Design and Testing of a High-Power Pulsed Load

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***Abstract*—This paper describes the design and testing of a two-channel 52-kW pulsed load. Its main feature is exceptionally low parasitic inductance, on the order of 200 nH. Such low inductance was needed in view of microsecond high-current pulses; it was realized by a compact design and careful layout. Small size is a prerequisite for minimizing the inductance; it was achieved by forced liquid cooling. Non-inductive bulk resistors were used at a power rating far exceeding their specifications detailed for operation in air and were found adequate for their mission. They were housed in standard stainless steel drums. The cooling liquid (water-propylene-glycol mixture) was circulated through a heat exchanger.**

Multiple aspects of the design are described, including resistor choice, calculating the load inductance, choice of busbars, details of kinematic scheme, heat transfer, HV, safety and other considerations for cooling agents, etc. Special attention was paid to avoiding turbulent flow that could result in the resistor cracking. Inductance measurements showed close correspondence with the calculations. High-power testing showed reliable operation with overheat about 40 K above ambient.

I. INTRODUCTION

Pulsed resistive dummy loads are widely used in various HV applications, e.g., testing capacitor charger systems, nanosecond and picosecond pulsers, etc. Such loads are characterized by several distinct requirements placing them apart from more conventional DC or AC loads. One of the most difficult requirements is providing low parasitic inductance. It must be of the order of several hundreds of nH, and tens of nH for microsecond and nanosecond applications, respectively. A natural way of minimizing the stray inductance is using low-inductive layouts, preferably, coaxial ones, *and* minimizing the overall load size. At high average power *and* high voltage, the latter is difficult to satisfy without effective cooling and keeping proper insulation distances. An additional typical requirement is good long-term resistance stability; this effectively excludes various aqueous solutions, such as copper sulfate aqueous solutions.

This paper describes the design and testing of a two-channel 52-kW load used in the development of a high repetition rate capacitor charger.

II. DESIGN

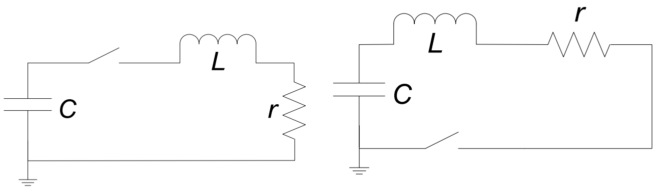
A. Specifications

The load was designed to the following specifications.

1. Storage capacitance C=5.3 μF (per channel)
2. Max charge voltage V_{ch}=1200 V
3. Max Average power P_{av}=52 kW (26 kW per channel)
4. Pulse width $t_{pulse}\approx 5\mu s$
5. Max pulse repetition frequency (PRF) 6 kHz
6. Load inductance
   (per channel, excluding leads) $L_{load}\approx 0.2$ μH
7. Voltage reversal (at maximum charge voltage)
   - in normal operation 200 V
   - in abnormal operation 600V
8. Possibility of reconfiguration to accept pulsed voltage of several tens of kV.

B. Circuit Considerations--Choice of Resistance

The test circuit can be represented by a capacitor discharge onto r, L circuit, r, L being the load resistance and inductance, respectively (Fig. 1), the latter including the leads' inductance.



a b

Fig. 1. Equivalent circuit for determining load resistance and inductance.

With zero initial conditions, in Mathcad notation, the load current, i, and the capacitor voltage, v, are given by the formulae

$$i(t,L,r) := \frac{V_0}{L\cdot\left(\alpha_1(L,r)-\alpha_2(L,r)\right)}\cdot\left(exp\left(\alpha_1(L,r)\cdot t\right) - exp\left(\alpha_2(L,r)\cdot t\right)\right)$$

$$v(t,L,r) := -\frac{V_0}{\left(\alpha_1(L,r)-\alpha_2(L,r)\right)}\cdot$$

$$\cdot\left(\alpha_2(L,r)\cdot exp\left(\alpha_1(L,r)\cdot t\right) - \alpha_1(L,r)\cdot exp\left(\alpha_2(L,r)\cdot t\right)\right)$$

where

$$\alpha_1(L,r) := \frac{-r}{2L} + \sqrt{\frac{r^2}{4L^2} - \frac{1}{L\cdot C}} \qquad \alpha_2(L,r) := \frac{-r}{2L} - \sqrt{\frac{r^2}{4L^2} - \frac{1}{L\cdot C}}$$

With the target loop inductance L=1.5 μH, the voltage reversal of approximately 200 V and $t_{pulse}\approx 5$ μs are realized with the load resistance r=0.6 Ω (Fig. 2). A reversal of ≈600V can be provided by increasing the leads' inductance to 10 μH, or decreasing r to 0.25 Ω. Fig. 3 illustrates the capacitor voltage waveforms for non-inductive discharge (L=0.2 μH) and artificially increased L=10 μH.

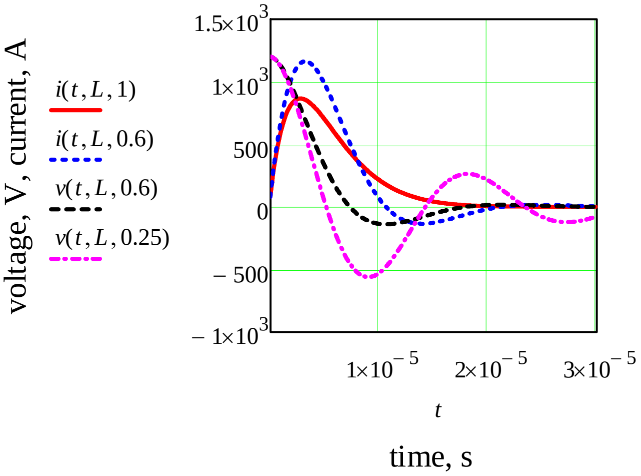


Fig. 2. Current and voltage waveforms for L=1.5 μH; r values (in SI) as indicated in variables' legends. r=1 Ω corresponds to critically damped discharge.

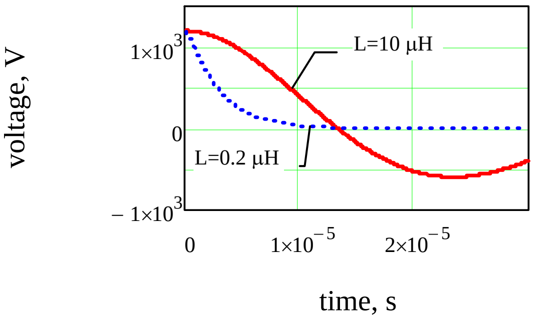


Fig. 3. Current and voltage waveforms for r=0.6 Ω.

Realizing the desired resistance and reconfiguring the load is convenient with relatively large number of fixed resistors. Their choice is of prime importance influencing the overall size, cost and reliability. In view of low inductive design, bulk ceramic resistors were chosen. They performed well in nanosecond applications with forced oil cooling [1], which was instrumental in obtaining small size, hence low inductance. Kanthal Globar series 510SP slab resistors are relatively inexpensive, compact and easy to mount. The largest parts are specified for the maximum power dissipation of 150 W in air; with oil cooling, based on previous experience, we anticipated good safety margin at a 500-W load. A brief testing of 887SP resistors in static transformer oil showed that it was capable of bearing the load of 500-1000 W without excessive stress. The main danger, as indicated by the manufacturer, is bringing the cooling agent to the boiling point, which would result in the ceramics cracking. Thus, it is important to avoid turbulent flow in order to decrease the temperature gradients at the boundary.

Finally, 6.3 Ω±20% resistors were chosen. With 48 resistors per channel (~500W per resistor), the connections are as shown in Fig. 4. The nominal resistance is 0.525 Ω, and the measured value is close to 0.6 Ω. The load can be reconfigured to 2.4 Ω, 1.2 Ω or 0.3 Ω without major changes.

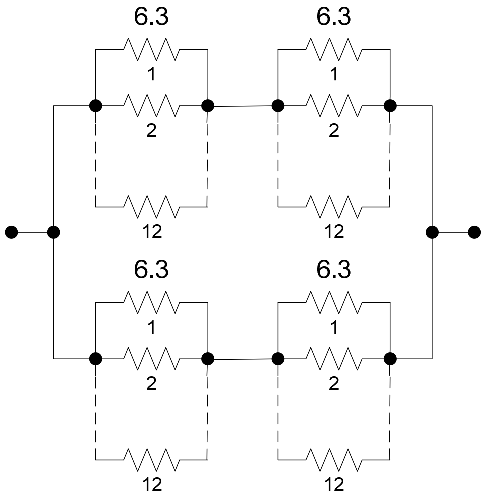


Fig. 4. Electrical connections (one channel).

C. Mechanical Layout

The load inductance L_{Load} is a sum of the resistor assembly inductance and the auxiliary and main busbars' inductances. An equivalent circuit (illustrating also the geometrical arrangement and parasitic resistances) is shown in Fig. 5. According to it, L_{load} can be calculated as

$$L_{load} = \left(L_R + L_{aub}\right)/2 + L_{mb},$$

where L_R is the inductance of the resistor pack of 12, and L_{aub}, L_{mb} are the auxiliary and main busbars inductances, respectively.

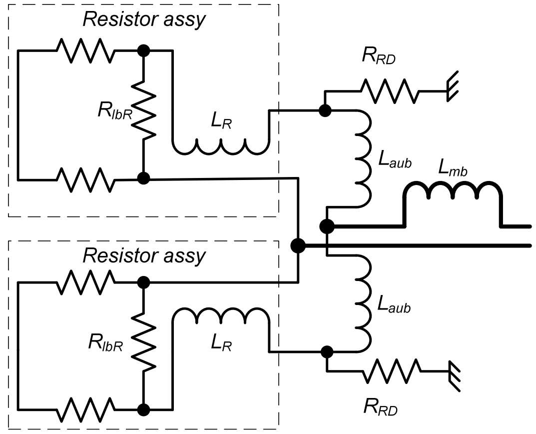


Fig. 5. Equivalent circuit of resistive load accounting for parasitic inductances and coolant conductance.

Minimizing the volume occupied by the magnetic field is key to achieving low inductance. With this in mind the resistors were grouped twelve in parallel in one plane, the return path being provided by another group of twelve (see photo Fig. 6a). The inductance calculation for such an arrangement may be performed for a flat busbar approximation using the following formula [2]:

$$L := \frac{\mu 0}{\pi} \cdot \left(ln\left(\frac{d}{b+c} \right) + \frac{3}{2} + f - \varepsilon \right)$$

where μ_0 is the permittivity of free space, d is mean distance between the bars, b, c are the bar thickness and width, respectively, f, ε are tabulated values. For the resistor assembly, d=0.06 m, b=0.02 m, c=0.3 m, f=0.8, ε=0.002, which yields L=2.5·10^{-7} H/m, or L_R=7.5·10^{-8} H for the resistor pack having a length of ~0.3 m. This calculation was also verified by finite element analysis. Since there are two packs connected in parallel, their inductance is halved (see equivalent circuit Fig. 5). The auxiliary and main busbars inductances L_{aub}, L_{mb} add ~100 nH, so the overall load inductance was expected not to exceed 200÷300 nH. Actual measurement provided a value of L=200 nH (Quadtech 1920 LCR meter, measurement taken at 10 kHz).

The resistor assembly fits into a standard 20-gal stainless steel drum (Fig. 6b) and is suspended by the main busses on a Lexan lid that serves also as a bushing.

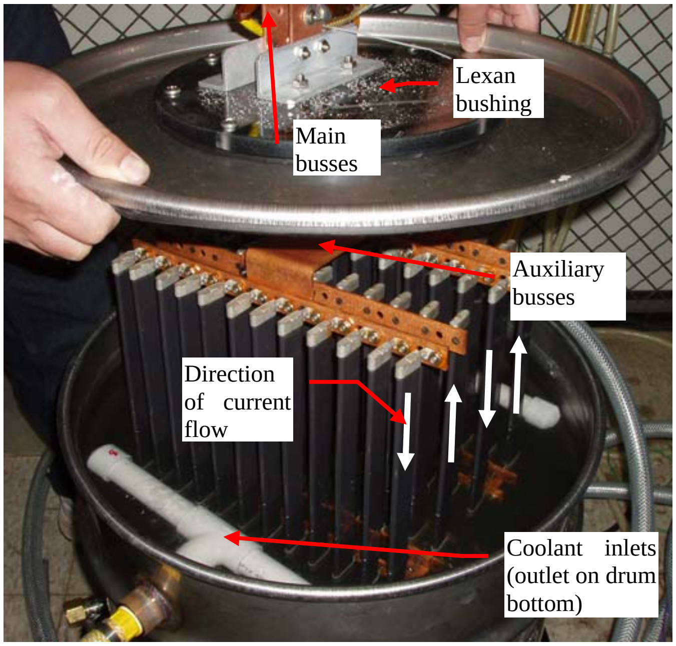


Fig. 6. Resistive load being immersed into coolant (one channel). Load is fully isolated from drum.

D. *Kinematic diagram*

The system works on a closed cycle. The cooling agent is circulated through the two vessels with loads by means of a pump and gives heat away in a heatsink provided by a fan (Fig. 7). The flow is monitored by flowmeters, and the flow rate can be roughly regulated by valves installed on the drums. The hosing system is symmetrical with regard to the loads; no other special means for balancing the load was designed. Overheat condition that may occur following the pump failure, clots, etc., is prevented by interlocking provided by thermoswitches monitoring the drum temperatures.

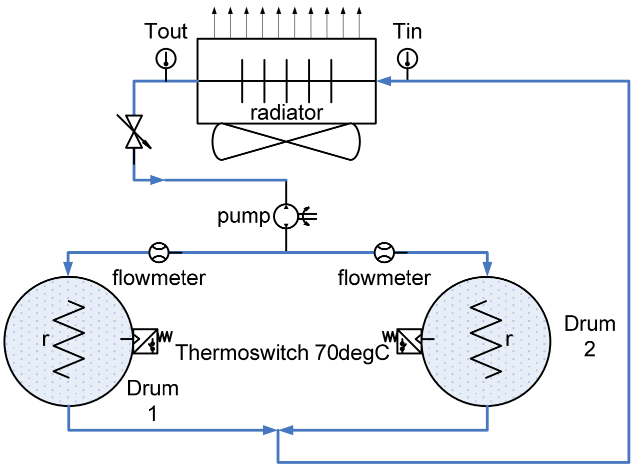


Fig. 7. Kinematic diagram of cooling system.

E. *Cooling Agents*

Insulating liquids, such as transformer or silicone oil have good dielectric properties and satisfactory cooling capability, and thus would be an ideal choice. The required flow rate can be calculated using the formula

$$m = \frac{P}{c_p \Delta T},$$

where P is the dissipated power, P=52 kW=177,000 BTU/hr, c_p is specific heat capacity, or just specific heat, at constant pressure, and ΔT is the target temperature difference. Assuming ΔT=50 ^{0}C between the drum and the outlet of the heat exchanger, we calculate the mass flow rate Q_m per channel for oil with c_p=2 kJ/kgK Q_m≈0.5 kg/s, or the volumetric flow rate Q_v≈30 l/min (≈8 gal/min). Such flow rate can be easily provided by conventional pumps. However, the problem in using oil is poor safety related to flammability and risk of spillage. Therefore, notwithstanding concerns about dielectric strength and corrosion, we considered Ethylene Glycol (EG), Propylene Glycol (PG) and their water mixtures used widely as antifreezes. Deionized water was discarded in view of expected corrosion and loss of dielectric properties over prolonged service.

EG and its water mixtures have been used in pulsed power (see, e.g., [3], [4]), mainly owing to large permittivity (≈40 for EG). For withstanding long pulses (several microseconds and longer) water should be clean, and the solution chilled.

Literary data on resistivity of EG and PG, and especially their solutions, are difficult to find. The only authoritative reference to this property was found in [5]. Some additional information is contained in [6]. According to [5], EG resistivity is $\rho\approx10^4\,\Omega\cdot$m at 20 ^{0}C. A short test was done in-house to estimate this parameter. Two flat electrodes with the area of 7 cm^2, distanced by 0.5 mm, were immersed into liquid. A Prestone EG-based coolant (presumably, 97% EG) had $\rho\approx140\,\Omega\cdot$m at room temperature at a DC voltage of 10 V. Deionized water had $\rho\approx0.7\cdot10^4\,\Omega\cdot$m at 200 V, so it was assumed that the mixture would have resistivity not less than that of EG. Curiously, the measured values can be considered favorable in the light of experimental data [7], where the maximum of the dielectric strength for electrolytes, in quasi-uniform fields under the application of long “oblique” pulses, was found at $\rho\approx2\div3.5\cdot10^2\,\Omega\cdot$m.

Obviously, the surrounding liquid acts as a shunt for the load resistors. For the described geometry, the coolant shunt resistance (see Fig. 5) may be estimated at 10 Ω at room temperature, considerably larger than the resistor assembly. The temperature rise may decrease this value greatly, by an order of magnitude for 20÷30 K, as inferred from [3], [4].

Analyzing possible load connections Fig. 1, we note that option **b**, when the load is tied to ground is preferable in that the voltage is applied to the coolant only during the capacitor discharge, and thus the coolant is stressed during several μs only. The parasitic current then flows between the resistor assemblies (resistances R_{lbR}) and between the resistors and the drum (resistances R_{RD})—see Fig. 5. In option *a*, the voltage across the coolant resides all the time during the charge, when the current flows through R_{RD}, and until the capacitor has been discharged.

We note that in the present implementation our primary concern resides with the resistance stability, and not with dielectric strength: the insulation distances are several centimeters and are ample enough to hold, probably, hundreds of kV at microsecond durations. We do not have substantive information on the dielectric properties of water-glycol mixtures at much longer pulses; however, some useful estimations can be made to this end. The power dissipation in the liquid is $P = {V_{ch}^2}/{R_{liq}}$, or 1 MW at V_{ch}=1200 V and R_{liq}=1.44 Ω (see Section III). If applied continuously, such power would bring the mixture to boiling, which can be considered as coinciding with breakdown at long pulses. Thus, the time to breakdown can be estimated as $\tau_{brd} = \frac{c_p m \Delta T}{P}$ assuming adiabatic heating and constant R_{liq}. For the liquid mass m=70 kg, ΔT=50 K, c_p=3.56 kJ/kg·K we calculate τ_{brd} =12 s. Such a situation, although hypothetical in view of the necessity to invest hugely excessive power to sustain the storage capacitor charged, cautions against connection Fig. 1a.

EG is highly toxic, so eventually a Prestone PG diluted by deionized water in a proportion of 50%-50% was chosen as a coolant. PG specific heat of 2.51 kJ/kg·K is close to that of EG (2.41 kJ/kg·K) [8], and in 50%-50% water mixture c_p=3.56 kJ/kg·K, about 85% of specific heat of water. Thus, the flow rate can be considerably lower than that for oil circulation.

III. TEST RESULTS

Prolonged runs at full power of 52 kW showed that the drums’ temperature (measured in the midsection using thermocouples) was 60 ^{0}C÷70 ^{0}C (depending on ambient temperature and the position of the heat exchanger) at a flow rate of 20 l/min. The ambient temperature in the test compartment was maintained by a chiller at 23 ^{0}C, although the temperature around the drums was considerably higher. No sign of resistors degradation except steel tabs rusting was noted; the coolant, however, became opaque and slimy, and the busbars were also coated with slime. The coolant resistance as measured at high current of up to 3 A using a DC power supply varied from 9 Ω at 11 ^{0}C (fresh mixture, kept in the drum for about a month) to 2.8 Ω at 18 ^{0}C (aged mixture), to 1.2 Ω at 54 ^{0}C (aged mixture). This corresponds to the observed increase of the discharge current by ~10 % at hot conditions (67 ^{0}C) compared to cold operation (23 ^{0}C—see Fig. 8).

Electro-corrosion that is disregarded in short-pulsed systems is an important issue for investigation for this application. However, it is beyond the scope of this paper.

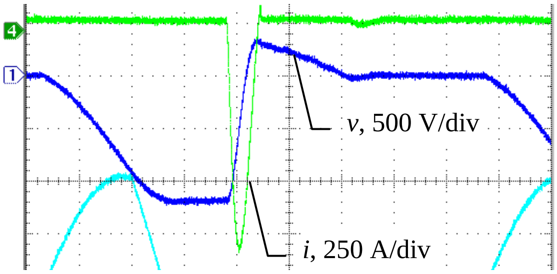


Fig. 8. Capacitor voltage and load current at 23 ^{0}C.

IV. ACKNOWLEDGEMENT

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