Asymmetry in wireless power transfer between a superconducting coil and a copper coil

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Abstract

Wireless power transfer (WPT) is of increasing interests today. HTS (high temperature superconducting) WPT has been demonstrated to be more efficient than copper WPT. In our previous work, the efficiency of WPT from a copper coil (as the transmitting coil) to a HTS coil (as the receiving coil) is lower than the efficiency of WPT from the same HTS coil to the same copper coil. Namely, asymmetry exists and degrades WPT performance. In this paper, it is demonstrated theoretically and experimentally that, for WPT between a HTS coil and a Litz coil: asymmetry does exist and influence properties; the root of the asymmetry is the different resistances between the HTS coil and the Litz coil; the effects of the asymmetry can be eliminated by optimizing the load; the proposed theoretical calculation fit the experimental results well.

Theoretical Analysis A. Coupled-mode Theory

In many WPT researches, coupled-mode theory is often employed as the method for theoretical analysis.

\[ R_c(t)=a(t)F(t) \] \( F(t) \) is the field of the two resonant objects in WPT system; \( a(t) \) and \( b(t) \) are the eigenmodes of object 1 and 2. The field amplitudes \( a(t) \) and \( b(t) \) can be written as

\[ \frac{da}{dt} = i\omega \cdot a_1 - \Gamma_a \cdot a_1 + \kappa_a \cdot a_2 + Fe^{-i\omega t} \]

\[ \frac{db}{dt} = i\omega \cdot b_2 - \Gamma_b \cdot b_2 + \kappa_b \cdot a_2 \]

The expression of the efficiency \( \eta \) can be written as

\[ \eta = \frac{\Gamma_1 \cdot \kappa_1 \cdot \Gamma_2 \cdot \kappa_2 \cdot \eta_{12}}{(1 + \Gamma_1 \cdot \Gamma_2) \cdot (1 + \kappa_1 \cdot \Gamma_2) \cdot (1 + \Gamma_1 \cdot \kappa_2)} \]

For given \( \Gamma_1 \) and \( \Gamma_2 \), the resonant efficiency is dependent only on \( \Gamma_2 \).

The effect of asymmetry maintaining \( \Gamma_2 = 3 \Omega \)

The transfer efficiency of Case 2 is higher.

Asymmetry does exist.

The efficiency reduction generated by asymmetry is dependent on the load.

Theoretical Analysis B. Circuit Theory

The equivalent circuit of a WPT system can be illustrated as:

\[ \begin{align*}
M & \text{ the mutual inductance; } \\
C_1 & \text{ the capacitance of the capacitors; } \\
L_1 & \text{ and } L_2 \text{ the inductance of the coils; } \\
R_1, R_2, \text{ and } R_z & \text{ the resistance of the load, and the resonators.}
\end{align*} \]

The AC source was supplied by Tektronix AFG3101 function generator and AE TECHRON 7796 amplifier.

The HTS: Bi2223 tapes;
The turns: 12.75;
The inner radius: 175 mm;
The inductance: 139.98 µH

Experiments A. Approach

Experiments B. Results and Discussion

For the case of resonance \((\omega L_1=\omega L_2)^{-1}\), we can determine the efficiency

\[ \eta = \frac{R_1 \cdot \omega M^2}{(1+R_1) \cdot (1+R_2) \cdot \omega M^2} \]

When \( R_z = 1 \): the efficiency is maximized. At such condition, the efficiency can be written as

\[ \eta_{\text{max}} = 1 - \frac{2}{\omega M^2} \]

For given \( R_1 \) and \( R_2 \), the resonant efficiency is dependent only on \( R_z \).

The efficiency reduction generated by asymmetry is dependent on the load.

The asymmetry does exist in wireless power transfer using one superconducting coil.

For given parameters, WPT using superconductors only for the transmitter produce the different efficiencies than only for the receiver.

The phenomena of asymmetry indeed exists. In the error range of 0.5%, the maximum efficiency in HTS-Litz is equal that in HTS-Litz and so the reduction in the efficiency generated by asymmetry can be eliminated by impedance matching.

Conclusion

Asymmetry can be thought of as a form of impedance mismatch.

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