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Energy extraction system using dual-capacitor switching for quench protection of HTS magnet

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Abstract

The superconducting magnets have a large inductance as well as high operating current. Therefore, mega-joule scale energy can be stored in the magnet. The energy stored in the magnet is sufficient to damage the magnet when a quench occurs. Quench heater and dump resistor can be used to protect the magnet. However, using quench heater to create quench resistors through heat transfer can be slower than instantly switching resistors. Also, electrical short, overheating and breakdown can occur due to quench heater. Moreover, the number of dump resistor should be limited to avoid large terminal voltage. Therefore, in this paper, we propose a quench protection method for extracting the energy stored in a magnet by charging and discharging energy through a capacitor switching without increasing resistance. The simulation results show that the proposed system has a faster current decay within the allowable voltage level.

Keywords: capacitor switching method, energy extraction, fast current decay, protection circuit, quench protection

1. INTRODUCTION

Superconducting magnets are widely used in various applications requiring high magnetic field, due to their high current density. As applications of superconducting magnets have been continuously expanding, the use of large-scale magnets is also increasing. In general, superconducting magnets can store tens of mega-joule energy in the magnet because of its high current density [1]. However, generated temperature is proportional to the square of transport current when a normal zone occurs in any part of a superconducting magnet. Therefore, high current flowing in the superconducting magnet can generate enough energy to instantaneously destroy the magnet in case of a quench. For these reasons, it is very important to rapidly spread or remove the energy stored inside the magnet when a quench occurs. In order to protect the magnet, there are two main ways to remove the energy stored in the magnet. The first one is increasing the series resistance of the magnet and the other is increasing the parallel resistance [2-4]. However, there are some limitations and problems with increasing both series and parallel resistance. To increase the series resistance (R_S), a quench heater (QH) is widely used. After detecting the quench, the QH is activated to increase normal zone inside the magnet which is the series resistance of the system. However, the protection method using QH cannot be induced quench rapidly in high temperature superconducting (HTS) wire because of its large energy margin. Also, the quench heater is fragile and easily causes electrical breakdown and it is troublesome to cover many parts of the coil surface [5]. Coupling Loss Induced Quench (CLIQ) protection system was recently developed at the CERN magnet test facility instead of QH with several disadvantages to increase R_S [6-8]. The CLIQ protection system injects the energy of a pre-charged in capacitor to generate an AC loss in the magnet [6]. However, CLIQ is difficult to be applied to HTS magnets due to its high energy margin between superconducting state and normal state. The other method is using parallel resistor which is connected to the magnet to extract the stored magnetic energy. However, the shortcoming of this method is current repartition as the magnet is charged. Also, when using a large parallel resistor to quickly remove energy, a high terminal voltage can be applied because the high magnet current flows instantaneously into the parallel resistor [9].

Therefore, in this paper, new quench protection method is proposed without increasing both series and parallel resistance. Proposed method can extract the stored magnetic energy using both dual-switch and capacitor. The capacitance is calculated to reduce the response time by using critically damped characteristic. Also, this proposed method can be applied with other quench protection system simultaneously. Moreover, it is possible to quickly decrease the current within allowable internal voltage level without increasing resistance.

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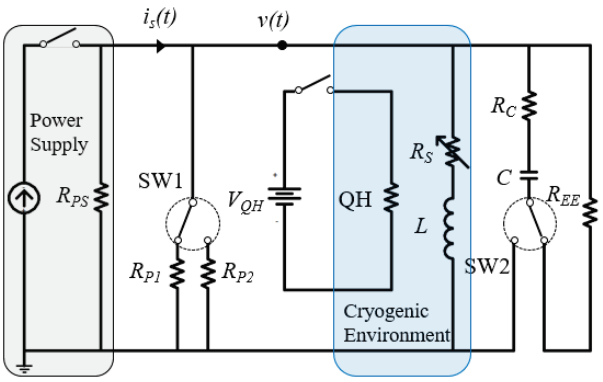

Fig. 1. Equivalent circuit of energy extraction system using dual-capacitor switching.

2. CONCEPT OF ENERGY EXTRACTION SYSTEM USING CAPACITOR SWITCHING

2.1. System Structure

The time constant for discharging the energy of the inductor through the resistor is given by $\tau = L/R$. On the other hand, the time constant of the capacitor and resistor is given by $\tau = R \cdot C$. The resistance of a superconducting circuit is so small that energy transfer rate through a capacitor is very faster than using RL circuit. When the capacitor is switched to the magnet, the current flowing through the parallel resistor is decreased. Therefore, large resistor within allowable voltage can be used for increasing charging capacity of capacitor when a capacitor is switched. Switching of large resistance also prevents the reduction of parallel impedance.

Fig. 1 shows the equivalent circuit of the entire protection system. A DC power supply consists of a switch and an internal resistor that can be shut down when the quench is detected. Two branches which are capable of switching between capacitor and two parallel resistors are connected on both sides of the magnet. In addition, an energy extraction resistor (R_{EE}), which can discharge the energy stored in the capacitor, is connected to SW2. In this system, energy extraction resistors are located in the room temperature environment. Therefore, joule heating is only generated outside the cryogenic environment.

2.2. RLC Damping Characteristic

The capacitor is switched between magnet and resistor for charging. When capacitors are connected in parallel, the circuit has various RLC damping response characteristics. The inductance is a fixed value when the target magnet is determined. And the parallel resistance is also a fixed value designed considering the allowable voltage level of the magnet. The second-order differential circuit equation by RLC parallel circuit is given as

$$\frac{d^2v(t)}{dt^2} + \frac{1}{C \cdot R_P}\frac{dv(t)}{dt} + \frac{v(t)}{C \cdot L} = \frac{1}{C}\frac{di_S(t)}{dt} \tag{1}$$

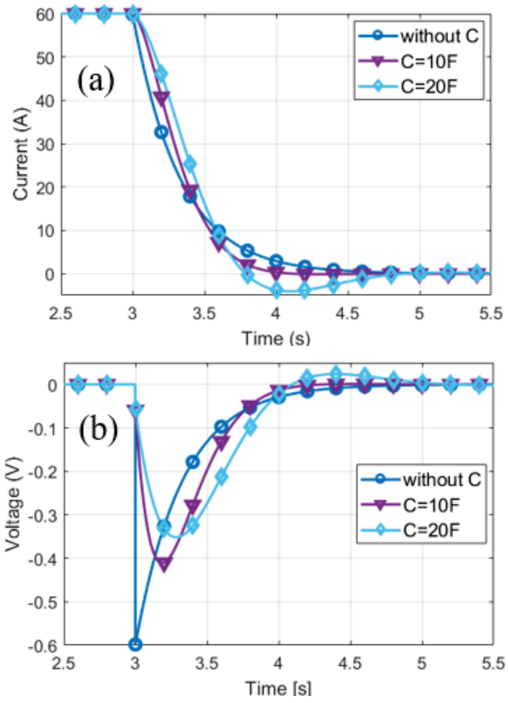

Fig. 2. Damping characteristic after current shutdown; (a) current of magnet, (b) terminal voltage of magnet.

where C is parallel capacitance, R_p is parallel resistance, L is the self-inductance of magnet, and $i_s(t)$ is power supply current, respectively. The general solution of (1) can be separated by particular solution (v_P) and complementary solution (v_c) as follows

$$v(t) = v_p(t) + v_c(t) \tag{2}$$

The complementary solution, which is the transient response of (2), becomes the homogeneous solution as follows

$$\frac{d^2v(t)}{dt^2} + 2\xi w_0 \frac{dv(t)}{dt} + w_0^2 v(t) = 0 \tag{3}$$

with $\xi = \sqrt{L \cdot C}/(2R \cdot C)$ and $w_0 = 1/\sqrt{L \cdot C}$.

This circuit has three different response characteristics according to the damping ratio (ξ) of (3).

$$v_c(t) = K_1 e^{-(\xi w_0 - w_0\sqrt{\xi^2-1})t} + K_2 e^{-(\xi w_0 + w_0\sqrt{\xi^2-1})t} \tag{4}$$

$$v_c(t) = e^{-\xi w_0 t}(A_1 \cos w_0\sqrt{1-\xi^2}t + A_2 \sin w_0\sqrt{1-\xi^2}t) \tag{5}$$

$$v_c(t) = B_1 e^{-\xi w_0 t} + B_2 t e^{-\xi w_0 t} \tag{6}$$

where the constants K_1, K_2, A_1, A_2, B_1, and B_2 can be obtained from the initial conditions of $v(0)$ and $dv(0)/dt$. Equations (4)-(6) show the responses of overdamping ($\xi > 1$), underdamping ($\xi < 1$), and critically damping ($\xi = 1$), respectively [10]. Damping ratio ξ from the circuit equation is as follows.

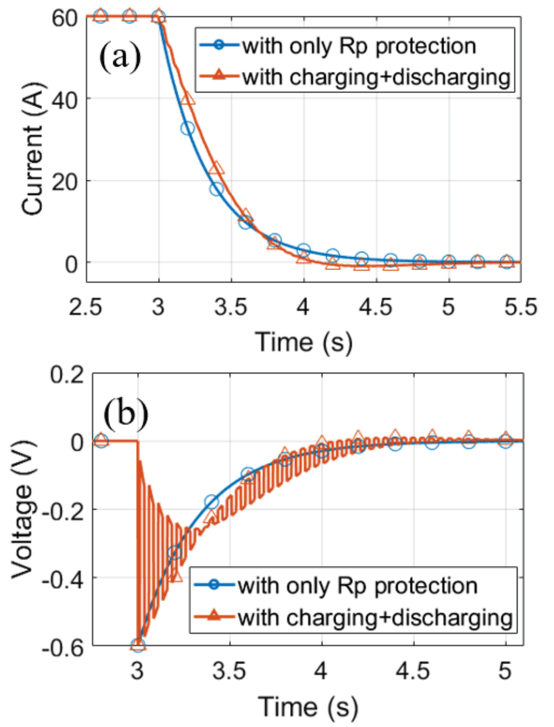

Fig. 3. Single capacitor switching for energy charging and discharging; (a) current of magnet, (b) terminal voltage of magnet.

$$\xi = \frac{\sqrt{LC}}{2CR} \tag{7}$$

Fig. 2. shows current and voltage according to capacitance when power supply is shut down after quench is detected. As a result, RLC circuit has various damping characteristics depending on the capacitance as shown in Fig. 2. In this circuit, as capacitance becomes smaller, the damping current becomes almost the same as the case without capacitor. In the simulation, the operating current was set to 60 A, the self-inductance of the coil was set to 3.3 mH, and the R_P was set to 0.01 Ω. As the capacitance increases, the ξ decreases and oscillation current occurred. When using a large capacitor, the time to reach zero current is faster but the current decay is slower in the high current section. Therefore, MIITs, time integral of a square of the current normalized to 10^6, are increased. The purpose of the RLC parallel circuit analysis is to find the fastest damping characteristic rather than reducing MIITs. The capacitance for critically damped characteristic, which is the fastest damping characteristic (ξ =1), is about 8.25 F from (7).

2.3. Charging and Discharging of Capacitor

A Single Pole Double Throw (SPDT) switch was used to repeat charging and discharging of the capacitor. Capacitance is satisfying critically damped characteristic and resistance of R_{EE} is 0.001 Ω. The energy stored in the magnet is extracted through the repeated charging-discharging of the capacitor and the time to reach zero current is faster than the method using only R_P as shown in Fig. 3(a). However, MIITs of the protection method using only R_P and capacitor switching are 0.000592 MA^{2}s and 0.000768 MA^{2}s, respectively. Fig. 3(a) shows that the capacitor switching method still has a longer decay time than the only R_P protection in the high current region. Therefore, although the energy is repeatedly extracted by the capacitor, the temperature rise of the magnet is larger than without capacitor switching. Fig. 3(b) shows that low voltage level and high voltage level are formed depending on the position of the capacitor. However, the allowable voltage level of arbitrary 0.6 V is not exceeded.

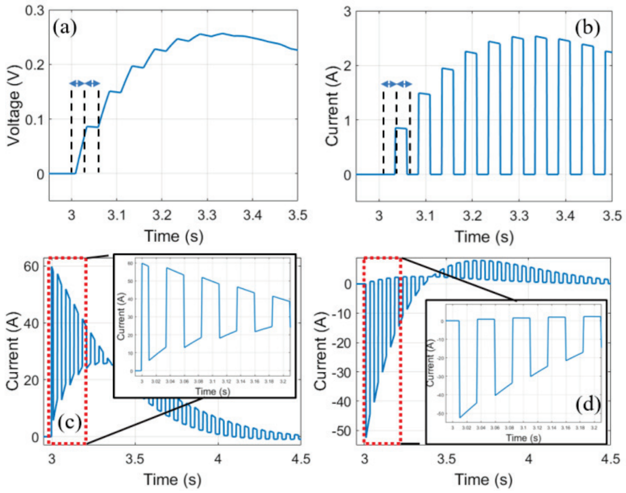

Fig. 4. Single capacitor switching for energy charging and discharging; (a) Voltage of capacitor, (b) current of R_{EE}, (c) current of parallel resistor, (d) current of capacitor.

2.4. Dual-switching for Fast-current Decay

The switching time of the capacitor is classified into two sections, charging from the magnet and discharging to the R_{EE}. Fig. 3(b) shows that the generated terminal voltage whose peak value is 0.6 V when the charging voltage of the capacitor is less than arbitrarily defined 0.6 V as shown in Fig. 4(a). As the capacitor is charged, the current flows through the parallel resistor and capacitor. Therefore, the terminal voltage decreases due to the decreased current of the parallel resistor as shown in Fig. 4(c). Therefore, allowable voltage margin is increased when capacitor is switched to magnet. As a result, energy charged in the capacitor is small and magnet current is reduced slowly. For this reason, the impedance of the protection circuit and the terminal voltage can be further increased. It is also possible to prevent slow extraction of the magnet energy because of the reduction of the equivalent parallel impedance when the capacitors are switched to the magnet. As a result, a switch that can convert low resistance to high resistance when capacitor switched is required. Therefore, the two switches were configured to operate at the same time to prevent the decrease in impedance. In this system, magnet energy is sequentially extracted by R_{PI} and capacitor. Fig. 4(b) and Fig. 4(d) show that the charging and discharging current of capacitor and R_{EE} due to capacitor switching. As shown in the Fig. 4(b), current flowing in the R_{EE} are very small.

TABLE I
CIRCUIT PARAMETERS.

Parameter	Value
Inductance(L)	33 mH
Capacitance(C)	6 F
Parallel resistance1(R_{P1})	0.01 Ω
Parallel resistance2(R_{P2})	0.2 Ω
Extraction resistance(R_{EE})	0.012 Ω
Switching frequency(f_{SW})	20 Hz

The energy consumed by the external resistor is given by

$$\Delta w = \int I^2 R_{EE} dt \tag{8}$$

where I is current in capacitor, and R_{EE} is external resistance. To increase energy consumption, it is necessary to increase the current by reducing the amplitude of the R_{EE} as shown in (8). However, when the energy extraction resistance is reduced, the discharge of the capacitor is delayed. After determining the inductance and the available frequency, the circuit parameters of the protection system that can reduce the maximum MIITs were determined by adjusting the reference C, R_{P2}, and R_{EE}. Table I shows the frequency and designed protection circuit parameters. When the quench occurs, the power supply is shut down and the capacitor that was isolated from the magnet is switched to the magnet for charging. After the capacitor is fully connected to the magnet, the resistor is switched from R_{P1} to R_{P2} to prevent a decrease in impedance. Before the capacitor is switched to R_{EE}, the resistor is switched back to R_{P1}. The charged capacitor is then switched to the external resistor for discharging. Through this sequence, charge and discharge are repeated and capacitors and resistors extract the energy stored in the magnet.

3. SIMULATION RESULT OF ENERGY EXTRACTION SYSTEM USING DUAL-CAPACITOR SWITCHING

Fig. 5 shows simulation results of quench protection using dual-switching between resistors and the capacitor. The switching frequency was set to 20 Hz. And a different pulse width was applied on two SPDT switches to avoid both switches are switched at the same time as shown in Fig. 5(d). The proposed protection system is not exceeded the allowable voltage level of 0.6 V as shown in Fig. 5(f). In addition, Fig. 4(b) and Fig. 5(c) show that the maximum current in the R_{EE} is increased from 2.5 A to 22.5 A. Fig. 5(a) shows that the capacitor is charged more than 0.4 V. When the capacitor is switched to the external resistor R_{EE}, all charged voltages are not discharged but generate a large current in R_{EE} as shown in Fig. 5(c). Simulation results show that there is no slow current decay region. Calculated MIITs are 0.000592 MA^{2}s and 0.000511 MA^{2}s when only R_P protection and dual-switching protection is applied in the magnet system.

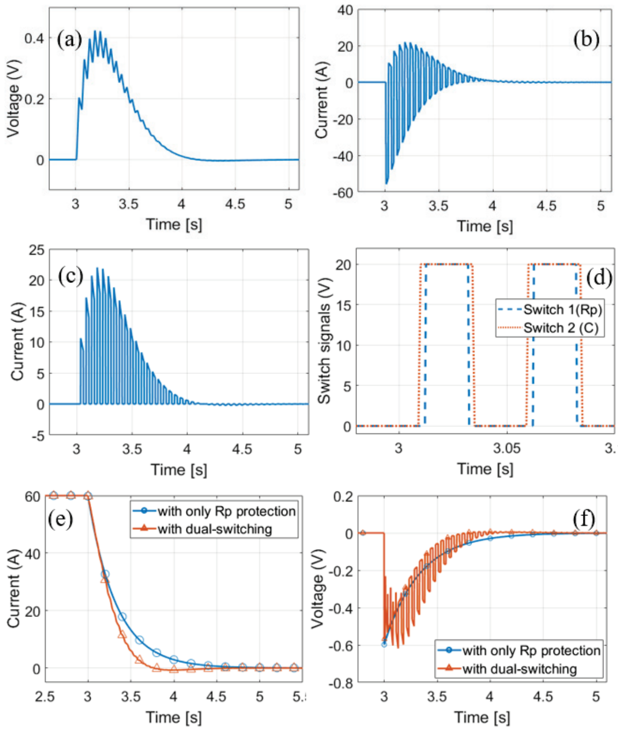

Fig. 5. Simulation result of energy extraction system using dual-capacitor switching; (a) voltage of capacitor, (b) current of capacitor, (c) current of R_{EE}, (d) switch input signal, (e) current of magnet, (f) voltage of magnet.

When proposed protection system is applied, the MIITs value was reduced by about 13.7 % compared to the protection method using only R_P.

4. CONCLUSION

Energy extraction system using dual-capacitor switching for quench protection of superconducting magnet was suggested and simulated. Proposed quench protection system was designed using two SPDT switch and capacitor without increasing resistance. Therefore, this system can be used for fast energy extraction system within allowable voltage level. The system can be applied by simply connecting the tabs at both ends of the magnet terminal. Therefore, it is expected that this method can be applied to all small, large, HTS and low temperature superconducting magnet.

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REFERENCES

[1] I. R. Dixon, W. D. Markiewicz, P. Murphy, T. A. Painter and A. Powell, “Quench detection and protection of the wide bore 900 MHz NMR magnet at the national high magnetic field laboratory,” *IEEE Trans. Appl. Supercond*., vol. 14, no. 2, pp. 1260–1263, 2004.

[2] F. Rodriguez-Mateos and F. Sonnemann, “Quench heater studies for the LHC magnets,” *Proc. IEEE PAC*, vol. 5, pp. 3451–3453, 2001.

[3] A. V. Fernández and F. Rodríguez-Mateos, “Reliability of the quench protection system for the LHC superconducting elements,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 525, no. 3, pp. 439–446, 2004.

[4] A. V. Dudarev, A. V. Gavrilin, H. H. J. Ten Kate, D. E. Baynham, M. J. D. Courthold and C. Lesmond, “Quench propagation and protection analysis of the ATLAS toroids,” *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 365–368, 2000.

[5] E. Ravaioli, et al., “First Implementation of the CLIQ Quench Protection System on a Full-Scale Accelerator Quadrupole Magnet,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 3–7, 2016.

[6] E. Ravaioli, V. I. Datskov, G. Kirby, H. H. J. ten Kate and A. P. Verweij, “A new hybrid protection system for high-field superconducting magnets,” *Supercond. Sci. Technol.*, vol. 27, no. 4, p. 44023, 2014.

[7] E. Ravaioli, et al., “Reprint of: First experience with the new Coupling Loss Induced Quench system,” *Cryogenics (Guildf)*, vol. 63, pp. 263–274, 2014.

[8] E. Ravaioli, et al., “First Implementation of the CLIQ Quench Protection System on a Full-Scale Accelerator Quadrupole Magnet,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 3–7, 2016.

[9] L. C. Hagedorn, V. Remondino and F. Rodriguez-Mateos, “LHC Magnet Quench Protection System,” *IEEE Trans. Magn.*, vol. 30, no. 4, pp. 1742–1745, 1994.

[10] J. D. Irwin and R. M. Nelms, “First-and second-order transient circuits in Basic engineering circuit analysis,” 10th ed., *Auburn: John Wiley & Sons*, pp. 296-368, 2010.