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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.

$\vec{F}(\vec{r},t)=a_1(t)\vec{F}_1(\vec{r})+a_2(t)\vec{F}_2(\vec{r})$: the field of the two resonant objects in WPT system;

$\vec{F}_1(\vec{r})$ and $\vec{F}_2(\vec{r})$: the eigenmodes of object 1 and 2.

The field amplitudes $a_1(t)$ and $a_2(t)$ the can be written as

$$\begin{cases}\dfrac{da_1}{dt}=i\omega_1\cdot a_1-\Gamma_1\cdot a_1+\kappa_{12}\cdot a_2+Fe^{-j\omega t}\\ \dfrac{da_2}{dt}=i\omega_2\cdot a_2-(\Gamma_2+\Gamma_L)\cdot a_2+\kappa_{21}\cdot a_1\end{cases}$$

ω_1 and ω_2: the individual eigenfrequencies;

Γ_1, Γ_2 and Γ_L: the intrinsic decay rates of object 1, 2 and load;

κ_{12} and κ_{21}: the coupling coefficients;

$Fe^{-j\omega t}$: the driving term.

The expression of the efficiency η can be written as

$$\eta=\frac{\Gamma_L|a_2|^2}{\Gamma_1|a_1|^2+(\Gamma_2+\Gamma_L)|a_2|^2}$$

$\Gamma_1|a_1|^2$ and $\Gamma_2|a_2|^2$: the energy dissipation in each object;

$\Gamma_L|a_2|^2$: the energy transferred into the load.

When the two objects are resonant ($\kappa^2|a_1|^2=(\Gamma_2+\Gamma_L)^2|a_2|^2$), we can determined the efficiency

$$\eta=\frac{\frac{\Gamma_L}{\Gamma_2}\frac{\kappa^2}{\Gamma_1\Gamma_2}}{(1+\frac{\Gamma_L}{\Gamma_2})^2+(1+\frac{\Gamma_L}{\Gamma_2})\frac{\kappa^2}{\Gamma_1\Gamma_2}}$$

For given $\Gamma_1\Gamma_2$ and Γ_L, the resonant efficiency is dependent only on Γ_2.

Asymmetry does exist.

When $(\Gamma_L/\Gamma_2)^2=1+\kappa^2/\Gamma_L\Gamma_2$, the efficiency is maximized. At such condition, the efficiency can be written as

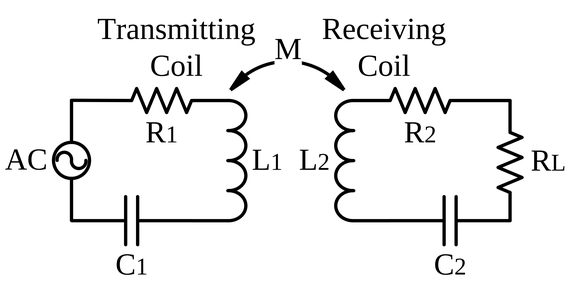
$$\eta_{max}=\frac{\Gamma_L-\Gamma_2}{\Gamma_L+\Gamma_2}=1-\frac{2}{\sqrt{1+\frac{\kappa^2}{\Gamma_1\Gamma_2}}+1}$$

By adjusting the load, the same maximum efficiency can be obtained.

The efficiency reduction caused by asymmetry can be eliminated.

Theoretical Analysis B. Circuit Theory

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



M: the mutual inductance;

C_1 and C_2: the capacitance of the capacitors;

L_1 and L_2: the inductance of the coils;

R_L, R_1 and R_2: the resistance of the load, and the resonators.

The efficiency could be written as

$$\eta=\frac{\omega^2M^2R_L}{\omega^2M^2(R_2+R_L)+R_1\left[(R_2+R_L)^2+(\omega L_2-\frac{1}{\omega C_2})^2\right]}$$

ω: the angular frequency.

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

$$\eta=\frac{\frac{R_L}{R_2}\frac{\omega^2M^2}{R_1R_2}}{(1+\frac{R_L}{R_2})^2+(1+\frac{R_L}{R_2})\frac{\omega^2M^2}{R_1R_2}}$$

For given ω_2M_2/R_1R_2 and R_L, the resonant efficiency is dependent only on R_2.

Asymmetry indeed exists.

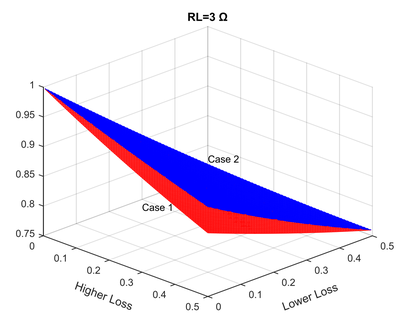
When $(R_L/R_2)^2=1+\omega^2M^2/\Gamma_L\Gamma_2$, the efficiency is maximized. At such condition, the efficiency can be written as

$$\eta_{max}=1-\frac{2}{\sqrt{1+\frac{\omega^2M^2}{R_1R_2}}+1}$$

The same maximum power transfer efficiency can be achieved by adjusting R_L.

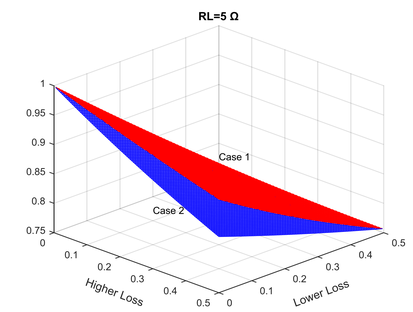
Asymmetry can be understood as a form of impedance mismatch.

Case 1: the coil of lower loss as the transmitting coil; Case 2: the coil of higher loss as the transmitting coil.



The effect of asymmetry maintaining R_l at 3 Ω

The transfer efficiency of Case 2 is higher.

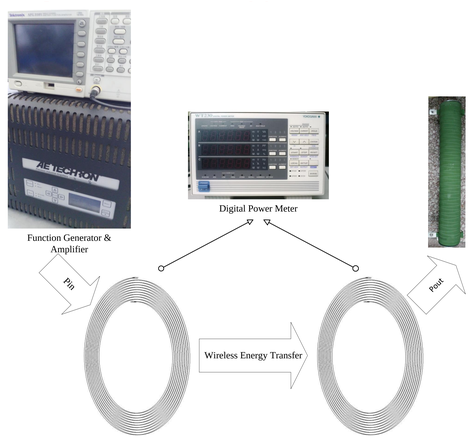


The influence of asymmetry for R_L=5 Ω

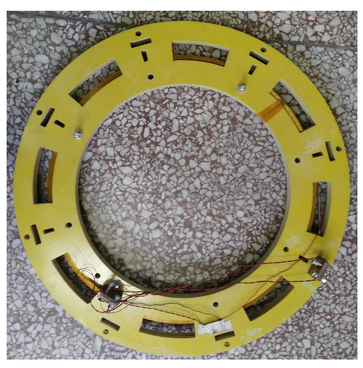
The transfer efficiency of Case 2 is lower.

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

Experiments A. Approach



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



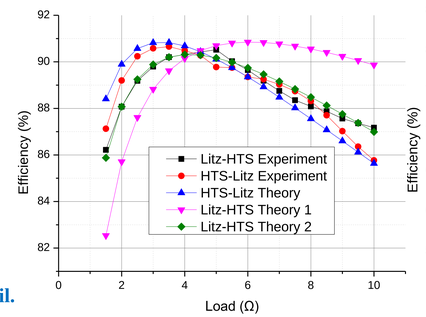
The HTS: Bi2223 tapes;

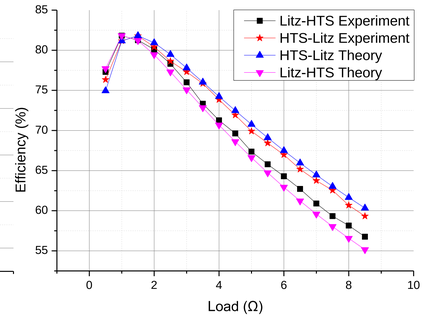
The turns: 12.75;

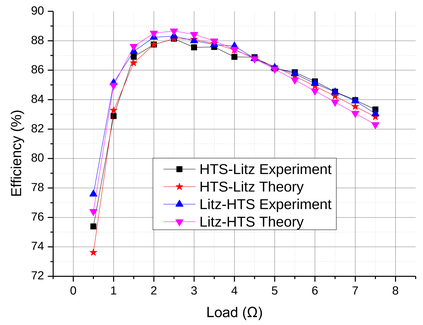
The inner radius: 175 mm;

The inductance: 139.98 μH.

Experiments B. Results and Discussion







The efficiencies at different resistance for 20 kHz, 3kHz and 5 kHz.

3 kHz: the optimal load of Litz-HTS (1 Ω) is smaller than that of HTS-Litz (1.5 Ω); 5 kHz: the optimal load of Litz-HTS (2.5 Ω) is the same as that of HTS-Litz (2.5 Ω); 20 kHz: the optimal load of Litz-HTS (5 Ω) is larger than that of HTS-Litz (3.5 Ω).

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

20 kHz: the maximum WPT efficiency in Litz-HTS is 90.653% (corresponding to 3.5 Ω) and that in HTS-Litz is 90.518% (corresponding to 5 Ω).

3 kHz: the maximum transfer efficiency in Litz-HTS is 81.81% (corresponding to 1 Ω) and that in HTS-Litz is 81.79% (corresponding to 1.5 Ω).

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

Conclusion

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 wireless power transfer using one superconducting coil.

By adjusting the load, the reduction in efficiency generated by asymmetry can be eliminated and the same maximum can be obtained.

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

Acknowledgements

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