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Resonator Impedance Optimization for Quasi-Static Magnetic Resonance Based Actuation

Introduction

Strongly coupled magnetic resonance (SCMR) is used to induce currents in a system of resonator coils. These induced currents are used to apply torque on a rotating resonator coil (rotor). The rotor angle dependent coil-coil torque interactions can be optimized by altering the impedance of the resonator coils, shifting their resonance frequency. A 14% gain in average torque is obtained for the considered system by detuning the capacitor values of the system’s resonators.

Two-Level Implementation of Resonant Wireless Power Transfer

Frequency Domain Analytical Force Model

Induced Voltage in Moving Coils Has Two Causes

\[ e_a = -\frac{d}{dt}[M_a(\theta) i_a] \]

\[ \frac{d}{dt}[M_a(\theta) i_a] = \frac{d}{dt}[M_a(\theta) i_a] + \frac{d}{dt}[M_a(\theta) i_a] \]

\[ = K_{a0}(\theta)i_a + M_{a0}(\theta)i_a \]

- Motional electromotive force \( K(\theta)i_0 \)
- Transformer electromotive force \( M(\theta)i_0 \)

System Equations for a Voltage Controlled Transmitter

\[
\begin{bmatrix}
R_t & j\omega M_{t} & j\omega M_{t} & R_t + j\omega & j\omega M_{t} + R_t + j\omega M_{t} \\
R_t & R_t + j\omega & j\omega & j\omega M_{t} + R_t + j\omega M_{t} \\
R_t & j\omega M_{t} + j\omega M_{t} & R_t + j\omega M_{t} + j\omega M_{t} & R_t + j\omega M_{t} + j\omega M_{t} \\
R_t + j\omega M_{t} + j\omega M_{t} & R_t + j\omega M_{t} + j\omega M_{t} & R_t + j\omega M_{t} + j\omega M_{t} & R_t + j\omega M_{t} + j\omega M_{t}
\end{bmatrix} \bullet = \begin{bmatrix} V_t \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

Quasi-Static Torque

\[ T_m(\theta) = \frac{1}{2} \sigma^T (PM) \frac{1}{2} = \frac{1}{2} \begin{bmatrix} 0 & 0 & K_r(\theta) \\ 0 & 0 & K_r(\theta) \\ K_r(\theta) & K_r(\theta) & 0 \end{bmatrix} \]

Experimental Validation

Applicability of Analytical/Numerical Models

- Tuning dependent rotational stability (unidirectional actuation)
- Analytical and numerical force and torque model validation
- Validation of iterative numerical design optimization

Watch the Setup in Action!

Resonant Wireless Power Transfer

The addition of passive resonators drastically increases the induced voltage at the receiver coil.

Resonator Impedance Optimization

Resonance in the Absence of Other Resonators

- Standard SCMR systems show optimal power transfer efficiency if the resonator coil impedance is minimized

\[
t_1 X_0 = j\omega L_0 + \frac{1}{j\omega C_0} = 0 \rightarrow C_0 = \frac{1}{\omega^2 L_0}
\]

Resonator Interactions Affect Torque Profile

- Coil-coil interactions (e.g. \( M_{sr}(\theta) \)) introduce phase-shifting between interacting currents in the transmitter, stator, and rotor coils.

- The quasi-static torque profile model indicates a high dependency on the rotor position (\( \theta \)) and resonator tuning \( (X_r, C_r) \).

Capacitor Detuning Improves the Torque Profile

- A gradient based (interior-point) optimization procedure is used to find the optimal tuning starting from the resonant condition.

- Detuning of the capacitors in the systems resonators can improve the average torque by 14% for the considered system.

Conclusions

- The principles of WPT can be used directly for unidirectional motoring
- The resonators of the SCMR motoring system can be detuned to increase the average torque of the considered system.
- A torque gain of 14% was obtained by detuning the resonators from their resonant condition.

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15th International Workshop on Optimization and Inverse Problems in Electromagnetism
Hall in Tirol, Austria