DESIGN OF A 16 kV, 100 kA, 2 Hz POWER SUPPLY FOR HIGH-FIELD, REPETITIVELY PULSED, SPLIT-PAIR MAGNETS

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Abstract

Los Alamos National Laboratory is installing in its Neutron Scattering Center a high-field, split-pair, pulsed magnet system as a user facility for neutron scattering experiments. The first magnet, to be designed and built by the National High Magnetic Field Laboratory, will be repetitively pulsed at a frequency of 2 Hz and is designed for a field strength of 23 T for 10e7 cycles and up to 30 T for 10e4 cycles. The 1.6 GVA pulsed power supply, which energizes the magnet, consists of a double ringing circuit with a capacitive energy storage unit. The parameters and the unique features of the major components of the supply, such as the capacitor bank including the charging unit, the solid-state closing switch, the free-wheeling diode, the auxiliary inductor and the cabling arrangement will be explained. In particular the design of the 16 kV, 100 kA, 2 Hz, solid-state closing switch, which is based on thyristor technology, will be presented. The overall electrical system is designed for 5x10e8 pulses. The fatigue life of each component must be evaluated. Fatigue life data for the major components, as presented in the literature and obtained from the component manufacturers, will be summarized and the fatigue life effect on the component design will be shown.

I. INTRODUCTION

Pulsed neutron beams are being used in solid-state physics research for diffraction and spectroscopic studies. With the addition of a pulsed magnet these neutron diffraction studies can be made with the magnetic field as an additional experimental variable. The Los Alamos pulsed spallation neutron source produces a string of neutron pulses at a frequency of 20 Hz with a neutron pulse width of 25 to 100 μs. Because the neutron source is not continuous but pulsed, it is advantageous to use also a pulsed magnetic field in synchronism with the neutron pulses. This approach has the advantage that a pulsed magnet can produce higher fields than a continuous magnet for the same average power consumption. We have selected 2 Hz as the frequency for the magnet to reduce the average power requirement and still reach fields above 16 T, which would be the limit for a superconducting, split-pair magnet. The sample, which is installed in the bore of the magnet, is illuminated by the neutron beam exposed in a magnetic field every tenth neutron pulse. Figure 1 shows the shape of the neutron pulse in relation to the magnetic field pulse. It is desirable to have the magnetic field constant during the neutron pulse. The generation of a sinusoidal field pulse is easier to accomplish than of a rectangular pulse. Sinusoidal fields are acceptable if the neutron pulse length is short compared to the field length and the neutron pulse is synchronized to the peak of the magnetic field.

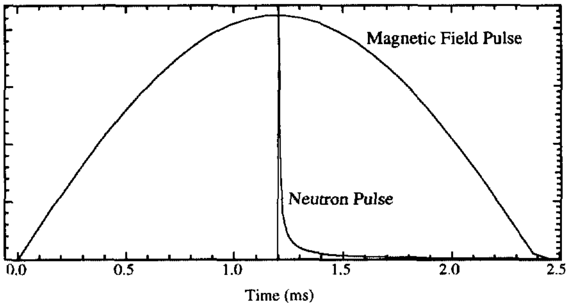

Fig.1. Neutron current and magnetic field pulse shape

II. CIRCUIT DESCRIPTION

Generation of repetitive, unidirectional fields can be accomplished in a circuit as suggested by Nishina and Kuroda, using an energy storage capacitor bank and two ringing circuits[1]. The circuit is shown in Fig. 2. The control of the charging supply CP allows for variation in the field amplitude. A variation of the circuit for both unidirectional and bidirectional magnetic field pulses is shown in Fig. 3. Besides the bidirectional nature of the switch S the major difference of the circuit for generating bidirectional fields is the replacement of the free-wheeling diode by a set of antiparallel thyristors. The sequence of positive and/or negative field pulses is arbitrary and is controlled by the triggering of the bidirectional switch S and freewheeling switch FWS. To obtain a large variation in the field amplitude, resistors may have to be installed in the free-wheeling switch path to absorb some energy. With reference to Fig.2, the charging supply CP charges the capacitor C with the polarity shown. When the switch S is triggered, the capacitor discharges through the magnet M and the protection inductor Lp in the first ringing circuit formed by C and M plus Lp, producing the desired field. The inductance value of the protection inductor is small compared to the magnet inductance. When the current in

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Los Alamos National Laboratory is installing in its Neutron Scattering Center a high-field, split-pair, pulsed magnet system as a user facility for neutron scattering experiments. The first magnet, to be designed and built by the National High Magnetic Field Laboratory, will be repetitively pulsed at a frequency of 2 Hz and is designed for a field strength of 23 T for lOe7 cycles and up to 30 T for lOe4 cycles. The 1.6 GVA pulsed power supply, which energizes the magnet, consists of a double ringing circuit with a capacitive energy storage unit. The parameters and the unique features of the major components of the supply, such as the capacitor bank including the charging unit, the solid-state closing switch, the free-wheeling diode, the auxiliary inductor and the cabling arrangement will be explained. In particular the design of the 16 kV, 100 kA, 2 Hz, solid-state closing switch, which is based on thyristor technology, will be presented. The overall electrical system is designed for 5xlOe8 pulses. The fatigue life of each component must be evaluated. Fatigue life data for the major components, as presented in the literature and obtained from the component manufacturers, will be summarized and the fatigue life effect on the component design will be shown.

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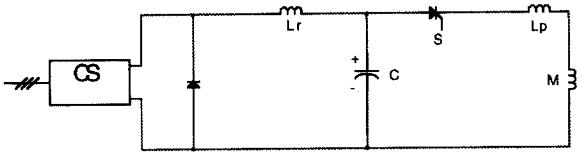

Fig. 2. Circuit diagram for generating repetitive, unidirectional pulsed magnetic fields

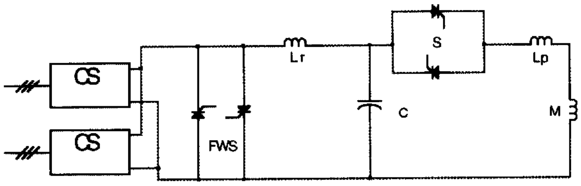

Fig. 3. Circuit for generating repetitive, bidirectional magnetic fields with an arbitrary positive or negative field sequence

the magnet reaches its maximum, the capacitor is completely discharged. The current will start charging the capacitor in the reverse direction, causing the diode to be forward biased and allowing current to flow in the second ringing circuit formed by C and Lr. By choosing the inductance of the ringing inductor Lr much larger than the inductance of the magnet, a decoupling between the two ringing circuits exists. The capacitor is first charged in the reverse direction, at which time the thyristor switch turns off. Then the capacitor discharges through the ringing inductance Lr to the polarity that was present initially. Because all the circuit components have losses, the voltage of the capacitor after one complete cycle is lower than the starting voltage. Most of the losses occur in the magnet M. In between pulses the charging supply recharges the capacitor to the initial voltage.

The parameters of the circuit are mostly determined by the magnet parameters, such as the desired field amplitude and length. The design of the magnet is a very challenging task and a reference magnet design for the first magnet has been completed[2]. The power supply is designed with some margin to accommodate a modest increase in voltage, current and energy of future magnets. The capacitance value was selected at 5 mF, resulting in a peak current of 89.9 kA at a 30 T peak field and a pulse length of 2.4 ms for the reference design magnet. Figure 4 shows, in a circuit simulation, the capacitor voltage and current, using the parameters of the reference magnet and the electrical circuit component parameters as given in Table I. The initial positive voltage is +14.7 kV, swinging to −12.3 kV at the end of the magnet pulse. During the next time period of 11 ms the capacitor charge reverses to +12.1 kV in the time the second ringing circuit is active. The simulation also shows the small time period of 0.6 ms when both ringing circuits are active. That time period is terminated when the switch current becomes zero and the thyristor returns to its blocking state. In the circuit simulation the resistance of the components was assumed to be independent of temperature and to be represented by resistance values which result in the same losses over a cycle as obtained by more complex, temperature dependent component modeling. The initial energy of the capacitor bank is 540 kJ. At the end of the two ringing occurrences the capacitor has a remaining energy of 366 kJ. During the next 450 ms the charging power supply must charge the capacitor back to the initial voltage. Before the next magnet pulse is initiated, the capacitor charge is kept constant at peak voltage for about 35 ms while a safety check is performed. The safety check determines the integrity of the magnet and the electrical system by comparing the last field profile with previous field shapes. In the case of abnormalities the next pulse is suppressed by inhibiting the trigger pulse to the switch.

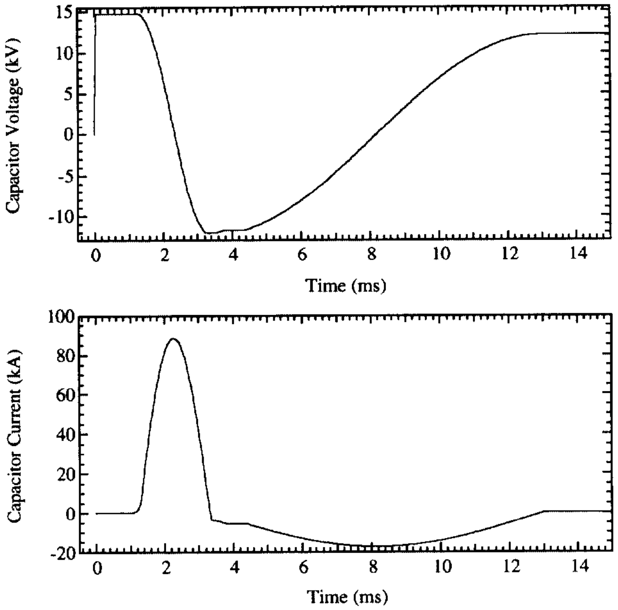

Fig. 4. Capacitor voltage and current shape under repetitively pulsed conditions for unidirectional field pulses

Table I. Electrical parameters of components

	inductance (mH)	resistance (mΩ)	losses (kJ)
magnet	0.107	13.43	131
diode		0.2	1.3
ringing inductor	2.5	9	16.3
switch		0.6	6
capacitor bank*	0.01	0.9	19
protection inductor	0.01	0.7	7
cabling in magnet ringing circuit*	0.005	0.2	2
cabling in Lr ringing circuit*	0.01	0.5	1
total losses			184

* estimate

II. COMPONENT SELECTION

The electrical system must be adequately designed for the first magnet and subsequent magnets, which might have higher power ratings. To stay within the budgeted cost envelope, the design of the electrical system only allows for a modest increase in rating over the required rating for the first magnet. The following limits for the electrical components were assumed. The electrical system should be capable to operate up to 16 kV, the peak current rating should be 100 kA with a 3 ms pulse length. The bank capacitance was chosen to be 5 mF. The overall cost for the electrical components is dominated by the cost of the capacitors. Because of the high number of repetitive cycles and the almost 100% voltage reversal, less expensive high energy density capacitors can not be used. The type of capacitor suitable for this application is the type of capacitor used in the power industry for power factor correction applications.

A. Capacitor Bank

The 5 mF capacitor bank will be designed for a peak voltage of 16 kV and 90% voltage reversal. There are many application in the pulsed power field for voltages between 3 to 40 kV, which use high energy density, self-healing capacitors. The cost/Joule for this type of capacitor is low(~5-7c/J) for voltage reversal to about 50% and number of pulses to 10e5. No reference installation with high energy density capacitors exists for an application which requires a very high number of pulses(5x10e8). Power factor correction type capacitors, as being used in the electric utility industry, are the most suitable for our application. These capacitors are designed for a long life(≥30 years at 60 Hz operation) and 100% voltage reversal. The dielectric stress in these capacitors is considerably lower than in high energy density capacitors, resulting in a lower Joule/weight ratio and therefore costs which are in the order of 7 to 10 times higher than high energy density capacitors. A bank designed with the low energy density capacitors becomes physically larger than one designed using high energy density capacitors.

The charging supply must compensate for the losses of all the circuit components and recharge the capacitor bank to the initial voltage in 450 ms. Using the values of the circuit simulation for the magnet reference design as indicated in Table I, and assuming constant current charging, requires a 500 kW charging supply with a 32 A current rating. The most cost effective solution for such a charger is a design which uses three-phase ac 480 V input regulation, a step up transformer and a diode rectifier.

B. Solid-State Switch

A repetitive, 2 Hz switch being capable of blocking 16 kV in the forward direction and 14.4 kV in the reverse direction, conducting a sinusoidal current with an amplitude of 100 kA with a pulse length of up to 3 ms is a challenging switch design. This is not an interrupting switch, as current ceases to flow in the switch caused by the ringing nature of the tuned circuit. The high number of operations does not allow the use of mechanical or even ignitron switches. High-power thyristor switches are suitable for the operation. Recently, experimental results with high power thyristor switches show encouraging results. Currents up to 180 kA in single pulsed mode operation have been reported in the literature with one single device[3]. The key to a solid-state switch design is the handling of the heat generation and removal of the heat from the thyristor wafer, thus staying within allowable temperature limits. Two further parameters influence the lifetime of the thyristor switch. As is shown in Fig. 5, the thyristor switch must block a high reversing voltage after the current ceases. Blocking of such a high reverse voltage is more readily being achieved with a cold thyristor. Also the lifetime is decreased by a high temperature excursion during a current pulse, thus demanding low junction temperature excursions during operation. The overload and di/dt capability of thyristor switches are not so great as for mechanical or ignitron switches. Therefore a protection inductor (Lp in Fig.2) is inserted in series with the switch to limit the short circuit current in the case of a solid magnet terminal short. Under normal operation the protection inductor is undesirable, causing the capacitor voltage to be increased for the same current in the magnet. The design of the switch takes into account up to five short circuit conditions plus the large number of cycles under normal operation. For the few short circuit currents a higher temperature excursion than for the normal operation is acceptable. A preliminary switch design has been made, using three 100 mm, 5 kV thyristors in parallel and four thyristors in series. For normal 100 kA, 3 ms current operation the peak wafer temperature has been calculated to be 27 ^{0}C. The switch cooling assembly must be designed to carry an rms current of 5.5 kA.

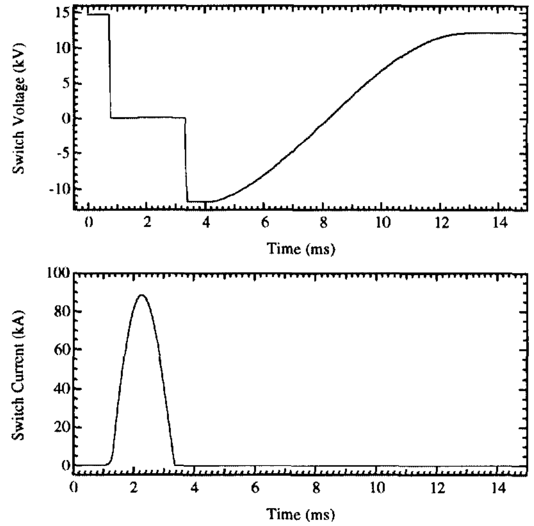

Fig. 5. Switch voltage and current shape

C. Ringing and Protection Inductor

When selecting the value for the ringing inductor it must be remembered that a minimum inductance value of approximately 20 times the magnet inductance must be chosen to achieve decoupling of the two ringing circuits.

Probably just cost determines the upper bounds for the value of Lr. For a fixed capacitor value the value for Lr and the the peak and rms value of the ringing current are interrelated. Increasing the ringing inductance reduces the ringing current and the ohmic losses. A 10 μH inductance value has been chosen for the protection inductor, the value being one tenth of the magnet inductance. In the case of the short circuit the protection inductor must carry a current of 300 kA peak for a pulse width of 1 ms. In a short circuit the protection inductor is exposed to the full voltage, therefore the inductor must be designed for the full 16 kV voltage. The major design parameters for the two inductors are summarized in Table II. Values of 2.5 mH and 10 μH were selected for the ringing inductance and protection inductance, respectively. For operational convenience air cooling of the conductor is preferred over water cooling for both inductances.

Table II
Electrical Parameters for Ringing and Protection Inductor

	Lr	Lp
Voltage rating(kV)	16	16
Peak current(kA)	18	100
Peak current under short circuit(kA)		300
Rms current(kA)	1.9	5.5

D. Free-Wheeling Diode

The free-wheeling diode must block the full capacitor voltage during charging. The diode peak and rms current equals the peak and rms current of the ringing inductor, when the charging current in the ringing inductor is neglected.

E. Cabling

The high pulsed current combined with the 2 Hz repetition rate causes the rms current in the cable for the magnet branch to be 4.4 kA for the reference design. To keep the electromagnetic noise low, coax cables must be used in this application. The largest cross section of existing coax cables is currently designed for 100 to 200 A current ratings. Therefore a large number of parallel cables must be used to conduct the current. We are working with a cable manufacturing company to design a 16 kV coax cable with both conductors having a 500 mcm(253 mm2) cross section. An 80 cm long prototype cable has been manufactured and is being tested.

IV. FATIGUE LIFE INFORMATION

Fatigue life information for the major components of the electrical system is not easily available from the manufacturer and has not been presented in the literature with the exception of the solid-state switch and the free-wheeling diode. The inductors can be designed using experiences from electrical utility components. For magnetic components in the utility industry ratios of peak currents to rms currents occur during short circuit conditions which are similar to the pulsed conditions in our application, except that only a very limited number of short circuits occur compared to the large number of magnet pulses. A conservative design approach must chosen for these components. The situation is similar with the capacitors and the capacitor bank. The pulsing nature of the current with a high peak current compared to the capacitor rms current requires special attention to individual components of the capacitors, such as the connections from the capacitor foil to the bushing conductor. In the field of solid-state devices one manufacturer of high power semiconductors has published the results of experimental investigations showing the dependency of semiconductor thermal fatigue as a function of the temperature excursions[4]. The summary of the experimental data shows a strong dependency of the semiconductor life time on the wafer temperature excursion. These findings are being used in the design of the switch and diode.

V. SUMMARY

The design of a high power electrical system for a repetitively pulsed magnet carries many challenges. The electrical system consists of a 540 kJ capacitive energy storage unit and two ringing circuits. The capacitor bank charging supply compensates for the losses occurring in the electrical components during the current conduction. The high repetition rate of the current pulses(2 Hz) requires a high-power(500 kW) charging supply for the given circuit losses. A 1.6 GVA(16 kV, 100 kA), solid-state closing switch initiates current conduction in the magnet. A preliminary switch design, consisting of 12 high power thyristors has been presented. Special attention is paid to the pulsed nature of the operation and the lifetime of the components designed for 5x10e8 cycles.

VII. REFERENCES

[1] M. Motokawa, H. Nojiri, J.Ishihara, and K. Ohnishi, "Production of repeating pulsed high magnet field," Physica B 155 (1989), 39-42.

[2] Y. M. Eyssa, R. P. Walsh, J. R. Miller, P. Pernambuco-Wise, M. D. Bird, H.-J. Schneider-Muntau, H. J. Boenig and R. A. Robinson, "25-30 T water cooled pulsed magnet concept for neutron scattering experiment," proceedings of fifteenth international conference on magnet technology, Science Press, 1998, pp 691-694.

[3] H. J. Boenig, J. W. Schwartzenberg, L. J. Willinger, D. E. Piccone, D. E. Lopez, H. A. Smolleck, "Design and testing of high power, repetitively pulsed, solid-state closing switches," in conference record of the 1997 IEEE Industry Application Society Annual Meeting, IEEE catalog number 97CB36096, pp. 1022-1028.

[4] I. L. Somos, D. E. Piccone, L. J. Willinger and T. H. Tobin, "Power semiconductors emperical diagrams expressing life as a function of temperature excursion," IEEE Transactions on Magnetics, Vol. 29, N0. 1, Jan 93, pp 517-522.