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RESEARCH ARTICLE

A Case Study for 50 kVA Toroidal Core Partially Superconducting Transformer

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ABSTRACT

We report some numerical results obtained for 50kVA single phase partially superconducting toroidal and core power transformers. Transformers are calculated using the Comsol Multiphysics software with ac/dc and heat transfer modules. They are modeled in such a way that their primary parts (medium voltage) consist of copper windings and secondary parts (low voltage) are formed by superconducting MgB_2 windings which are immersed into the liquid helium. Magnetic flux density profile on the iron core, primary and secondary currents, transformer power, and AC losses in superconducting windings are explored for one full cycle of AC voltage. Short-term temperature investigation for quenching showed that AC losses act as a heat source. We think that these numerical results are very important in terms of industrial-scale superconducting transformer applications because there are very few studies on MgB_2 transformers. Our results will enable the design of toroidal-type power transformers that may be operable in practice. According to the numerical simulation results, it seems that a compact low cost superconducting MgB_2 toroidal transformer can be realized with advances in cryostat systems and reducing AC losses. We suggest that the present study will contribute to the literature according to both the models applied and the results obtained.

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Introduction

In electricity transmission/distribution, there will be no more than 2.5% loss in overhead lines. Three to five percent loss occurs between the power plant and the step-down transformer center and as much loss occurs on the line up to the user. Increasing efficiency in electricity transmission and distribution is still a requirement, as total loss is on average between 8-15% by country. Superconducting materials cannot be used as widely as desired due to cooling costs. In current cryogenic cooling technologies, the required power for 1 W cooling power at 20 K is about 200-800 W. When the cooling systems have higher capacity, the ratio of the power used to the cooling power (kW/W) gets smaller for each cryogenic temperature (ter Brake & Wiegerinck, 2002).

Low AC loss and high current capability are mandatory for the realization of superconducting transformers (Hayashi et al., 2007). The total loss is equal to the sum of the heat input from the outside and the heat produced inside. Heat entering from the outside enters through the walls of the cryostat. The heat generated inside the transformer occurs due to the current terminals, windings and the iron core. On the other hand, core loss is decreased in the air-core transformer, but since more superconducting windings and/or higher current is required, the heat produced in the current transfer elements and the AC loss in the superconducting windings increase. Although technically

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air-core superconducting transformers are possible (Yamaguchi et al., 1992; Yamaguchi et al., 1996; Suarez et al., 2005; Wu et al., 2013), they will not be economically viable due to the large amount of superconducting wire to be used and increasing AC loss in the windings.

Fe core loss is large in the superconducting transformer used in LHe and thus Fe core is not immersed into LHe cryostat (Donnier-Valentin et al., 2001; Schwenterly et al., 2002; Iwakuma et al., 2015; Dai et al., 2016). There are studies in which the core is also cooled in high-T_c superconducting transformers operating in LN_2 (Šouc & Gömöry, 2002; Schlosser et al., 2003). The magnetic behavior of the core materials differs little at low temperatures (Bogdanov et al., 2004), so the effect of cooling of the core on the total inductance will be negligible.

Although toroidal transformers are widely used in low-current electronic applications, they are not yet used in energy systems. Studies published in the literature have shown that toroidal transformers made using copper wire are superior to traditional core and mantel (shell-shell) type transformers (Gómez et al., 2011; Hernández et al., 2011; Pleşca, 2013). This is because leakage flux loss originates in flux lines that do not pass through both primary and secondary windings. Magnetic flux leakage in a toroidal transformer is smaller due to its high symmetry. There are also studies for coiled coils in which primary and secondary windings are placed alternately between each other in order to reduce the leakage magnetic flux in conventional two-cell core type transformers (Kim et al., 2003; Hascicek et al., 2009). This method has also been studied in toroidal core transformers (Musenich et al., 2014; Dimitrov et al., 2015). There are toroidal transformers built and tested using high temperature superconductors (HTS) [Grzesik & Stepien, 2014].

In studies on MgB_2 superconducting transformers and superconducting fault current limiters (SFCL) [Hascicek et al., 2009; Pei et al., 2015], it was pointed out that the use of MgB_2 wires would be more economical than other options. In our study, the design of MV/LV (medium voltage/low voltage) toroidal core superconductor transformer using metal sheathed superconducting MgB_2 wire has been studied. The design of the transformer, whose LV winding coil is superconducting with a power level of 50 kVA, has been studied numerically.

Materials and Methods

50 kVA toroidal and core superconducting transformers have been studied numerically using the Comsol Multiphysics software with ac/dc and heat transfer modules. Simulated design for a toroidal core transformer is given in Figure 1. The parameters used for the calculation are given in Table 1. Temperature and magnetic field dependence of critical current density (J_c) in MgB_2 wires is given as

$$J_c(T) = J_{c0}\left[1-\left(\frac{T}{T_c}\right)^2\right]^{1.5} \quad (1)$$

$$J_c(B,T) = J_c(T)\left(1-\frac{\sqrt{B_r^2+B_z^2}}{B_1}\right)\left(1+\frac{\sqrt{B_r^2+B_z^2}}{B_0}\right)^{-\alpha} \quad (2)$$

Where, J_{c0} is the critical current density at 0 K, fitting parameters are $\alpha = 0.25$, $B_0 = 0.034$ T, $B_1 = 3.12$ T. AC loss for MgB_2 domains is calculated in (W/m) by Yazdani-Asrami et al. (2021).

$$Q = \frac{1}{T}\int_0^T \int E \cdot J ds dt \quad (3)$$

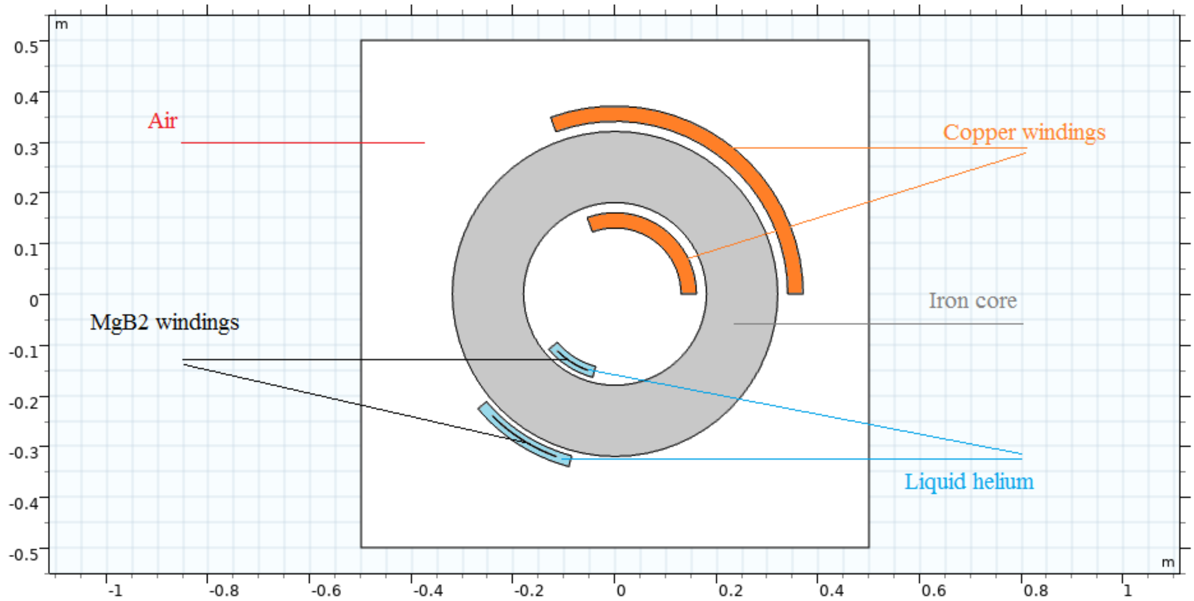

Figure 1. Components of toroidal core transformer.

Table 1. Important parameters used in the numerical calculation method.

Parameter	Value	Description
E_c	10^{-4} V/m	Critical electric field
n	40	n-value for MgB_2
f	50 Hz	AC voltage frequency
T_c	39 K	Critical temperature for MgB_2
T_a	4.2 K	Working temperature
ρ_{Cu}	1.68×10^{-8} Ω.m	Resistivity of copper
V_{ac}	34500 V	Medium voltage
N_s	50	Number of windings for LV
N_p	7500	Number of windings for MV
d_{out}	640 mm	Iron core outer diameter
d_{in}	360 mm	Iron core inner diameter

Results and Discussion

The results shown in Figures 2(a) to 2(c) were obtained for a 50 kVA toroidal core transformer and a voltage drop from 34500 V to 220 V was achieved. Figure 2(d) is obtained by changing the J_{c0} values of the wires between 1×10^9 A/m^2 and 1.5×10^9 A/m^2. Here, the current density of the LV windings is used for the J value. It is seen in Figure 2(d) how the AC loss increases on a logarithmic scale with a decrease in the J_{c0} value of the wire. Since the iron core is outside the liquid helium cryostat in the modeling, the most important heat mechanism is AC losses. If the critical current density value of the MgB_2 wire to be used is low, it is understood that the AC loss increases significantly. This result shows us that windings consisting of parallel superconductors may be necessary. The MV current is about 1.6 A, and the LV voltage is about 220 V without power loss (Figure 3).

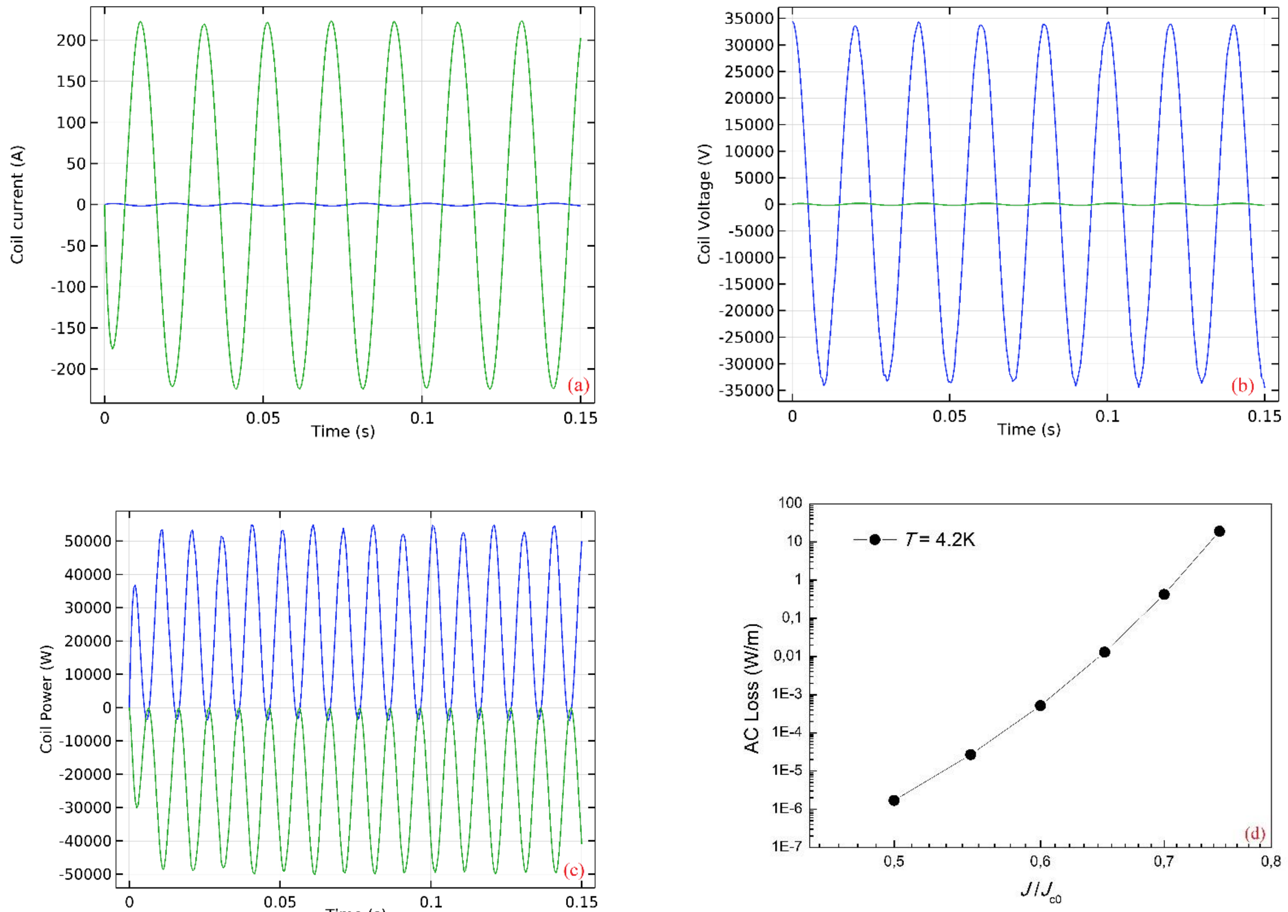

Figure 2. (a) Coil currents, **(b)** voltage values, **(c)** power values and **(d)** AC loss in the superconducting windings for a toroidal transformer design. Green lines represent LV and blue lines represent MV sides.

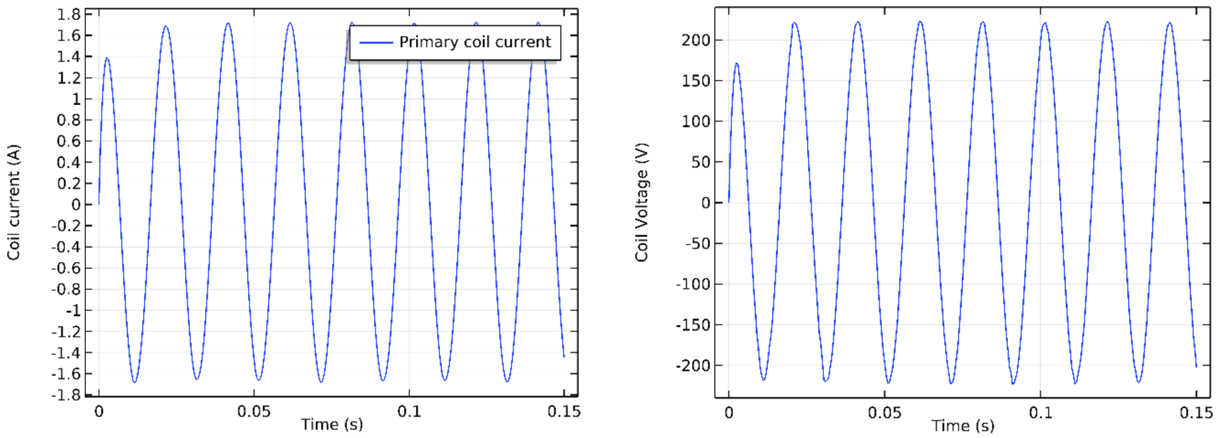

Figure 3. The figure on the left shows the current passing through the MV windings and the figure on the right shows the AC voltage value on the LV windings.

It is seen from Figure 4 that the magnetic flux density formed on the core is around the maximum $B = 0.45$ T. The flux density is higher in the inner part of the core and lower in the outer part. Direction changes in magnetic flux induced during one full cycle for a frequency value of 50 Hz are seen.

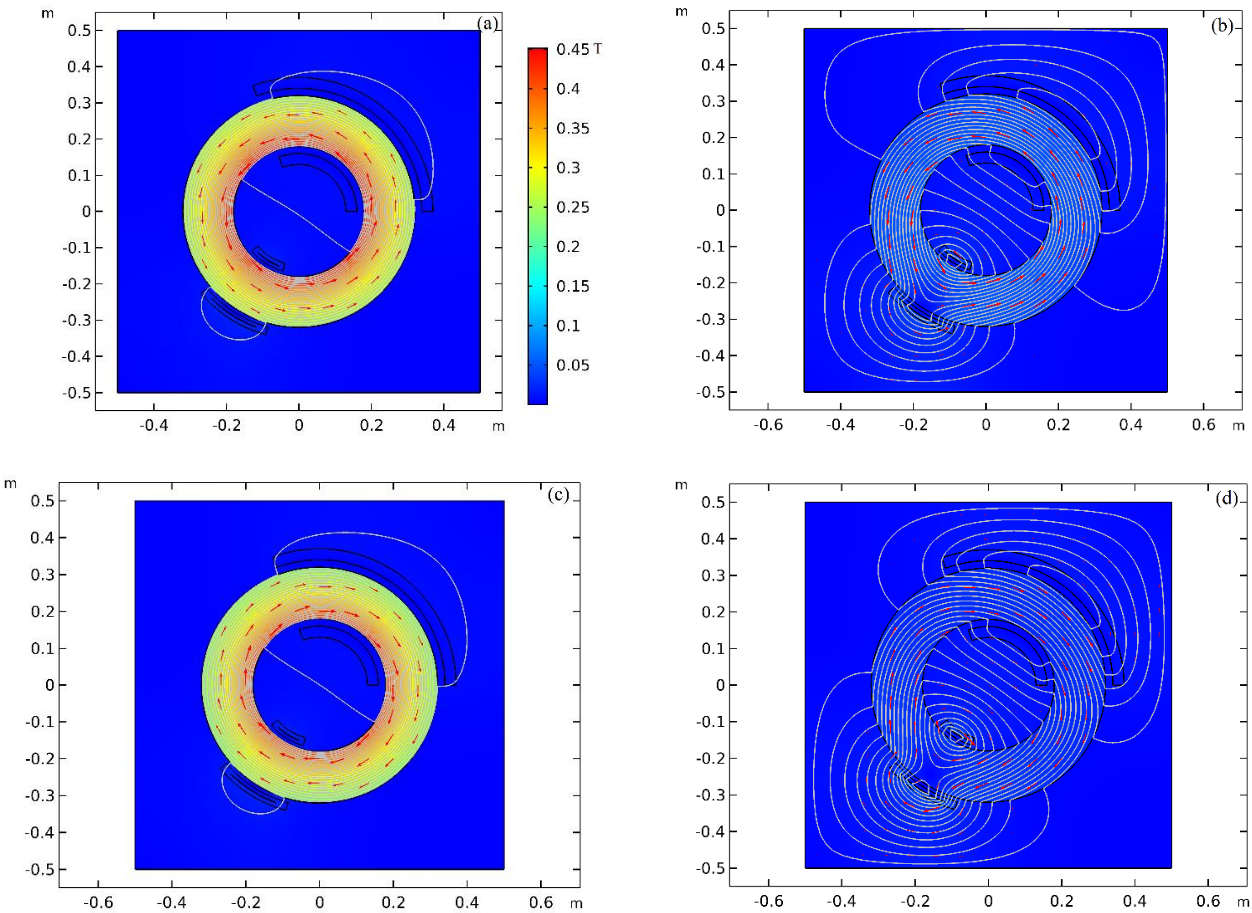

Figure 4. Magnetic flux density and current directions on the core are shown for **(a)** $t = 0.005$ s, **(b)** 0.01 s, **(c)** 0.015 s, and **(d)** 0.02 s.

Figure 5 shows the temperature changes measured inside and outside of the superconducting windings. Here, the temperature change graphs obtained from two end points of the inner windings and the outer windings, obtained from a total of four different points, are shown. The figure on the left is 9.5×10^{8} A/m^{2} and the figure on the right is obtained from superconducting windings with a critical current density of 1.0×10^{9} A/m^{2}. For a lower critical current density, it was observed that the temperature value of the windings increased from 4.2 K to 5.2 K for about 24 s. On the other hand, for J_{c0} =

1.0×10^9 A/m^2, the temperature rising rate is slower and the maximum temperature is lower than that of 9.5×10^8 A/m^2, so the temperature increases from 4.2 K to 4.85 K in 55 s at the inner endpoints. Although the temperature is 4.2 K in liquid helium, temperature gradients are inevitable in real physical situations involving time-dependent heat transfers, such as in a working transformer.

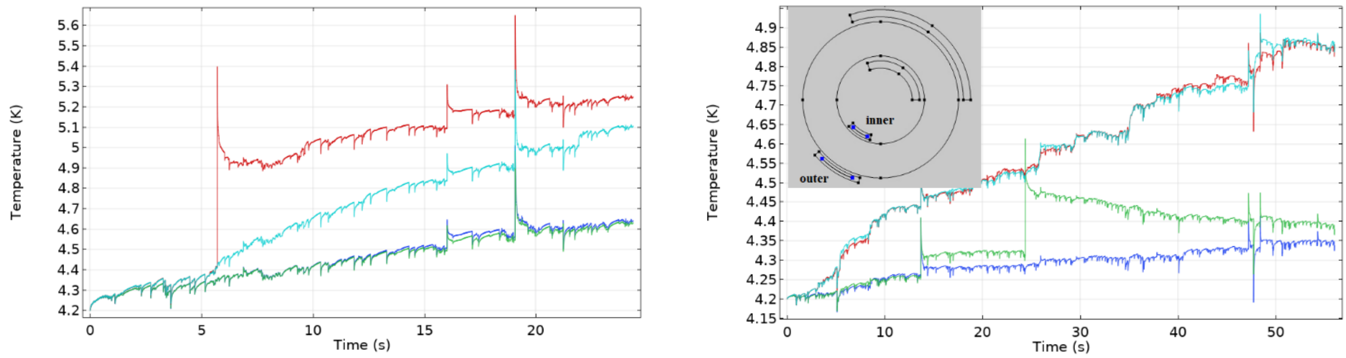

Figure 5. Temperature variation of superconducting windings of toroidal transformer designed from wires with different critical current densities. The figure on the left is for $J_{c0} = 9.5\times10^8$ A/m^2 and the right is for 1.0×10^9 A/m^2. Red-light blue colors represent inner endpoints and dark blue-green colors represent outer endpoints.

Figure 6 shows the changes in current, voltage, power and magnetic flux as a function of time for a 50 kVA square core superconducting transformer. When the Figure 6 is compared with the graphs obtained for the toroidal transformer in Figure 2, it is observed that when the core is transformed from a cylindrical section to a square section, the magnetic flux leakage increases and the transformer power decreases up to 40 kVA.

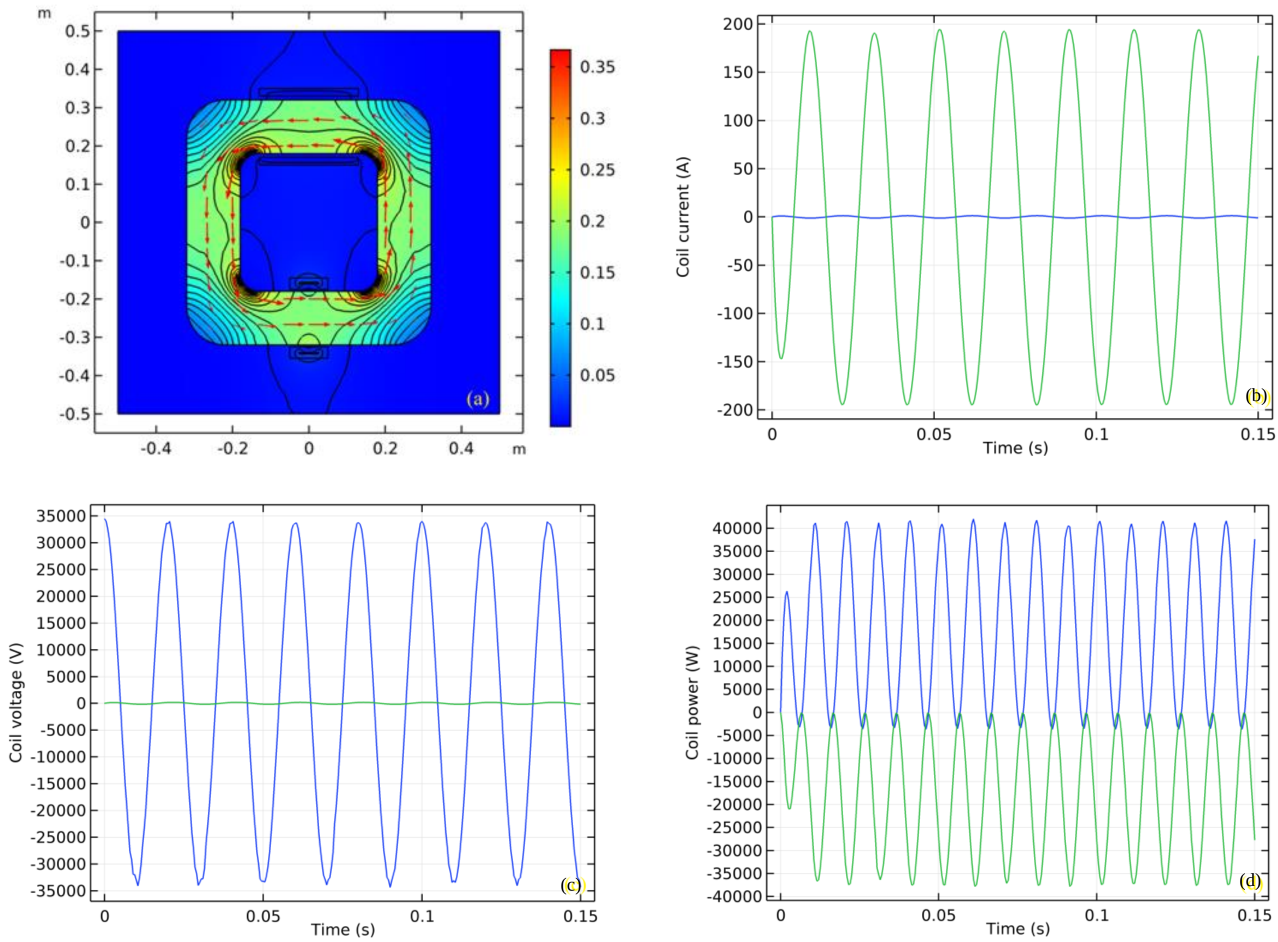

Figure 6. (a) Magnetic flux density, **(b)** current values, **(c)** voltage values, and **(d)** power values obtained by numerical calculation method for square type core transformer. The magnetic flux density and current direction formed on the core are shown for $t = 0.005$ s. The frequency value is $f = 50$ Hz and the critical current density is $J_{c0} = 1.0\times10^9$ A/m^2.

Conclusion

In our study, it has been revealed that a 50 kVA toroidal superconducting transformer is possible in terms of power applications. The results are very important for industrial-scale superconducting transformer applications and will enable the design of toroidal-type power transformers that may be more useful in practice. According to the calculated results, it also seems possible to minimize magnetic flux losses and power losses by choosing a square or stepped geometry with rounded corners instead of full toroidal geometry. In this way, it seems that a more suitable and lower cost superconducting transformer form can be obtained for cryostat systems.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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