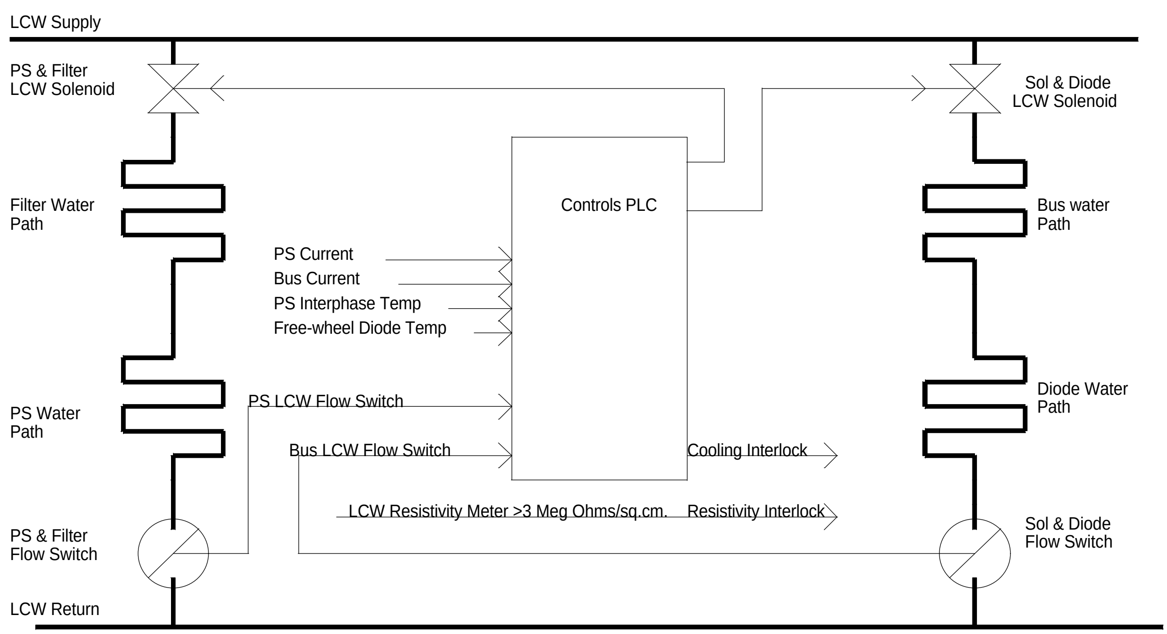
Date: 10/29/97
Rev Date: 4/7/98

Project: Solenoid Energization, Control, Interlocks and Quench Protection
Doc. No: H971029A

Subject: Solenoid Power Supply and Bus Cooling and Condensation Control

The 5000 Amp PE-150 power supply (PS) and interconnecting bus that energize the DZERO central tracking solenoid are water cooled with low-conductivity chilled water (LCW). The temperature of this water is expected to be routinely less than the dew point in the power supply room and/or over the route of the bus. If this water is allowed to circulate through the power supply or bus when no heat is being generated, then condensation may occur inside the power supply or on the surface of the bus. Condensation accelerates corrosion which increases connector resistance. Condensation may also result in unwanted current paths leading to equipment failure. This note explains the cooling and condensation control system. This system reduces the occurrence of condensation by halting the flow of LCW through the power supply and bus unless it is needed to carry away heat during operation.

The controls programmable logic controller (PLC) orchestrates the condensation control[1]. For the purpose of condensation control, the PLC monitors the power supply current, power supply interphase transformer temperature, flow switch in cooling water suction line from power supply and filter, absolute solenoid current, and flow switch in cooling water suction line from solenoid bus and free wheeling diode. The PLC then controls the solenoid valves that route cooling water to the power supply and filter; and to the water-cooled bus and free-wheeling diode. See Sheet-16 of drawing #3823-111-ED-330052 for complete hardware details. The system appears schematically as follows:



[1] The control system, including the PLC is described in D0 Engineering Note 3823-111-EN-418 which is the "Specification for Solenoid Energization, Controls, Interlocks and Quench Protection".

Configuration:

The two separate LCW circuits are used to accommodate the different modes of operation. During charging and normal operation, current flows in the power supply, filter, and water-cooled bus. Therefore all of these devices require LCW flow for cooling. However, during a slow dump, which can last more than 15 minutes, current may not flow continuously in the power supply or filter because they are bypassed by the free-wheeling diode. The LCW to the power supply and filter is shutoff when it is not needed to avoid problems with condensation. Likewise, when the system is idle and no current is flowing, the LCW to the water-cooled bus and the free-wheeling diode are shutoff.

The power supply and filter are connected in series. This economizes on plumbing and utilizes the filter coils to preheat the water to the power supply. Both devices have generously sized fittings and internal piping which allow adequate water flow at nominal pressure differentials. Likewise, the water-cooled bus and the free-wheeling diode are connected in series. The LCW flows first through the bus to preheat the water, then through the diode heatsink.

Controls:

The LCW solenoid valves are controlled by the same PLC system which is used to provide the control and monitoring of the solenoid energization, controls, interlocks and quench detection. The control system operator interface known as Distributed Manufacturing Automation and Control Software (DMACS) has a page that provides a user with information as to the state of the solenoid valves and flow switches. The page is accessible from the "DZERO SOLENOID DC" page of DMACS. The PLC hardware and software monitors the power supply current, water-cooled bus current, LCW flow switches, power supply interphase transformer temperature, and free-wheeling diode temperature. It uses this information to decide when to energize the solenoid valves and allow the LCW to flow. It also provides a signal to the hardware interlock chassis to indicate that cooling flow is OK. If the PLC fails to control the LCW properly or to open the interlock if cooling fails, then a series string of strategically located "klixon" thermal fuses provides ultimate protection against overheating by opening a "temperature" interlock and disabling the power supply. The control LCW algorithms implemented in the PLC are as follows:

- If (PS current is >= 50 Amps "OR" interphase temperature >= than 40 deg C.)
  then energize the PS / filter LCW solenoid. Once the solenoid is energized, keep it energized as long as the (PS current >= 25 Amps "OR" the interphase temperature > 35 deg C.) (hysteresis)
- If (water-cooled bus current >= 50 Amps "OR" free-wheeling diode temperature >= 40 deg C.)
  then energize the water-cooled bus / diode LCW solenoid. Once the solenoid is energized, keep it energized as long as the (water-cooled bus current >= 25 Amps "OR" the free-wheeling diode temperature > 35 deg C.) (hysteresis)
- If (PS LCW is flowing "OR" (PS current < 100 Amps "AND" interphase temp < 45 deg C.)) "AND" (Bus LCW is flowing "OR" (bus current < 100 Amps "AND free-wheeling diode temperature <45 deg C.))
  then provide a signal to the interlock system that the LCW FLOW interlock is OK.
- Also, provide an interlock OK override signal for the first five seconds after the solenoids have turned on to prevent interlock trips due to electronics being faster than mechanics in the system.

LCW Supply:

LCW is piped into the room via 1.5" ID copper pipes. Taps are provided at strategic locations in the room to allow easy piping to components. Taps are ¾" ID pipe fittings. Manual ball valves are located on the pressure and suction lines at each tap. There exists a requirement that the resistivity of the LCW be greater than 3 Meg Ohms per cm^2. This will be accomplished with a separate hardware interlock derived from a resistivity meter. Furthermore, if that interlock fails and the resistivity is low enough such that the total dc resistance to ground is too low, then the "ground fault detector" circuitry will open its hardware interlock (see EN 3823-111-EN-418 which is the system specification).

When all devices are connected as shown on the schematic, and both solenoid valves are "on" as in the normal operating mode; then the following pressures and flow rates are nominal[2]:

- High side/low side water pressure differential: 60 psi
- Nominal water temperature at input to room: 70 deg F. (estimated summer - full load temp)
- Water flow through filter coils and power supply circuit: 6 gpm (6 gal/min · 60 min · 8.33 lb/gal ≅ 3000 lb/hr).

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[2] Engineering Note H971106A R. Hance "LCW Flow Tests - Rm511" .

- Water flow through water-cooled bus (bus to pit area and return) and free-wheeling diode circuit: > 5 gpm (flow meter limited to 5 gpm). 5 gal/min · 60 min · 8.33 lb/gal ≅ 2500 lb/hr.

Cooling Analysis:

Enough cooling water must flow through the individual components to keep them safely operating within specs during normal operation which is also worst case operation i.e. maximum load of 5000 Amps. Each component is evaluated below against available information to determine if cooling is clearly adequate or questionable.

- **Filter -** The filter coils each have a dc resistance of 1.42×10^{-4} Ohms[3]. The resistance of both coils in series is then 2.84×10^{-4}. The power dissipated in the coils (I^2R) is then: $5000A^2 \times 2.84 \times 10^{-4}\ \Omega = 7.1$ kW. The expected temperature rise (ΔT) from 7.1 kW-hr applied to the 3000 lb/hr of LCW as it flows through the filter is calculated from the basic heat equation:

$$Q1 = \frac{W \cdot Cp \cdot \Delta T}{3.412}$$

  Q1 = Heat required to raise temperature (Watt-hours)
  W = Pounds of material
  Cp = Specific heat of material (1 BTU/lb/°F)
  ΔT = Temperature rise of material (°F)

  Thus:

$$\Delta T = \frac{7100 Watts \cdot 3.412 Btu/Watt}{3000 lb \cdot 1 Btu/lb/°F} = 8.1°F$$

  Therefore the filter cooling is expected to be adequate since the temperature of the copper coils should be approximately equal to the temperature of the exiting LCW which is expected to be approximately 70 + 8 = 78 °F.

- **Power supply -** The power supply is in series with the filter coils. The power supply specification requires 4 gallons per minute of flow at a maximum water temperature of 45 degrees centigrade[4] (113 °F). Nominal flow as described previously is expected to be 5 gpm @ ≈ 78 °F (70 °F + 8 °F temperature rise contributed by filter). The power supply cooling is clearly adequate since the LCW flow rate exceeds the specification and concurrently, the LCW temperature is well below the specification. In addition, the power supply will be operated at a maximum of 75 kW which is 50% of its specified capacity.

- **Water-cooled bus -** The LCW circuit of the water cooled bus is in series with and ahead of the free-wheeling diode. The length of the bus, as it appears at this time, will not exceed 100 feet. The dc resistance of the bus is 4.97 μΩ/ft at 122 °F[5] (50 °C) . Thus the total dc resistance of the bus supply & return in series is 4.97 μΩ/ft X 200 ft = 994 μΩ. The power dissipated in the bus (I^2R) is then 5000^2 A X 994μΩ= 24.9 kW. The expected temperature rise (ΔT) from 24.9 kW-hr applied to the 2500 lb/hr of LCW as it flows through the bus is calculated from the basic heat equation:

$$\Delta T = \frac{24{,}900 Watts \cdot 3.412 Btu/Watt}{2500 lb \cdot 1 Btu/lb/°F} = 34°F$$

  Thus, the bus should operate at about 70 + 34 = 104 °F which is a very comfortable operating point which should avoid condensation problems under all conditions.

- **Free-wheeling diode -** The diode is "double sided cooled" on a water cooled heat sink. The LCW circuit of the diode is in series with and following the water cooled bus. This allows the bus to "preheat" the LCW to avoid condensation problems on the diode. The diode only conducts current when the solenoid is discharging. Nevertheless, we have chosen to provide LCW to it anytime there is current flowing in the solenoid bus. This will lesson the prospect of damage to the semiconductor during the first few seconds of a rapid discharge (slow dump) when 4875 Watts would be

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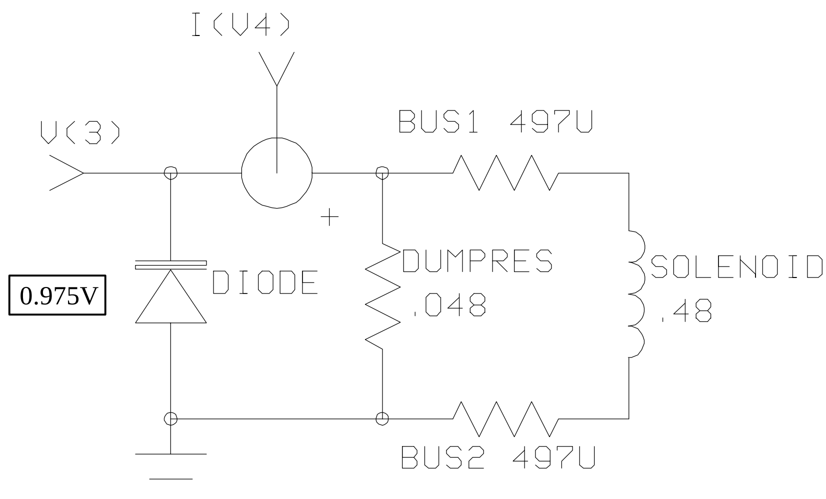
[3] Engineering Note H960625A R. Hance "CDF Air Core Coil Characteristics".

[4] Data Sheet: PEI 150-5 power supply - A.T. Visser 6/1/83, rev. 5/1/93.

[5] Engineering Note H950306A R. Hance "Bus Length Calculations".

dissipated in the diode junction (0.975V X 5000A). A normal discharge will consist of an initial 5000 Amps conducted through the diode, decreasing exponentially to zero over a period of approximately 900 seconds (15 minutes). A SPICE analysis of the simple dc equivalent circuit shown below was used to quickly evaluate the energy dissipated in the diode during a discharge. Starting with an initial condition of 5000 Amps flowing in the solenoid, the circuit was analyzed over the first 60 seconds of discharge. This essentially evaluates the worst case condition i.e. the first minute after commencement of discharge and gives us easy units to work with. The diode was modeled closely to the manufacturers specification -- 0.975 Volts @ 5000 Amps. SPICE was used to divide the first 60 seconds into 600 time slices. Then, voltage and current was multiplied at each time slice to compute Wattage; and the results were numerically integrated to derive the total energy. SPICE analysis concludes that 271k Joules is absorbed by the diode in the first 60 seconds.



We have previously shown that at least 5 gallons per minute of LCW flows through the diode (2500 pounds/Hour); and that the temperature is approximately 104 °F having been preheated by the solenoid bus. Now we use the heat equation to determine the expected temperature rise of the water in an ideal situation of zero “junction to heatsink thermal impedance”; and constant power dissipation. In reality, the thermal impedance is approximately 0.015 °C/W and power dissipation is decaying exponentially. We first convert the 271k Joules into Watt-Hours (271k Joules = 271k Watt·Seconds; and 271k Watt·Seconds X 1 Minute/60 Seconds X 1 Hour/60 Minute = 75.3 Watt·Hour). Additionally, we first convert the 2500 Pounds/Hour LCW flow into Pounds/Minute. 2500 Pounds/Hour X 1 Hour/60 Minutes = 41.7 Pounds/Minute:

$$\Delta T = \frac{75.3kW \cdot 3.412 Btu / Watt}{41.7 lb \cdot 1 Btu / lb / ^\circ F} = 6.16^\circ F$$

Thus the LCW flowing through the diode heat sinks will rise to approximately 110 °F (104 + 6 = 110). Now we quickly review the effect of “junction to heatsink thermal impedance” that we neglected in the previous analysis. The initial power dissipation in the diode was determined to be 4875 Watts. The thermal impedance of 0.015 °C/W can be expected to raise the junction temperature by 4875 W X 0.015 °C/W = 73 °C higher than that of the heat sink. Assuming the heat sink temperature to be at the LCW temperature of 110 °F (of course it will be somewhat higher). 110 °F = 43 °C. The junction can be expected to reach a temperature of 73 + 43 = 116 °C during the initial seconds of a slow discharge. The diode specification for Tjmax is 190 °C. Thus, the diode can be considered to be adequately cooled by a wide margin. In fact, it would take and additional (190-116)/0.015 = 4933 W to drive the junction temperature to its limit. Although we did not consider the thermal impedance between the heat sink and the water, we are encouraged by the fact that the expected LCW flow is greater than 5 gpm. 5gpm was the maximum range of the flow meter used to test the actual flow. Furthermore, the maximum dissipation values we used for this analysis occurs only during the first few seconds of a slow discharge.

- **Free-Wheeling Diode >> AC Power Failure -** A special case exists when the building AC power fails. The power supply is disabled and ceases to deliver current. Thus the solenoid goes into a slow dump mode. However, the power failure also disables the LCW pumps resulting in no cooling water circulation. The water-cooled bus clearly has enough copper mass to absorb its share of the discharge energy (several hundred pounds of copper). However, if the slow dump were allowed to proceed until the solenoid energy is discharged (900 seconds), then the free-wheeling diode would have to dissipate 1.47M Joules (408 Watt-Hours) of energy (derived from the previous SPICE analysis) without the aid of water cooling. The 1kg diode contains 1.66 pounds of copper . The two pieces of heat sink each contain 5.03 pounds of copper. Thus the total weight of copper is 11.7 pounds which has a specific heat of 0.092 Btu/lb/°F. Disregarding the small amount of water in the heatsink, and the conduction of heat away by the water (water is a poor heat conductor), The diode and heatsink face the prospect of getting very hot as follows:

$$\Delta T = \frac{408W \cdot 3.412\,Btu/W}{11.7lb \cdot 0.092\,Btu/lb/^\circ F} = 1290^\circ F$$

  1290°F would destroy the diode. This situation however, is prevented by the "dump switch" which opens automatically by design when AC power is interrupted (undervoltage contactor in the trigger mechanism). The dump switch opens simultaneously with the disabling of the power supply. Thus the solenoid energy is diverted to the air-cooled dump resistor[6] in a so-called "fast dump". During a fast dump, the power supply, filter, and free-wheeling diode are removed from the solenoid circuit. The dump switch is spring loaded and opens without the need for AC power.

Conclusion:

Although this first order analysis is rather crude, All LCW cooled components clearly receive adequate flow as long as the LCW system is operating normally. In the event of a power failure and subsequent loss of LCW flow, the free-wheeling diode loses its cooling water; however an automatic fast dump occurs which removes the free-wheeling diode from the discharge circuit. The designers had intended to provide uninterruptable power to the dump switch. The intention was that in the event of an AC power loss, the solenoid would execute a slow dump. However, this analysis has shown that a fast dump is desired in order to protect the free-wheeling diode from sure destruction if it were to remain in the discharge circuit without adequate cooling. If a slow dump were desired during a power outage, then the free-wheeling diode would require an approximately 65 pound heatsink and the dump switch would require an uninterruptible power supply.

[6] Engineering Note H960917B R. Hance "Dump Resistor Review".