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Practical Investigations of Wireless Multiple-Power Charging Unit for Electron Quench Detection Device in the Super High Field Superconducting Magnet

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Abstract

A rapid and reliable quench detection is vital for high current superconducting magnet system to prevent irreversible damage to a magnet by the quench phenomenon. The method for detecting the occurrence of a resistive transition has been widely adopted in the superconducting magnet. In the case of the voltage monitoring by means of dedicated taps, the electron quench detection device (EQDD) conversion unit, which converts detected high voltages into voltage-drop signal, should be required in the superconducting high field magnet. The power source of traditional quench detecting system, which can monitor for superconducting magnet with middle power operation, is supplied through the power transformer since the transformer can provide galvanic isolation between circuits. On the other hand, in the case of the super high magnet systems such as Korea Superconducting Tokamak Advanced Research and International Thermonuclear experimental reactor, since the maximum operation current and voltage of the super high field magnet keep over 60 kA and 50 kV DC, a passive component, which has strong an isolation device and high dielectric resistor qualities, has been required in the super high field magnet. If the power transformer is adopted in the super high field magnet, it can cause high cost for volume capacity since it needs for higher dielectric resistance value over 500 MΩ. Authors proposed the wireless resonance antenna and multi-receiver coils which can keep high level of dielectric resistance value with stability. As well as, the wireless power charging unit can reduce system volume due to multi-charging receivers for one antenna. In this study, authors investigated the effect of inserted resonator (Sx) coil between antenna and receiver coils, as well as, evaluated the electric field and magnetic field among the resonance coils under 300 W 370 kHz RF power generator since the strong electro-magnetic fields by the resonance coils can affect the electron devices inside of the EQDD module.

Keywords Isolated multiple-wireless · Charging unit · Quench detection system · Super high field magnet

Extended author information available on the last page of the article

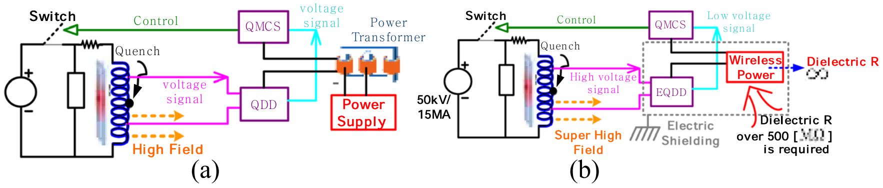

Fig. 1 Illustrations of traditional quench detection system (**a**), and suggested electron quench detection device (EQDD) including isolated wireless multiple charging (WMC) module under super high field magnet (**b**)

1 Introduction

A reliable quench detection system is an irreversible transition of the conductor from superconducting to normal resistive state, which is an abrupt, localized transition from the superconducting state during an off-normal event. The detection has to be fast enough (1–2 s) to initiate the dumping of the magnetic energy into the external resistors and avoid irreversible damage of the systems. If a quench does occur and is not rapidly detected, all of the magnetic stored energy will dissipate into the quenched region and overwhelm the cooling capacity leading to quench propagation, strong temperature rises, and thermally induced stress gradients that can damage or destroy the magnet, rendering the entire device inoperable until coil repair or replacement is implemented. [1, 2]. From these reasons, as an indispensable device, various alternative investigations to quench detecting system (QDS) have been required in the superconducting high-power applications. In the case of QDS for medium operating power of the superconducting magnet, as the conventional QDS needs to an isolated power including a power transformer, which can provide galvanic isolation between circuits and couple together signal-processing circuits as shown in Fig. 1a, the power transformers have been reasonably adopted since the transformers play a role to keep an isolated power device due to high insulating and durable characteristics [3, 4]. On the other hand, in the super high-power operation magnet systems such as the KSTAR (DC current of up to 35 kA) and ITER (DC current of up to 50 kA) magnet systems, the different passive components (power transformers), which keep stronger isolation and higher dielectric resistance (500 MΩ) qualities to keep stability, should be required. As well as, since detected high voltages at middle taps cause a high risk due to high voltage sparking detected, the detected high voltage signals at magnet should be digitized such as trigger pulses, which are voltage-drop signals using electron quench detection device (EQDD) [5–7]. As the EQDD should be insulated by high voltage enclosure under the condition of the super high field magnets, the proposed isolated power system with wirelessly resonance coils for EQDD should be required as shown in Fig. 1b. From these intrinsic reasons, the wireless power transfer (WPT) technology via resonance coupling method has been promisingly expected as a reasonable option since the insulation resistance between receiver (Rx) and antenna (Tx) coils of WPT technology can keep almost infinity with high stability. In a viewpoint of cost, as one antenna resonance Tx coil can supply multiple Rx coils (over 10) with electric power based on strong resonance coupling method, the number and cost of the transformers can be minimized when the WMC units can charge multiple EQDD devices. Furthermore, when the traditional power transformer can be replaced by wireless multi-charging (WMC) units, the WMC units can avoid the effect of dielectric resistance volume. In this paper, authors investigate the effect of inserted resonators (Sx) and thermal distributions between Tx and Rx coils. Also, authors examine distributions of electric field (EF) and magnetic field (MF) among resonance coupling coils for wireless multi-charging unit inside of the EQDD module under 300 W, 370 kHz of RF power generator.

2 Structure and Mechanism

2.1 Structure of Electron Quench Detection Device including Wireless Multi-charging (WMC) Unit for Super High Field Magnet

Figure 2a shows the conceptual processing illustration of EQDD including isolation WMC module via the strong resonance coupling method. The input part of the EQDD unit is electrically connected to high voltage signal cable of the magnet conductor through a protection system. The detected high voltage signals convert into voltage-drop signals through optic converter and such a pulse signal is sent into quench monitoring system through optic cable. The quench monitoring and control system (QMCS) through optical cable in real time is useful for detecting control of the rapid cooling in liquid nitrogen or helium. Figure 2b shows the mechanism illustration of the inserted dual-resonator (Sx) coil to expand distance in the wireless multi-charging unit. If the gap between antenna coil (Tx) and receiver coil (Rx) is broadened, the phases of voltage and current waves for each coil are proportionally shifted. Thus, the shifted phase of transmitting wave causes reactive power loss (thermal loss). The Sx coil plays a role to keep strong resonance coupling and reduce phase shift between Tx and Rx. The strong resonance associates with techniques to

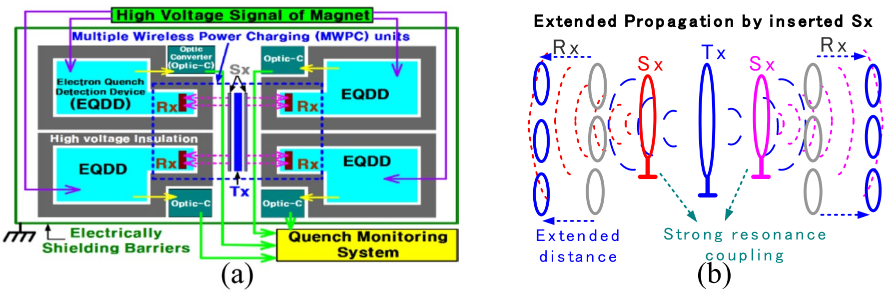

Fig. 2 **a** Processing illustration of quench detection system including electron quench detection device (EQDD) with isolated wireless multi- charging (WMC) units for super high field magnet. **b** Mechanism illustration of distance expansion by inserted dual-resonator (Sx coil) via strong resonance coupling method of wireless power transfer technology

improve efficiency and expand gaps. If multiple Sx coils are inserted between Tx and Rx coils at regular intervals, the transfer distance can be expanded all the more.

2.2 Properties of Multiple Resonators Between Tx and Rx Coils

Figure 3 shows experimental performances and thermal distributions for different Sx conditions with RF generator 200 W 370 kHz. The reflected power ratio is kept below 10 W (5%). Certainly, the inserted double Sx coils play a role to expand transferred power and delivery distance from Tx and Rx coils compared with non-Sx coils since the inserted Sx coil keeps the strong resonance coupling between Tx and Rx coils. The thermal losses are strongly generated at Sx_2 coil ([#1]), Sx_1coil ([#2]) due to the strong resonance coupling. Even though the strong resonance coupling between Tx and Rx coils is intrinsically sensitive to intervals between coils, the inserted Sx coils have a benefit to keep strong resonance coupling. Figure 4 shows the measured voltage and current waves at Tx, Sx and Rx coils under the different conditions of Fig. 3. In the condition of [# 1], the peak magnitudes of voltage and current waves at Tx, Sx_1, Sx_2 and Rx are 129, 24, 13, 95 V and 2.5, 1.4, 1.2, 0.42 A, respectively. In the condition of [# 2], the peak magnitudes of voltage and current waves at Tx, Sx_1, and Rx are 134, 29, 102 V, and 2.9, 1.3, 0.42 A, respectively. In the condition of [# 3], the peak magnitudes of voltage and current waves at Tx, and Rx are 154, 111 V, and 3.1, 0.45 A, respectively. Based on the results, the peak amplitudes of voltage waves at Rx coils of the condition [# 1] decreased about 15% compared with condition [# 3]. On the other hand, in the condition of [# 1], the transferred distance between Tx and Rx coils expanded over 50% compared with condition [# 3]. That is, even though the small thermal losses are generated in the Sx coil, it has a benefit to expand the delivery distance compared with non-Sx coil. The phase angle difference between Tx and Rx at condition [# 3] is certainly shifted, compared with other conditions. That means the phase angle difference between Tx and Rx causes increase in reflected power and then it induces the fragile resonance coupling between Tx and Rx coils under without Sx coils. In other words, the inserted Sx coil is effective to expand the transferred distance and keep maximized transfer power from Tx to Rx coils.

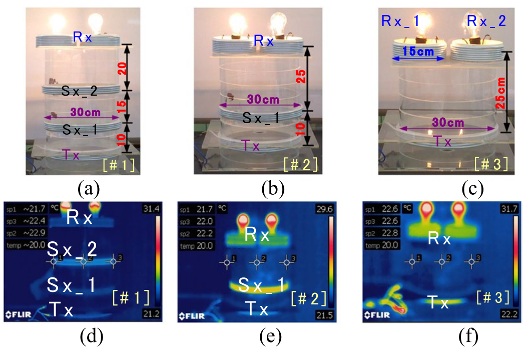

Fig. 3 Performance photographs and thermal distributions between Tx and Rx coils with 370 kHz of 200 W under different inserted Sx coil conditions; **a** and **d** are double Sx coils, **b** and **e** are single Sx coil, **c** and **f** are non-Sx coil

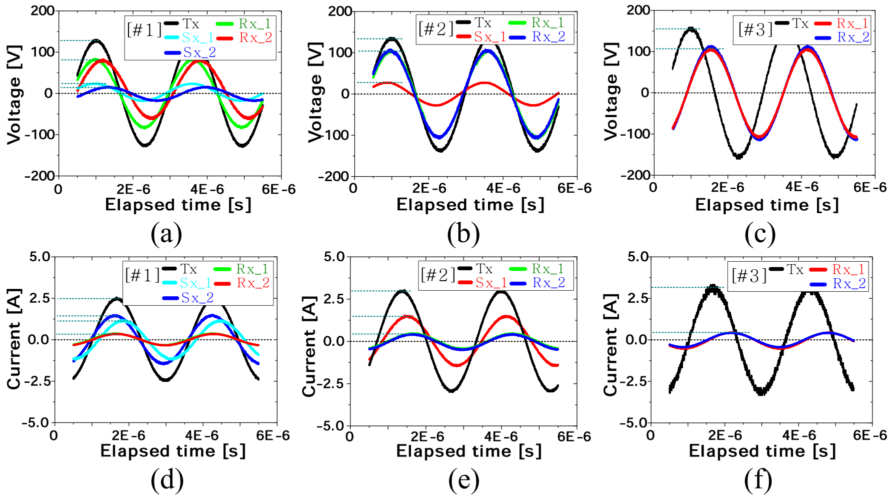

Fig. 4 Measured results of voltage and current waves for Tx, Sx and Rx resonance coils under different conditions of Fig. 3: The input power is 370 kHz of 200 W

3 Experimental Results and Conclusions

3.1 Measured Distributions of Electric Field and Magnetic Field between Resonance Coupling Coils

Figure 5 shows the practical experimental setup and performance for wireless charging unit inserted resonator with 300 W, 370 kHz of RF generator The measurement areas, which are 50 cm × 100 cm, are at the center positions between Tx and Sx coil, Sx and Rx coils, respectively. The measurement device of MASTFUYI EMF meter, which diameter of measuring cover is 5 cm, is adopted. Figure 5d and e shows the experimental performance with 300 W, 370 kHz of RF generator. In order to compare transferred power ratio fairly, the reflected power ratio is kept below 9 W (3%). Figure 5e and f shows the measured results of voltage and current waves at Tx and Rx coils for Tests 1 and 2. The measured peak magnitudes of voltage and current waves at Tx, Rx of Test, Rx of Test 2 are 209, 102, 82 V and 2.2, 1.4, 0.77, 0.76 A, respectively. Based on the results, the amplitude of current waves for Tests 1 and 2 is little changed. On the other hand, the amplitude of voltage waves of Rx coil at Test 1 increased over 18% compared with Test 2. The different multi-charging units for two patterns including different size of inserted Sx coils are carried out to realize the proposed structure of EQDD including WMC module. The dual Sx coils, which are installed in the both sides of Tx coil, play an important role to expand transferred power and delivery distance for both ways with high stability.

Figure 6a and b shows the measured distributions of the magnetic field (MF) and the electric field (EF), respectively, at the marked Fig. 5a. The measurement areas are over Sx coils under the different size of small Tx and long Sx coils. The intensity of the EF is concentrated at the center of Sx coils, however, the intensity

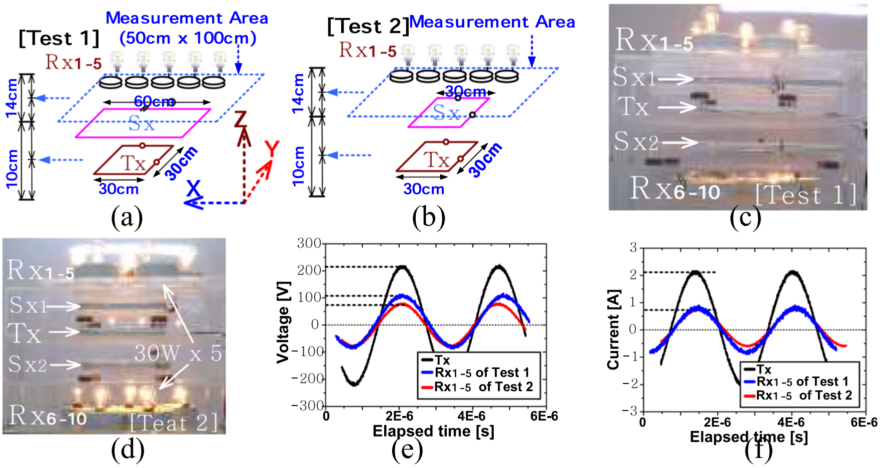

Fig. 5 Schematic illustrations, photograph of experimental setup and measured results of voltage and current waves at Tx and Rx coils with RF generator of 370 kHz, 300 W. The measurement areas are 50 cm × 100 cm: **a** Test 1 is different size of Tx and Sx coils. **b** Test 2 is same size of Tx and Sx coils. **c** and **d** are experimental performance of Test 1 and 2. **e** and **f** are the measured voltage and current distributions of Tx and Rx coils for Tests 1 and 2

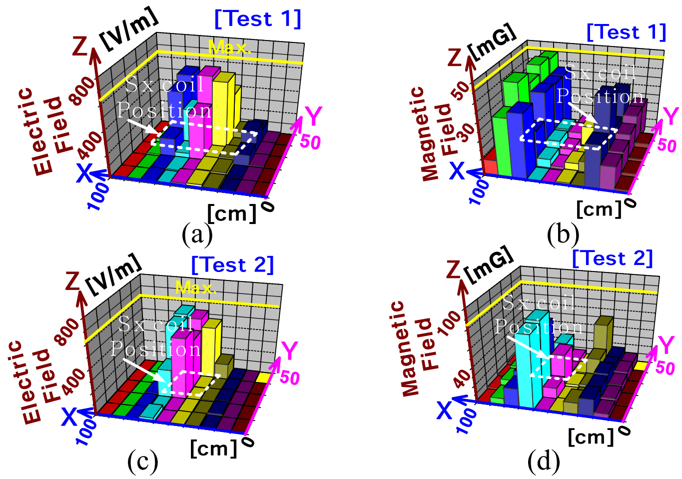

Fig. 6 Measured results of magnetic and electric field distributions with the different size of Tx and Sx coils including five loads in marked measurement area of Fig. 5a, b

of the MF is weakly concentrated at the center of Sx coil. The measured peak values of the EF and MF over Tx coil are 631 V/m and 46 mG. On the other hand, Fig. 6c and d shows the measured distributions of the magnetic field (MF) and the electric field (EF), respectively, at the marked Fig. 5b. The measurement areas are over Sx coils under the same size of small Tx and Sx coils. The intensity of the EF is strongly concentrated at the center of Sx coil, however, the intensity of the

MF is strongly distributed outside of Sx coil. The measured peak values of the EF and MF over Tx coil are 606 V/m and 90.7 mG, respectively. That is, propagations of the EF are strongly concentrated inside of Sx coils, however, the MF is strongly concentrated outside of Tx and Sx coils. Especially, the intensities of EF and MF are concentrated at the inside and outside of Sx coil frame, respectively.

4 Conclusions

Based on the investigated results of the conditions [#1] to [#3], even though the power delivery distance inserted double Sx coils is higher over 50% compared with non-Sx coil under same intervals under 370 kHz range, the peak amplitude of voltage waves decreased about 15%. On the other hand, the peak amplitude of current waves under the condition [# 1] decreased about 8% compared with the condition [#3]. That is the inserted Sx coil has a benefit to expand the delivery distance between Tx and Rx coils. In addition, the amplitude of voltage waves under large Sx coil of Test 1 increased over 18% compared with Test 2. That means the measured results of propagation distributions and intensity for EF and MF around Sx profit the arrangement plan of electron devices in the EQDD module. Thus, the proposed WMC unit for EQDD unit can be expected as one of reasonable options under super high field magnet with highly insulating stability. In the next study, the design considerations of the EQDD module including electric sub-circuits for the electro-magnetic interference (EMI) and electro-magnetic compatibility (EMC) should be evaluated based on the distributions and intensities of measured EF and MF under the inserted Sx coil conditions.

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Author Contribution Prof Chung wrote the main manuscript text. Dr. Chu supported the experimental concept and instruments. Prof. Kim supported technical method for the experiment and reviewed the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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